

IAEA

International Atomic Energy Agency

**Eddy Current Testing at
Level 2: Manual for the
Syllabi Contained in
IAEA-TECDOC-628.Rev. 2
"Training Guidelines for
Non Destructive
Testing Techniques"**

Eddy Current Testing at Level 2:
Manual for the Syllabi Contained in IAEA-
TECDOC-628/Rev. 2, 'Training Guidelines for Non-
Destructive Testing Techniques'

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TRAINING COURSE SERIES NO. 48

**Eddy Current Testing at Level 2:
Manual for the Syllabi Contained
IAEA-TECDOC-628/Rev. 2
'Training Guidelines for
Non-Destructive
Testing Techniques'**

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2011

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FOREWORD

The International Atomic Energy Agency has been active in the promotion of non-destructive testing (NDT) technology in the world for many decades. The prime reason for this interest has been the need for stringent standards for quality control for safe operation of nuclear as well as other industrial installations. It has successfully executed a number of programmes including technical co-operation (TC) projects (national and regional) and the coordinated research projects (CRP) of which NDT was an important part. Through these programmes a large number of persons in the Member States have been trained, leading to establishment of national certifying bodies (NCB) responsible for training and certification of NDT personnel. Consequently, a state of self-sufficiency in this area of technology has been achieved in many of them.

All along there has been a realization of the need to have well established training guidelines and related books in order, firstly, to guide the IAEA experts who were involved in this training programme and, secondly, to achieve some level of international uniformity and harmonization of training materials and consequent competence of NDT personnel.

The syllabi for training courses have been published in the form of IAEA-TECDOC publications. The first was IAEA-TECDOC-407 (1987), which contained syllabi for the basic five methods, i.e. liquid penetrant testing, magnetic particle testing, eddy current testing, radiographic testing and ultrasonic testing. To accommodate advancements in NDT technology, later versions of this publication were issued in 1991, 2002 and 2008, the current version being IAEA-TECDOC-628/Rev.2 (2008), which includes additional and more advanced NDT methods. This IAEA-TECDOC, as well as most of the international standards on the subject of training and certification of NDT personnel including ISO 9712 (2005), define three levels of competence. Among these, level 1 is the lowest and level 3 the highest. The intermediate level 2 is considered to be the most appropriate for persons who, beside other duties, are expected to independently undertake practical testing in the relevant method of NDT; develop NDT procedures adapted to various problems; prepare written instructions; make accept/reject decisions in accordance with relevant standards and specifications; organize and report NDT results and be able to train and supervise the level 1 staff under them.

The next logical step has been to compile the text books and training manuals in accordance with these syllabi. Work in this regard has been undertaken and the manuals on liquid penetrant testing, magnetic particle testing, radiographic testing and ultrasonic testing have already been published in the Training Course Series. These play a vital role for training and certification of NDT personnel throughout the world.

Compilation of this book is a continuation of that effort. The first draft of the book was developed as a home-based assignment by experts from Australia, the Republic of Korea and Pakistan. It was reviewed and finalized by an RCA consultants meeting of experts from Australia, the Republic of Korea and the United Kingdom, held in Vienna during 2009. This has been done by putting in additional material wherever needed and then rearranging the whole in accordance with the format of level 2 eddy current testing syllabi in IAEA-TECDOC- 628/Rev.2 (2008). The section on materials, manufacturing processes and defects and quality assurance, which is common to all the NDT methods, has been adapted from the previous publications in the Training Course Series.

The IAEA wishes to express its appreciation to all those who contributed to the production of this book in the Training Course Series. The IAEA officers responsible for this publication were P. Dias and K. Sukasam of the Department of Technical Cooperation and J.-H. Jin and A.A. Khan of the Division of Physical and Chemical Sciences.

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CONTENTS

| | | |
|------|--|-----|
| 1. | GENERAL KNOWLEDGE | 1 |
| 1.1. | Basic Principles of Non-Destructive Testing (NDT) | 1 |
| 1.2. | Materials and defects | 12 |
| 1.3. | Processing and defects | 24 |
| 1.4. | Materials in service | 72 |
| 1.5. | Quality and standardization | 81 |
| 2. | PHYSICAL PRINCIPLES | 89 |
| 2.1. | Electricity | 89 |
| 2.2. | Magnetism | 98 |
| 2.3. | Magnetic field produced by a current | 105 |
| 2.4. | Electromagnetic induction law | 109 |
| 2.5. | Factors effecting eddy currents | 112 |
| 3. | INSTRUMENTATION | 116 |
| 3.1. | Principles and basic characteristics of eddy current probes | 116 |
| 3.2. | Eddy current distribution relative to coil position | 121 |
| 3.3. | Reaction of different types of probes according to coil layout | 124 |
| 3.4. | Technology and Practical characteristics of probes | 126 |
| 3.5. | Main function and adjustment of the equipment | 127 |
| 3.6. | Different types of eddy current equipment | 136 |
| 3.7. | Auxiliary devices | 139 |
| 4. | TESTING PROCEDURES | 143 |
| 4.1. | Influence of defect position and orientation | 143 |
| 4.2. | Influence of material temperature | 146 |
| 4.3. | Influence of structure and geometry of tested parts (noise) | 147 |
| 4.4. | Coupling influence | 150 |
| 4.5. | Influence of relative part/probe speed | 151 |
| 4.6. | Reference standards used in eddy current testing | 152 |
| 4.7. | Inspection method | 154 |
| 4.8. | Preparation of written instructions for level 1 | 154 |
| 5. | APPLICATIONS | 155 |
| 5.1. | Surface testing | 155 |
| 5.2. | Tube testing | 186 |
| 5.3. | Multi-frequency testing | 200 |
| 6. | PRESENTATION OF RESULTS | 201 |
| 6.1. | Eddy current testing codes and standards | 201 |
| 6.2. | Standards for equipment characteristics and verification | 202 |
| 6.3. | Written procedures for eddy current testing | 202 |
| 6.4. | Inspection techniques and their use | 203 |
| 6.5. | Records and reports | 204 |
| 6.6. | Safety | 205 |

| | |
|---|-----|
| APPENDIX I. EDDY CURRENT SYMBOLS AND UNITS | 207 |
| APPENDIX II. GLOSSARY OF TERMS FOR EDDY CURRENT TESTING..... | 208 |
| APPENDIX III. EXAMPLE EDDY CURRENT PROCEDURE AND REPORT..... | 214 |
| APPENDIX IV. DEVIATION FROM SYLLABUS FORMAT OF IAEA-TECDOC-628 REV2. (2008)..... | 219 |
| BIBLIOGRAPHY | 221 |
| CONTRIBUTORS TO DRAFTING AND REVIEW | 225 |

1. GENERAL KNOWLEDGE

1.1. Basic Principles of Non-Destructive Testing (NDT)

1.1.1 Definition and importance of NDT

Non-destructive testing is the use of physical methods which will test materials, components and assemblies for flaws in their structure without damaging their future usefulness. NDT is concerned with revealing flaws in the structure of a product. It, however, cannot predict where flaws will develop due to the design itself. All NDT methods have the following common characteristics:

- (a) The application of a testing medium to the product to be tested.
- (b) The changes in the testing medium due to the defects in the structure of the product.
- (c) A means by which it detects these changes.
- (d) Interpretation of these changes to obtain information about the flaws in the structure of the product.

Importance of NDT

NDT plays an important role in the quality control of a product. It is used during all the stages of manufacturing of a product. It is used to monitor the quality of the:

- (a) Raw materials which are used in the construction of the product.
- (b) Fabrication processes which are used to manufacture the product.
- (c) Finished product before it is put into service.

Use of NDT during all stages of manufacturing results in the following benefits:

- (a) It increases the safety and reliability of the product during operation.
- (b) It decreases the cost of the product by reducing scrap and conserving materials, labour and energy.
- (c) It enhances the reputation of the manufacturer as producer of quality goods.

All of the above factors boost the sales of the product which bring more economical benefits to the manufacturer. NDT is also used widely for routine or periodic determination of quality of the plants and structures during service. This not only increases the safety of operation but also eliminates any forced shut down of the plants.

1.1.2 Types of NDT methods

The methods of NDT range from the simple to the complicated. Visual inspection is the simplest of all. Surface imperfections invisible to the eye may be revealed by penetrant or magnetic methods. If really serious surface defects are found, there is often little point in proceeding to more complicated examinations of the interior by ultrasonics or radiography. NDT methods may be divided into groups for the purposes of these notes: conventional and non-conventional. To the first group may belong the methods which are commonly used and include visual or optical inspection, liquid penetrant testing, magnetic particle testing, eddy current testing, radiographic testing and ultrasonic testing. The second group of NDT methods are those used only for specialized applications and consequently are limited in use. Some of these methods which are being mentioned here merely as a curiosity for the reader include neutron radiography, acoustic emission, thermal and infrared testing, strain sensing,

microwave techniques, leak testing, holography etc. It must also be remembered that no one of these methods can give us solutions to all the possible problems, i.e. they are not optional alternatives but rather complementary to each other. The basic principles, typical applications, advantages and limitations of the methods of group one will now be briefly described.

1.1.3 Visual testing (VT)

Often overlooked in any listing of NDT methods, visual inspection is one of the most common and most powerful means of non-destructive testing. Visual testing requires adequate illumination of the test surface and proper eye-sight of the tester. To be most effective visual inspection does however, merit special attention because it requires training (knowledge of product and process, anticipated service conditions, acceptance criteria, record keeping, for example) and it has its own range of equipment and instrumentation. It is also a fact that all defects found by other NDT methods ultimately must be substantiated by visual inspection. Visual testing can be classified as direct visual testing, remote visual testing and translucent visual testing. The most common NDT methods MT and PT are indeed simply scientific ways of enhancing the indication to make it more visible. Often the equipment needed is simple FIG. 1.1 a portable light, a mirror on stem, a 2× or 4× hand lens, one illuminated magnifier with magnification 5× or 10×. For internal inspection, light lens systems such as borescopes allow remote surfaces to be examined. More sophisticated devices of this nature using fibre optics permit the introduction of the device into very small access holes and channels. Most of these systems provide for the attachment of a camera to permit permanent recording.

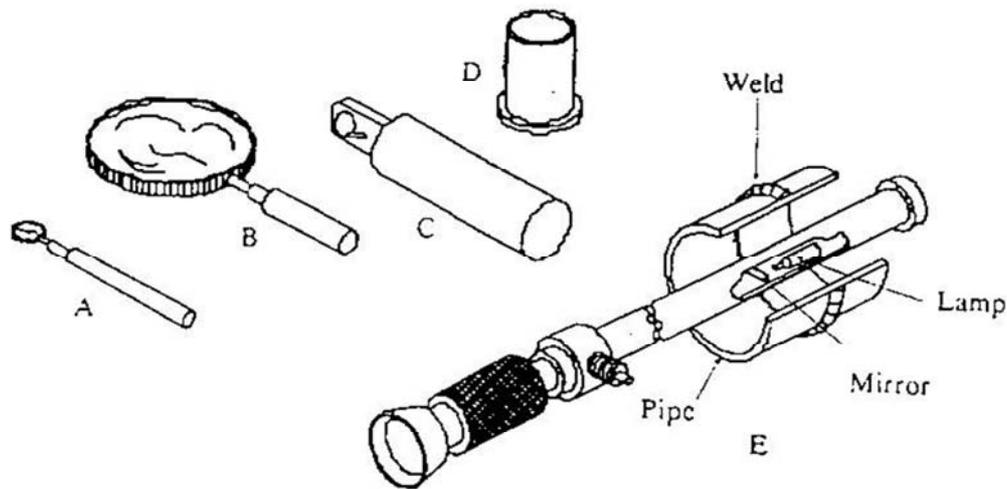


FIG. 1.1. Various optical aids used in visual inspection. (a) Mirror on stem: may be flat for normal view or concave for limited magnification. (b) Hand magnifying glass (magnification usually 2–3×). (c) Illuminated magnifier; field of view more restricted than D (magnification 5–10×). (d) Inspection glass, usually fitted with a scale for measurement; the front surface is placed in contact with the work (magnification 5–10×). (e) Borescope or intrascope with built-in illumination (magnification 2–3×).

The applications of visual testing include:

- (a) Checking of the surface condition of the test specimen.
- (b) Checking of alignment of mating surfaces.
- (c) Checking of shape of the component.

- (d) Checking for evidence of leaking.
- (e) Checking for internal side defects.

1.1.4 Liquid penetrant testing (PT)

This is a method which can be employed for the detection of open-to-surface discontinuities in any industrial product which is made from a non-porous material. This method is widely used for testing of non-magnetic materials. In this method a liquid penetrant is applied to the surface of the product for a certain predetermined time, after which the excess penetrant is removed from the surface. The surface is then dried and a developer is applied to it. The penetrant which remains in the discontinuity is absorbed by the developer to indicate the presence as well as the location, size and nature of the discontinuity. The process is illustrated in FIG. 1.2.

Penetrants used are either visible dye penetrant or fluorescent dye penetrant. The inspection for the presence of visible dye indications is made under white light while inspection of presence of indications by fluorescent dye penetrant is made under ultraviolet (or black) light under darkened conditions. The liquid penetrant processes are further sub-divided according to the method of washing of the specimen. The penetrants can be: (i) water-washable, (ii) post-emulsifiable, i.e. an emulsifier is added to the excess penetrant on surface of the specimen to make it water-washable, and (iii) solvent removable, i.e. the excess penetrant is needed to be dissolved in a solvent to remove it from the test specimen surface.

In order of decreasing sensitivity and decreasing cost, the liquid penetrant processes can be listed as:

- (a) Post emulsifiable fluorescent dye penetrant.
- (b) Solvent removable fluorescent dye penetrant.
- (c) Water washable fluorescent dye penetrant.
- (d) Post emulsifiable visible dye penetrant.
- (e) Solvent removable visible dye penetrant.
- (f) Water washable visible dye penetrant.

Some of the advantages of liquid penetrant testing are as follows:

- (a) Relatively low cost.
- (b) Highly portable NDT method.
- (c) Highly sensitive to fine, tight discontinuities.
- (d) Fairly simple method.
- (e) Can be used on a variety of materials.
- (f) All surface discontinuities are detected in one operation, regardless of orientation.

Some of the limitations of liquid penetrant testing are as follows:

- (a) Test surface must be free of all contaminants (dirt, oil, grease, paint, rust, etc.).
- (b) Detects surface discontinuities only.
- (c) Cannot be used on porous specimens and is difficult to use on very rough surfaces.
- (d) Removal of all penetrant materials, following the test, is often required.
- (e) There is no easy method to produce permanent record.

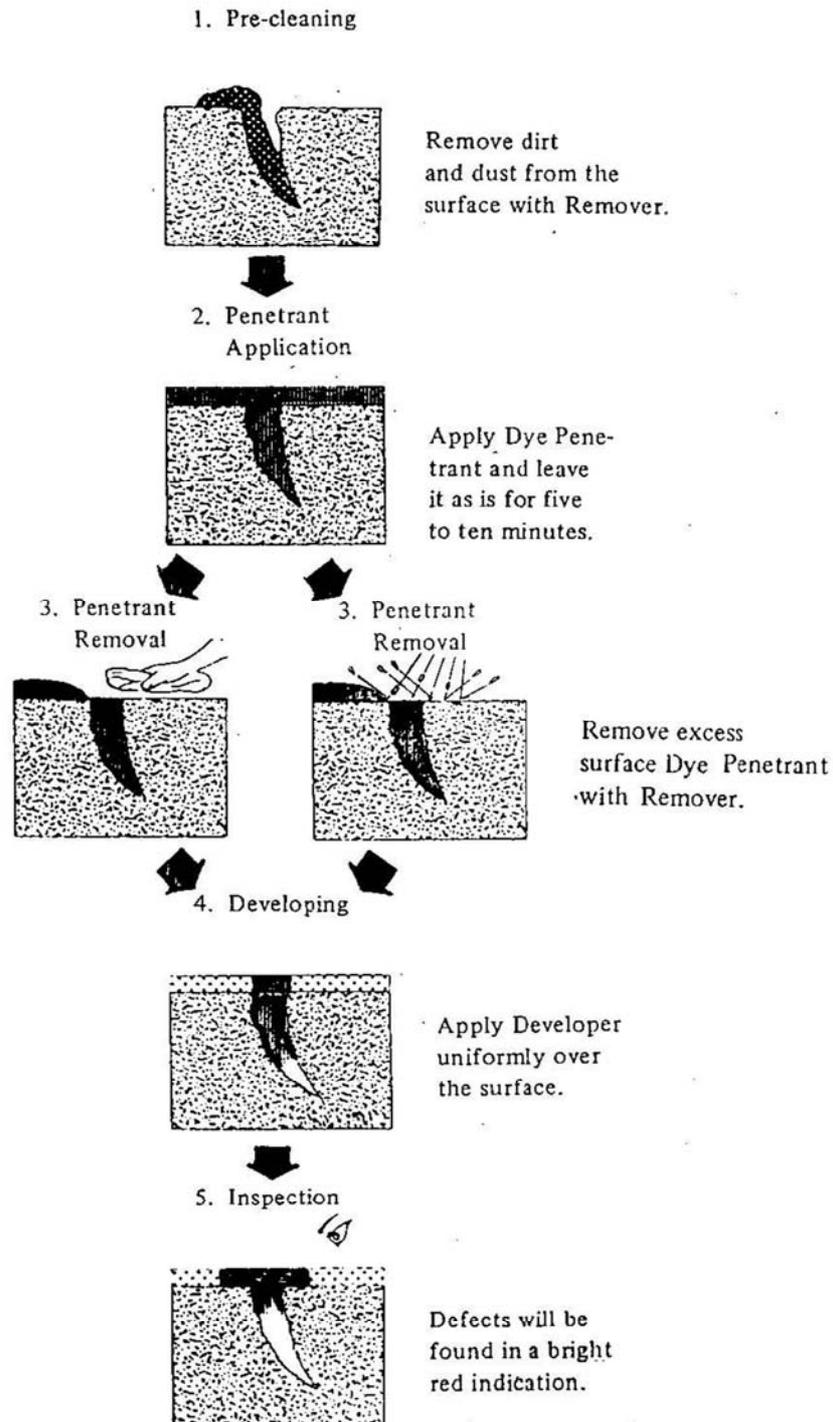


FIG. 1.2. Different stages of liquid penetrant process.

1.1.5 Magnetic particle testing (MT)

Magnetic particle testing is used for the testing of materials which can be easily magnetized. This method is capable of detecting open to surface and just below the surface flaws. In this method the test specimen is first magnetized either by using a permanent or an electromagnet or by passing electric current through or around the specimen. The magnetic field thus introduced into the specimen is composed of magnetic lines of force. Whenever there is a flaw which interrupts the flow of magnetic lines of force, some of these lines must exit and re-enter the specimen. These points of exit and re-entry form opposite magnetic poles. Whenever minute magnetic particles are sprinkled onto the surface of such a specimen, these particles are attracted by these magnetic poles to create a visual indication approximating the size and shape of the flaw. FIG. 1.3 illustrates the basic principles of this method.

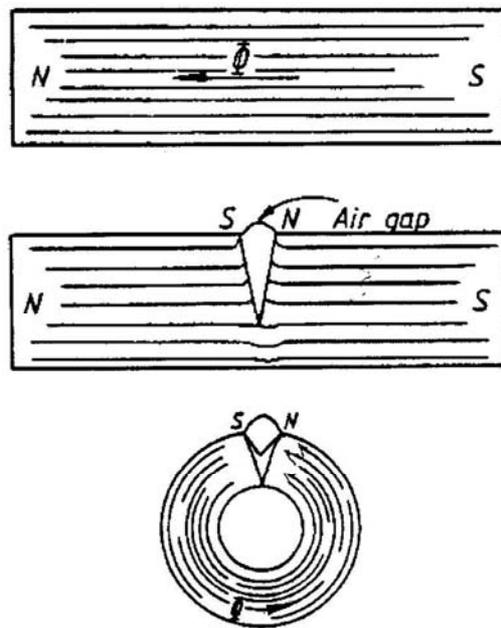


FIG. 1.3. Basic principle of magnetic particle testing.

Depending on the application, there are different magnetization techniques used in magnetic particle testing. These techniques can be grouped into the following two categories:

- (a) Direct current techniques: These are the techniques in which the current flows through the test specimen and the magnetic field produced by this flow of current is used for the detection of defects. These techniques are shown in FIG. 1.4 (a, b & c).
- (b) Magnetic flux flow techniques: In these techniques magnetic flux is induced into the specimen either by the use of a permanent magnet or by flowing current through a coil or a conductor. These techniques are shown in FIG. 1.4 (d–g).

Advantages of magnetic particle testing include the following:

- (a) It does not need very stringent pre-cleaning operation.
- (b) Best method for the detection of fine, shallow surface cracks in ferromagnetic material.
- (c) Fast and relatively simple NDT method.
- (d) Generally inexpensive.
- (e) Will work through thin coating.

- (f) Few limitations regarding the size/shape of test specimens.
- (g) Highly portable NDT method.
- (h) It is quicker.

Some of the limitations of magnetic particle testing include the following:

- (a) Material must be ferromagnetic.
- (b) Orientation and strength of magnetic field is critical.
- (c) Detects surface and near-to-surface discontinuities only.
- (d) Large currents sometimes required.
- (e) 'Burning' of test parts a possibility.
- (f) Parts must often be demagnetized, which may be difficult.

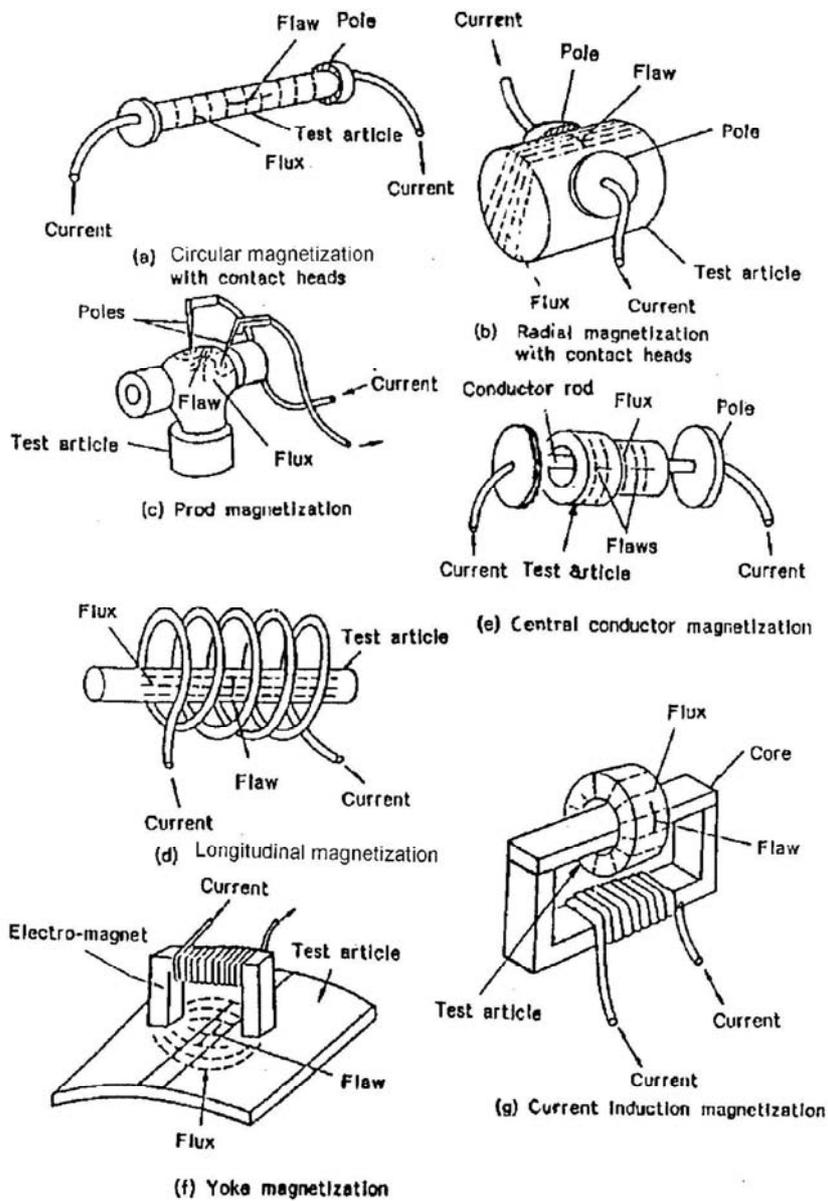


FIG. 1.4. Different magnetizations used in magnetic particle testing.

1.1.6 Eddy current testing (ET)

This method is widely used to detect surface flaws, to sort materials, to measure thin walls from one surface only, to measure thin coatings and in some applications to measure case depth. This method is applicable to electrically conductive materials only. In the method eddy currents are produced in the product by bringing it close to an alternating current carrying coil. The alternating magnetic field of the coil is modified by the magnetic fields of the eddy currents. This modification, which depends on the condition of the part near to the coil, is then shown as a meter reading or cathode ray tube presentation. FIG. 1.5 gives the basic principles of eddy current testing.

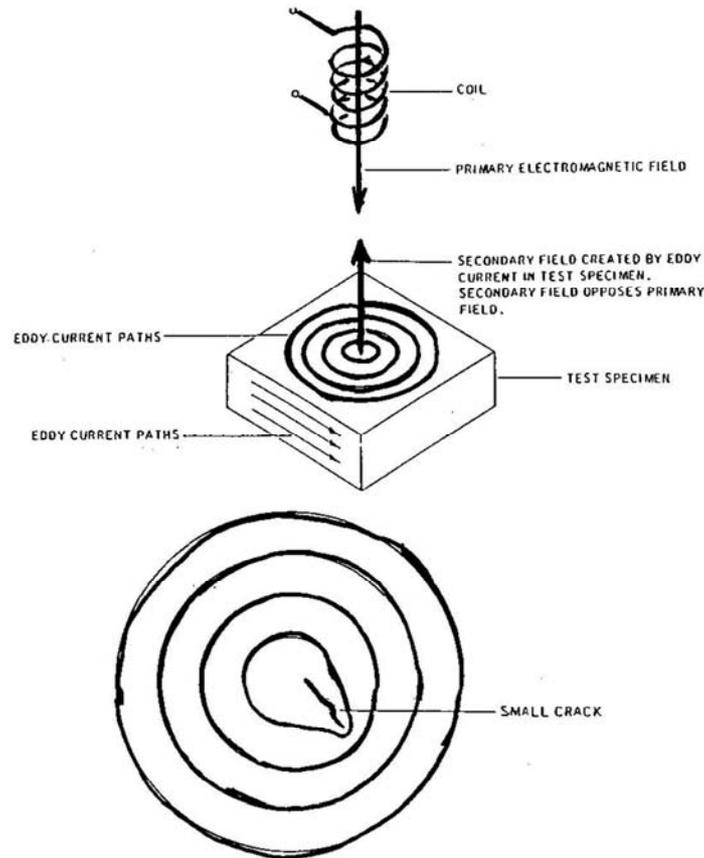


FIG. 1.5. (a) Generation of eddy currents in the test specimen. (b) Distortion of eddy currents due to defect.

There are three types of probes (FIG. 1.6) used in eddy current testing. Internal probes are usually used for the in-service testing of heat exchanger tubes. Encircling probes are commonly used for the testing of rods and tubes during manufacturing. The uses of surface probes include the location of cracks, sorting of materials, measurement of wall and coating thickness, and case depth measurement.

This method may be used for:

- (a) For the detection of defects in tubings.
- (b) For sorting materials.
- (c) For measurement of thin wall thickness' from one surface only.
- (d) For measuring thin coatings.
- (e) For measuring case depth.

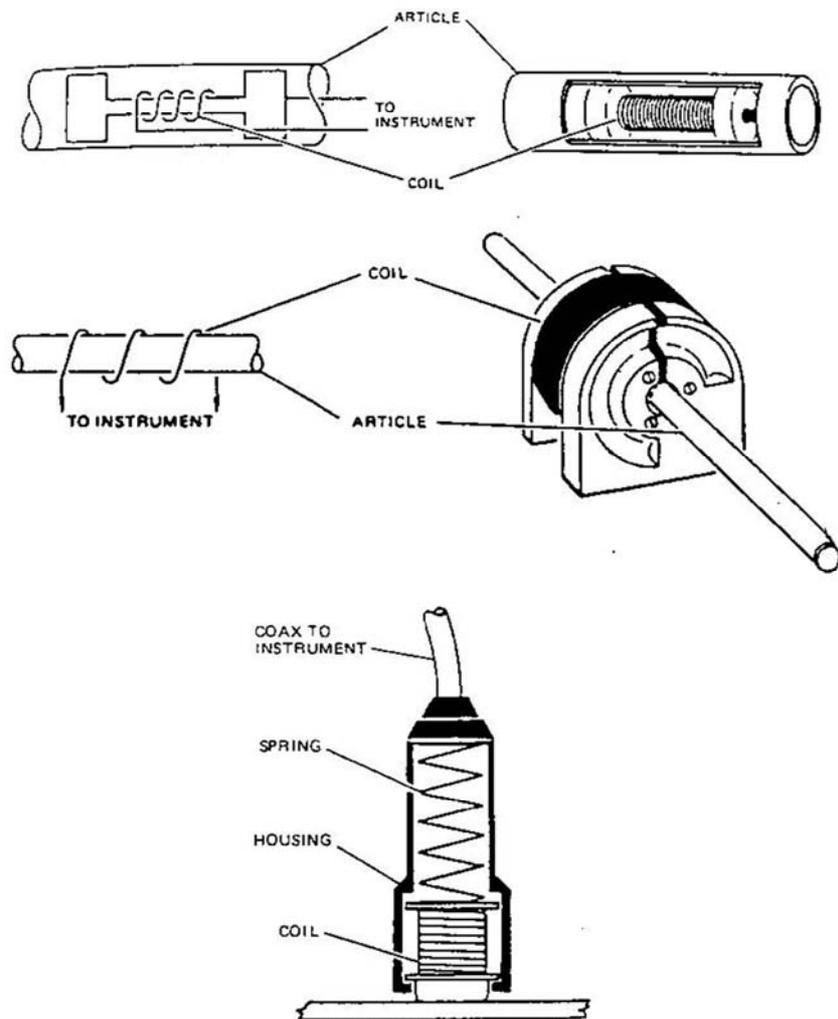


FIG. 1.6. Types of probes used in eddy current testing. (a) internal coil (c) encircling coil (c) surface probe.

Some of the advantages of eddy current testing include:

- (a) Does not require couplant.
- (b) It gives instantaneous response.
- (c) Has uncomplicated steps during set-up.
- (d) Is extremely sensitive to flaws.
- (e) Is very repeatable.
- (f) High scanning speeds can be used.
- (g) Is very accurate for dimensional analysis of flaws or coating thickness.

Some of the limitations of eddy current testing include the following:

- (a) The theory requires a good academic background in electrical principles and in mathematics.
- (b) Extremely sensitive to surface variations and therefore requires a good surface.
- (c) It is applicable to conductor materials only.

- (d) Can be used on non-magnetic and magnetic material but is not reliable on carbon steel for the detection of subsurface flaws.
- (e) Its depth of penetration is limited.
- (f) Crack tightness and orientation of eddy current flow to a crack or linear discontinuity will affect detectability.

1.1.7 Radiographic testing method (RT)

The radiographic testing method is used for the detection of internal flaws in many different materials and configurations. An appropriate radiographic film is placed behind the test specimen (FIG. 1.7) and is exposed by passing either X rays or gamma rays (Co-60 & Ir-192 radioisotopes) through it. The intensity of the X rays or gamma rays while passing through the product is modified according to the internal structure of the specimen and thus the exposed film, after processing, reveals the shadow picture, known as a radiograph, of the product. It is then interpreted to obtain data about the flaws present in the specimen. This method is used on wide variety of products such as forgings, castings and weldments.

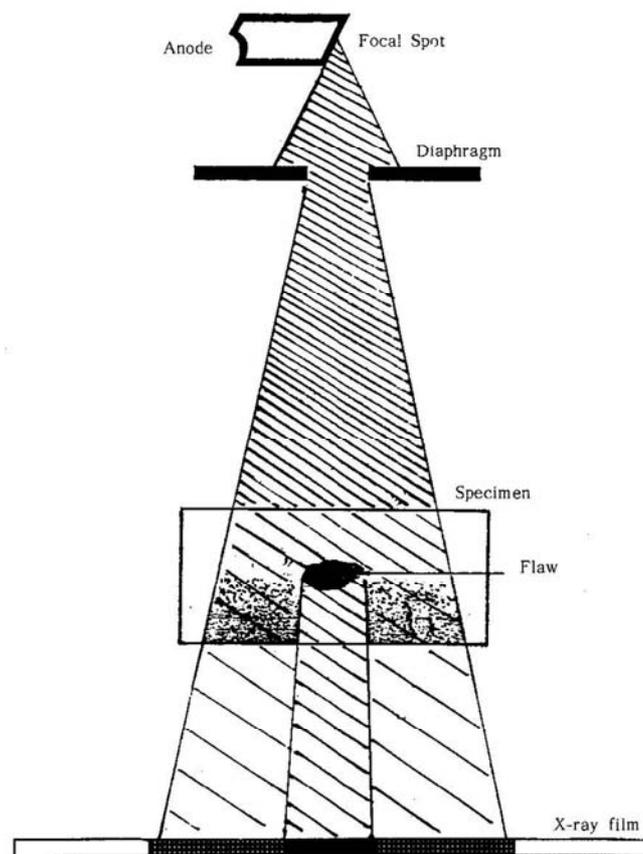


FIG. 1.7. Arrangement for radiographic testing method.

Some of the advantages of radiographic testing include:

- (a) It can be used to inspect large areas at one time.
- (b) It is useful on wide variety of materials.
- (c) It can be used for checking internal malstructure, misassembly or misalignment.
- (d) It provides permanent record.

- (e) No calibration needed on the job site.
- (f) Devices for checking the quality of radiograph are available.
- (g) Interpretation of radiographs can be done in comfortable conditions.

Some of the limitations of this method are:

- (a) X rays and gamma rays are hazardous to human health. The IAEA's Radiation Safety Series are referred for personal safety and radiation protection.
- (b) It cannot detect planar defects readily.
- (c) Access to both sides of the specimen is required.
- (d) Thickness range that can be inspected is limited.
- (e) Certain areas in many items cannot be radiographed because of the geometric consideration.
- (f) Sensitivity of inspection decreases with thickness of the test specimen.
- (g) It is more costly.
- (h) It cannot be easily automated.
- (i) It requires considerable skill for the interpretation of the radiographs.
- (j) Depth of discontinuity not indicated.

1.1.8 Ultrasonic testing (UT)

Ultrasonic inspection is a non-destructive method in which high frequency sound waves are introduced into the material being inspected. Most ultrasonic inspection is done at frequencies between 0.5 and 20 MHz, well above the range of human hearing which is about 20 Hz to 20 kHz. The sound waves travel through the material with some loss of energy (attenuation) due to material characteristics. The intensity of sound waves is either measured, after reflection (pulse echo) at interfaces (or flaw) or is measured at the opposite surface of the specimen (pulse transmission). The reflected beam is detected and analyzed to define the presence and location of flaws. The degree of reflection depends largely on the physical state of matter on the opposite side of the interface, and to a lesser extent on specific physical properties of that matter, for instance, sound waves are almost completely reflected at metal-gas interfaces. Partial reflection occurs at metal-liquid or metal-solid interfaces. Ultrasonic testing has a superior penetrating power than radiography and can detect flaws deep in the test specimen (say up to about 6 to 7 metre of steel). It is quite sensitive to small flaws and allows the precise determination of the location and size of the flaws. The basic principle of ultrasonic testing is illustrated in FIG. 1.8.

Ultrasonic testing method is:

- (a) Mostly used for detection of flaws in materials.
- (b) Widely used for thickness measurement.
- (c) Used for the determination of mechanical properties and grain structure of materials.
- (d) Used for the evaluation of processing variables on materials.

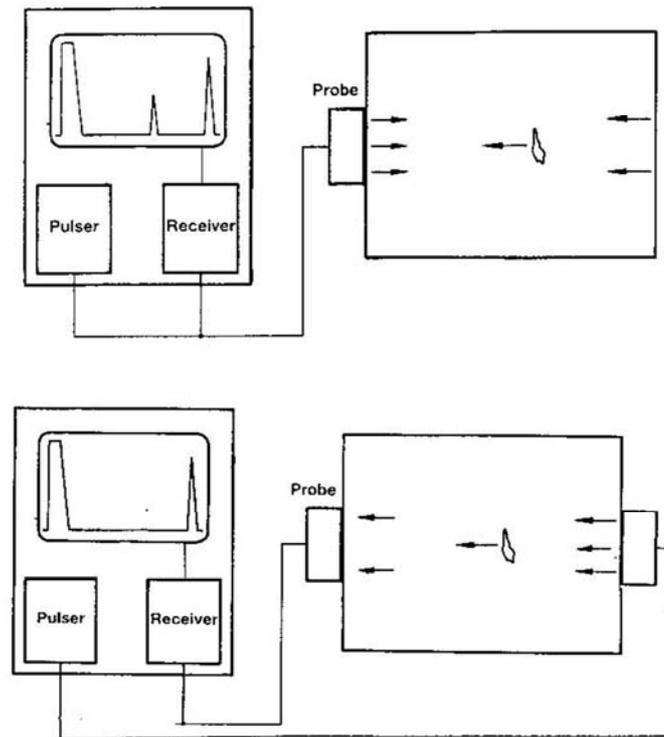


FIG. 1.8. Basic components of an ultrasonic flaw detection system. (a) pulse echo method. (b) through transmission method.

Some of the advantages of ultrasonic testing are:

- (a) It has high sensitivity which permits detection of minute defects.
- (b) It has high penetrating power (of the order of 6 to 7 metres in steel) which allows examination of extremely thick sections.
- (c) It has a high accuracy of measurement of flaw position and size.
- (d) It has fast response which permits rapid and automatic inspection.
- (e) It needs access to only one surface of the specimen.

Some of the limitations of this method are:

- (a) Unfavourable geometry of the test specimen causes problems during inspection.
- (b) Inspection of materials having undesirable internal structure is difficult.
- (c) It requires the use of a couplant.
- (d) The probe must be properly coupled during scanning.
- (e) Defect orientation affects defect detectability.
- (f) Equipment is quite expensive.
- (g) Highly skilled manpower is required.
- (h) Reference standards and calibration required.
- (i) Rough surfaces can be a problem and surface preparation is necessary.

1.1.9 Comparison of different NDT methods

Frequently it may be necessary to use one method of NDT to confirm the findings of another. Therefore, various methods must be considered complementary and not competitive, or as optional alternatives. Each method has its particular merits and limitations and these must be taken into account when any testing programme is planned. Table 1.1 gives a summary of the most frequently used NDT methods.

TABLE 1.1. COMPARISON OF VARIOUS NDT METHODS (A: highest cost, D: lowest cost)

| Technique | Access requirements | Equipment cost | Inspection cost | Remarks |
|--------------------------|---|----------------|-----------------|---|
| Optical methods | Can be used to view the interior of complex equipment. One point of access may be enough. | B/D | D | Very versatile; Little skill required; Repays consideration at design stage. |
| Radiography | Must be able to reach both sides. | A | B/C | Despite high cost, large area can be inspected at one time. Considerable skill required in interpretation. |
| Ultrasonics | One or both sides (or ends) must be accessible. | B | B/C | Requires point-by-point search hence extensive work needed on large structures; Skilled personnel required. |
| Magnetic particle | Requires a clean and reasonably smooth surface. | C | C/D | Only useful on magnetic materials such as steel; Little skill required; Only detects surface breaking or near surface cracks. |
| Penetrant flaw detection | Requires flaw to be accessible to the penetrant (i.e. clean and at the surface). | D | C/D | For all materials; Some skill required; Only detects surface-breaking defects; Rather messy. |
| Eddy current | Surface must (usually) be reasonably smooth and clean | B/C | C/D | For electrically conductive materials only; For surface breaking flaws; Variations in thickness of coatings, or comparison of materials; For other than simple comparison considerable skill is usually required. |

1.2. Materials and defects

1.2.1 Structure of metals and alloys

The properties of metals can be explained in terms of the manner in which the atoms of a metal are bonded together. In this bond, called the 'metallic bond' which is formed among

similar metal atoms when some electrons in the valence shell separate from their atom and exist in a cloud surrounding all the positively charged atoms. These positively charged atoms arrange themselves in a very orderly pattern. The atoms are held together because of their mutual attraction for the negative electron cloud FIG. 1.9.

Because the electrons are free to move in an electric field, metals conduct electricity. Because free electrons absorb and then radiate back most of the light energy that falls on them, metals are opaque and lustrous. Because free electrons can transfer thermal energy, metals conduct heat effectively. The metallic bond is non-specific, which explains why different metals can be alloyed or joined one to another. It is also non-directional, pulling equally hard in all directions. It therefore binds the metal atoms tightly, so that their cores (nuclei and inner shell electrons) fit closely among one another. The close packing favoured by the metallic bond is best realized in certain regular crystalline structures. These structures, although resistant to tension, offer less resistance to shearing forces, and thus they explain the ductility of metals. They are by definition dense, and thus they explain the comparative heaviness of metals.

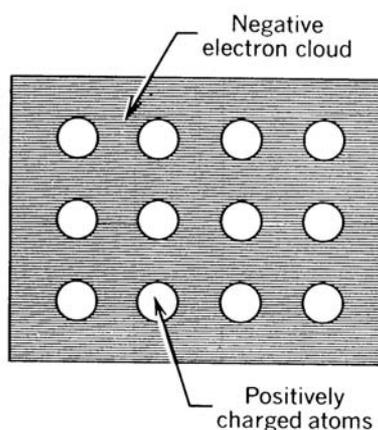


FIG. 1.9. Schematic illustration of a metallic bond.

Crystal structure

All matter is considered to be composed of unit substances known as chemical elements. These are the smallest units that are distinguishable on the basis of their chemical activity and physical properties. The elements are composed of atoms which have a distinct structure characteristic of each element. Atoms are too small to be seen with the aid of ordinary microscopes, but the outline of molecules has been detected with such devices as the ion field emission microscope and the electron microscope. The chemical elements may be roughly classified into three groups: metals, metalloids, and non-metals. Some of the properties that an element must have to be considered a metal are: (1) crystalline structure; (2) high thermal and electrical conductivity; (3) ability to be deformed plastically; (4) metallic luster or high reflectivity of light (5) ability to donate electrons and form a positive ion. Metalloids resemble metals in some respects and non-metals in others. Examples of metalloids are carbon, boron and silicon. The remaining elements are known as non-metals. This includes the inert gases, the elements in Group VII A, and N, O, P and S.

The mechanical properties of metals, then derive from their crystalline structure. That is, the atoms in the solid state of a metal are arranged in definite three dimensional geometric patterns to form crystals or grains of the metal. The network formed by joining the centre of the atoms in a crystal is called the 'space lattice' or 'crystal lattice' of the metal. The smallest

volume in a space lattice which properly represents the position of the atoms with respect to each other is known as the unit cell. There are fourteen types of unit cells but the structures of most of the common and commercially important metals in the solid state are constructed from the following three types of unit cells:

(a) Body-centred cubic (BCC)

The body-centred cubic cell is made up of nine atoms. Eight are located on the corners of the cube with the ninth positioned centrally between them FIG. 1.10 a. The body-centred cubic is a strong structure, and in general, the metals that are hard and strong are in this form at normal temperatures. These metals include, for example, chromium, molybdenum, barium, tungsten, sodium and vanadium. Steel under 723°C also has this structure, and is called alpha iron or ferrite.

(b) Face-centred cubic (FCC)

Face-centred cubic cells consist of fourteen atoms with eight at the corners and the other six centred in the cube faces FIG. 1.10 b. This structure is characteristic of ductile metals, which include aluminium, copper, gold, lead, nickel, platinum and silver. Iron, which is body-centred cubic at room temperature, is also of the face-centred structure in the temperature range from about 910°C to $1,400^{\circ}\text{C}$ and is called gamma iron or austenite.

(c) Hexagonal close-packed (HCP)

Seventeen atoms combine to make the hexagonal close-packed unit cell. Seven atoms are located in each hexagonal face with one at each corner and the seventh in the centre. The three remaining atoms take up a triangular position in the centre of the cell equidistant from the two faces FIG. 1.10 c. The metals with this structure are quite susceptible to work-hardening. Some of the more commonly used metals that crystallize with this structure are cadmium, cobalt, magnesium, titanium and zinc.

Grains (crystals) and grain boundaries

When a metal is cooled from the liquid state to the solid state, because cooling cannot be exactly the same for every atom, certain atoms will be attracted to each other to form a unit cell ahead of others. This unit cell becomes the nucleus for crystal formation. As the cooling continues other atoms will take up their positions alongside this nucleus and the crystals, or as it is usually referred to for metals, the grain, will grow in size. This orderly growth of the grain continues in all directions until it runs into interference from other grains that are forming simultaneously about other nuclei. FIG. 1.11 illustrates the process of the formation of grains and grain boundaries.

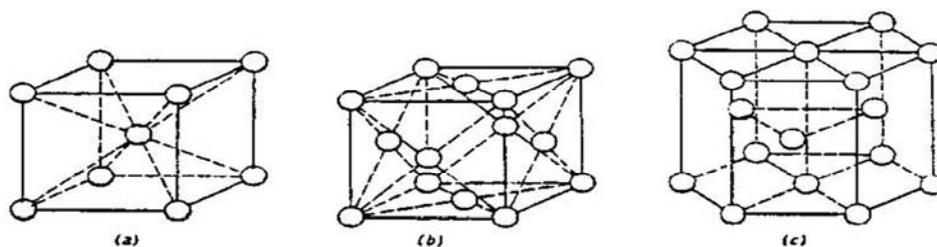


FIG. 1.10. Crystal types. (a) Body-centred cubic (BCC) (b) Face-centred cubic (FCC) (c) Hexagonal close-packed (HCP)

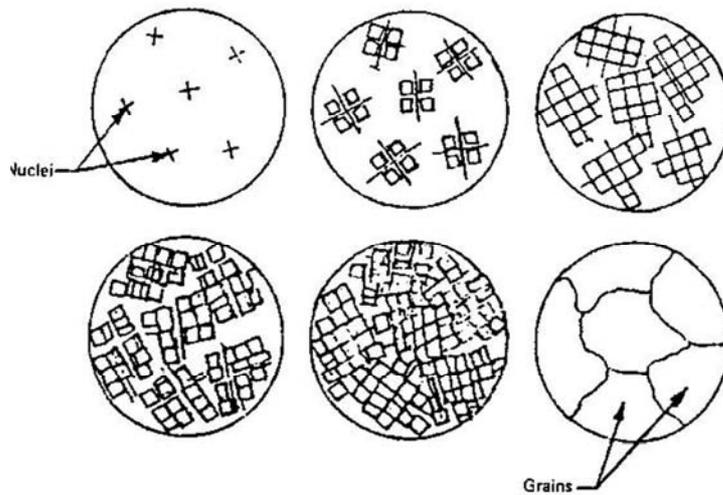


FIG. 1.11. Growth of crystals and grains during solidification.

Although with some metals with special treatment it is possible to grow single crystals several inches in diameter, in most metals at the usual cooling rates, a great number of crystals are nucleated and grow at one time with different orientations. If two grains that have the same orientation meet, they will join to form a larger grain, but if they are forming about different axes, the last atoms to solidify between the growing grains will be attracted to each and must assume compromise positions in an attempt to satisfy a double desire to join with each. These misplaced atoms are in layers about the grains and are known as grain boundaries. They are interruptions in the orderly arrangement of the space lattices and offer resistance to deformation of the metal. A fine-grained metal with a large number of interruptions, therefore, will be harder and stronger than a coarse-grained metal of the same composition and condition.

Structure of alloys

An alloy is a substance that has metallic properties and is composed of two or more chemical elements, of which at least one is a metal. Most commercially used metallic materials are not pure metals but alloys which consist of more than one elements. Some of them may be non-metallic elements. Fundamentally, three modes of arrangement of atoms or phases exist in alloys. These three modes (phases) are; pure metal, solid solution and inter-metallic compound. For simplicity of illustration, an alloy with two elements A and B shall be considered in the following discussion.

(a) Pure metal

There exist no B-atoms in A-crystal grains and no A-atoms in B-grains, i.e. mixture of pure A- and B-crystal grains. A and B metals are mutually insoluble. This complete lack of inter-solubility is theoretically almost impossible (The solubility of one component in an other may be exceedingly small but hardly zero).

(b) Solid solution

Any solution is composed of two parts: a solute and a solvent. The solute is the minor part of the solution or the material which is dissolved, while the solvent constitutes the major portion of the solution. There exist B-atoms (solute) in A-crystal grains (solvent). Solid solutions are of two types: substitutional solid solutions and interstitial solid solutions.

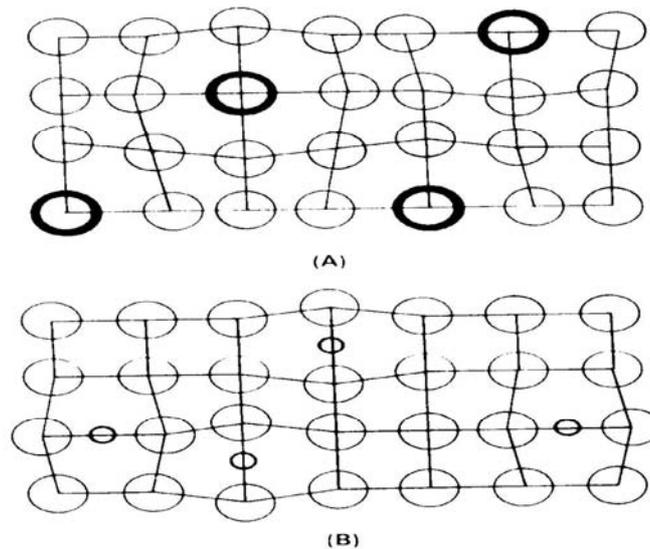


FIG. 1.12. Schematic illustration of substitutional and interstitial solid solutions.

Substitutional solid solution

A substitutional solid solution is a solution of two or more elements with atoms that are nearly of the same size. This requirement is necessary in that the alloying atoms need to replace the regular atoms in the lattice structure as shown in FIG. 1.12 (a). Examples of substitutional solid solutions are gold dissolved in silver, and copper dissolved in nickel.

Interstitial solid solution

Interstitial solid solutions are made up of alloying elements or atoms that differ greatly in size. The alloying atoms must be small enough to fit within the lattice structure of the base material. This type of solid solution is called interstitial, and is illustrated in FIG. 1.12 (b). Small amounts of carbon, nitrogen, and hydrogen can alloy interstitially in iron and other metals.

Inter-metallic compounds

These are generally formed between chemically dissimilar metals and are combined by following the rules of chemical valence. Since they generally have strong bond (ionic or covalent), their properties are essentially non-metallic. Elements A and B form an inter-metallic compound AB. In contrast to a solid solution, the ratio of the number of A-atoms to B-atoms is fixed (m: n), and the crystal structure is quite different from both A- and B-metal crystals and usually very complicated. Almost all the intermetallic compounds are very hard and brittle due to their complicated crystal structure.

Allotropic transformation

Many metals exist in more than one crystal structure. The transformation when a metal changes from one crystal arrangement to another is called an 'allotropic transformation' or 'phase transformation'. Iron exists in three allotropic forms: BCC (below 1330°F or 704°C), FCC (above 1670°F or 911°C), and delta iron (between 2550°F or 1398°C and 2800°F or 1538°C). The exact temperature is determined by the amount of carbon and other alloying elements in the metal. The properties of iron and steel are governed by the phase

transformations they undergo during processing. Understanding these transformations is essential to the successful welding of these metals. Steel is an iron alloy containing less than two per cent carbon. The presence of carbon alters the temperatures at which freezing and phase transformations take place. The addition of other alloying elements also affects the transformation temperatures. Variations in carbon content have a profound affect on both the transformation temperatures and the proportions and distributions of the various phases (austenite, ferrite, and cementite). The iron-carbon phase diagram is shown in FIG. 1.13. On cooling, delta ferrite to austenite transformation occurs at 2535 °F (1390°C) in essentially pure iron, but in steel, the transformation temperature increases with increasing carbon content to a maximum of 271 °F (1492) °C. Steels with more than 0.5 per cent carbon freeze directly to austenite at a temperature below 27 °F (1492), °C and therefore, delta ferrite does not exist in these steels. On further cooling, austenite transforms to ferrite plus iron carbide. This is one of the most important transformations in steel. Control of it is the basis for most of the heat treatments used for hardening steel. This transformation occurs in essentially pure iron at 1670 °F (910 °C). In steel with increasing carbon content, however, it takes place over a range of temperatures between boundaries A₃ and A₁, FIG. 1.13. The upper limit of this temperature range (A₃) varies from 1670 °F (910 °C) down to 1333°F (723 °C). For example, the A₃ of a 0.10 per cent carbon steel is 1600 °F (870 °C), while for a 0.50 per cent carbon steel it is 143 °F (775 °C). Thus, both at high and low temperature the presence of carbon promotes the stability of austenite at the expense of delta and alpha ferrite. The lower temperature of the range (A₁) remains at 1330 °F (723 °C) for all plain carbon steels, regardless of the carbon level. Austenite can dissolve up to 2.0 per cent of carbon in solid solution, but ferrite can dissolve only 0.025 per cent. At the A₁ temperature, austenite transforms to ferrite and an inter-metallic compound of iron and carbon (Fe₃C), called cementite. Ferrite and cementite in adjacent platelets form a lamellar structure, known as pearlite.

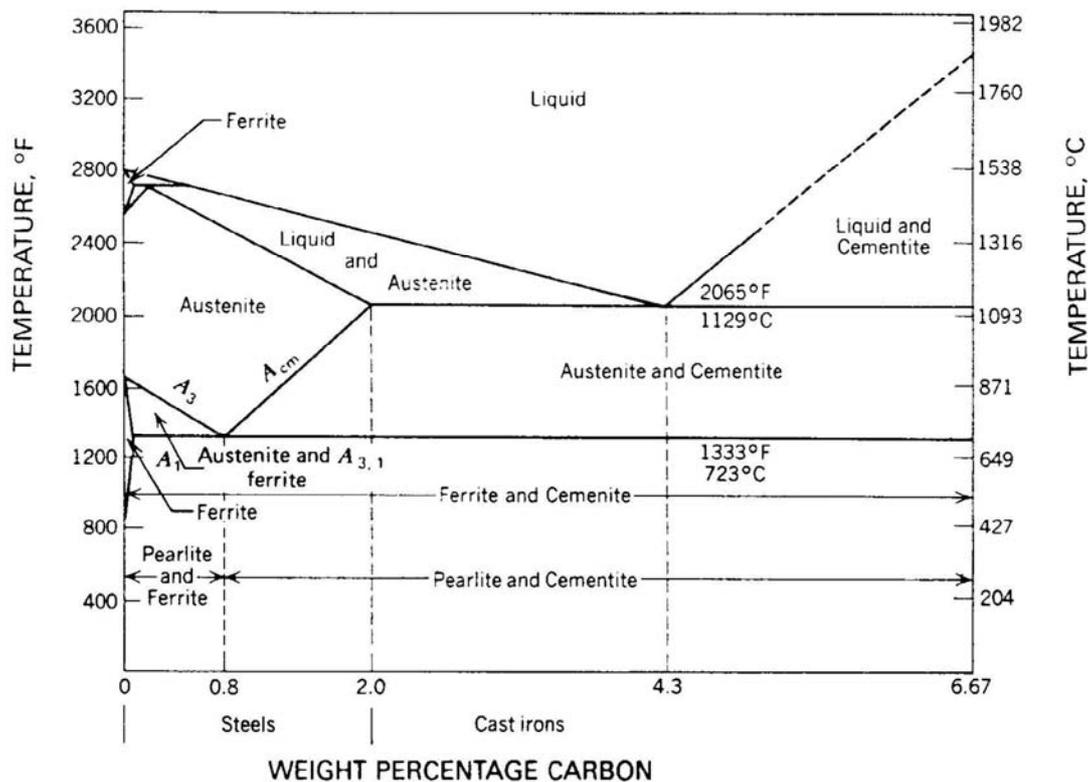


FIG. 1.13. The iron-carbon phase diagram.

Most of the common alloying elements added to steel further alter the transformation temperatures. Room temperature microstructures of iron-carbon alloys at the equilibrium conditions covered by this diagram include one or more of the following constituents:

- (a) Ferrite: A solid solution of carbon in alpha iron.
- (b) Pearlite: A mixture of cementite and ferrite that forms in plates or lamellae.
- (c) Cementite: Iron carbide, Fe_3C , present in pearlite or as massive carbides in high carbon steels.
- (d) Austenite: A solid mixture of carbon in gamma iron.
- (e) Leborite: A eutectic mixture of austenite & cementite.

When carbon steels are slowly cooled from the austenitic temperature range, the relative amounts of these three constituents at room temperature depend on the chemical composition. However, austenite decomposition is suppressed when the cooling rate is accelerated. When transformation does begin, it progresses more rapidly, and larger volumes of pearlite are formed. As the cooling rate is further increased, the pearlite lamellae become finer (closely spaced platelets). At fast cooling rates, still lower transformation temperatures are encountered, and a feathery distribution of carbides in ferrite is formed instead of pearlite. This feathery arrangement of shear needles with fine carbides in a ferrite matrix is called bainite. It has significantly higher strength and hardness and lower ductility than fine pearlitic structures. With very fast cooling rates (severe quenching), martensite is formed. Martensite is the hardest austenite decomposition product. When the cooling rate is fast enough to form 100 per cent martensite, no further increases in hardness can be achieved by faster quenching. The decomposition of austenite is an important consideration in the welding of steel alloys because the weld metal and parts of the heat-affected zone undergo this transformation.

1.2.2 Properties of materials (metallic & non-metallic)

Metallic materials

Mechanical properties are defined as the properties of a material that reveal its elastic and inelastic (plastic) behaviour when force is applied, thereby indicating its suitability for mechanical applications, for example, modulus of elasticity, tensile strength, elongation, hardness, and fatigue limit. Other mechanical properties, not mentioned specifically above, are yield strength, yield point, impact strength, and reduction of area, to mention a few of the more common terms. In general, any property relating to the strength characteristics of metals is considered to be a mechanical property. Physical properties relate to the physics of a metal such as density, electrical properties, thermal properties, magnetic properties and the like. These and other properties will be described here in slightly more detail.

Elasticity and plasticity

When stress or force is applied to a metal, it changes shape. For example a metal under a compressive stress will shorten and metal in tension will lengthen. This change in shape is called strain. The ability of metal to strain under load and then return to its original size and shape when unloaded is called elasticity. The elastic limit (proportional limit) is the greatest load a material can withstand and still spring back into its original shape when the load is removed. Within the elastic range stress is proportional to strain and this is known as Hooke's law. The relationship between applied stress or load and the consequent strain or change in length is shown in FIG. 1.14. The end of the straight line portion is known as the elastic limit.

A point on the curve slightly higher than the elastic limit is known as the yield point or yield strength. The allowable or safe load for a metal in service should be well below the elastic limit. If higher loads are applied, however, the range of elasticity or elastic deformation is exceeded and the metal is now permanently deformed. Now it will not return to its original dimensions even when the load is removed. For this reason, the area of the stress strain curve beyond the elastic limit is called the plastic range. It is this property that makes metals so useful. When enough force is applied by rolling, pressing or hammer blows, metals can be formed, when hot or cold, into useful shapes. If the application of load is increased in the plastic region a stage comes when the material fractures.

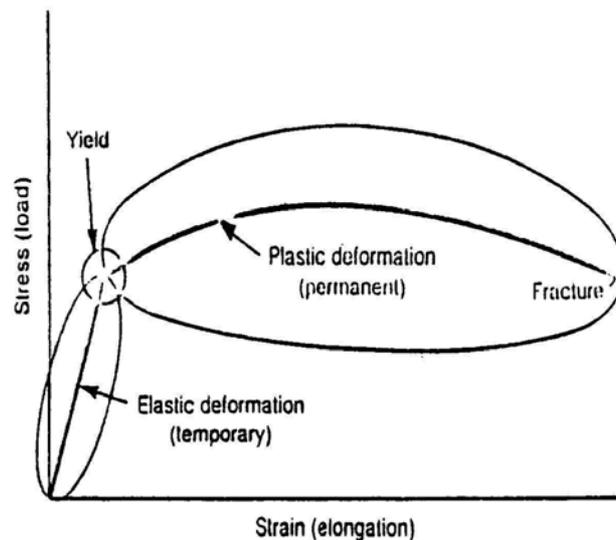


FIG. 1.14. Stress-strain curve showing elastic and plastic portions of a typical curve.

A very important feature of the stress-strain curve must be pointed out. The straight-line or elastic part of the stress-strain curve of a given metal has a constant slope. That is, it cannot be changed by changing the microstructure or heat treatment. This slope, called the modulus of elasticity, measures the stiffness of the metal in the elastic range. Changing the hardness or strength does not change the stiffness of the metal. There is only one condition that changes the stiffness of any given metal, that is temperature. The stiffness of any metal varies inversely with its temperature; that is, as temperature increases, stiffness decreases, and vice versa.

Strength

The strength of a metal is its ability to resist change in shape or size when external forces are applied. There are three basic types of stresses namely tensile, compressive, and shear. When we consider strength, the type of stress to which the material will be subjected must be known. Steel has equal compressive and tensile strength, but cast iron has low tensile strength and high compressive strength. Shear strength is less than tensile strength in virtually all metals.

The tensile strength of a material can be determined by dividing the maximum load by the original cross-sectional area before testing. Thus:

$$\text{Tensile strength} = (\text{Maximum load})/(\text{Original cross - sectional area}) \quad (1.1)$$

Metals are 'pulled' on a machine called a tensile tester. A specimen of known dimensions is placed in the tensile testing machine and loaded slowly until it breaks. Instruments are sometimes used to make a continuous record of the load and the amount of strain (proportional change in length). This information is put on a graph called a stress-strain diagram. A stress-strain diagram can be made for any metal.

Hardness

The hardness of a metal is its ability to resist being permanently deformed. There are three ways that hardness is measured; resistance to penetration, elastic hardness, and resistance to abrasion. Hardness varies considerably from material to material. This variation can be illustrated by making an indentation in a soft metal such as aluminium and then in a hard metal such as alloy tool steel. The indentation could be made with an ordinary centre punch and a hammer, giving a light blow of equal force on each of the two specimens. In this case just by visual observation one can tell which specimen is harder. Of course, this is not a reliable method of hardness testing, but it does show one of the principles of hardness testers; measuring penetration of the specimen by an indenter or penetrator, such as a steel ball or diamond point.

Rockwell, Vicker and Brinell hardness testers are the most commonly used types of hardness testers for industrial and metallurgical purposes. Heat treaters, inspectors, and many others in industry often use these machines. The Rockwell hardness test is made by applying two loads to a specimen and measuring the difference in depth of penetration in the specimen between the minor load and the major load.

The Brinell hardness test is made by forcing a steel ball, usually 10 millimetres (mm) in diameter, into the test specimen by using a known load weight and measuring the diameter of the resulting impression. A small microscope is used to measure the diameter of the impressions. Various loads are used for testing different materials, for example, 500 kilograms (kg) for soft materials such as copper and aluminium and 3000 kg for steels and cast irons. Generally the harder the material is, the greater its tensile strength will be, that is, its ability to resist deformation and rupture, when a load is applied.

Ductility

The property that allows a metal to deform permanently when loaded in tension is called ductility. Any metal that can be drawn into a wire is ductile. Steel, aluminium, gold, silver, and nickel are examples of ductile metals.

The tensile test is used to measure ductility. Tensile specimens are measured for area and length between gauge marks before and after they are pulled. The per cent of elongation (increase in length) and the per cent of reduction in area (decrease of area at the narrowest point) are measures of ductility. A high per cent elongation (about 40%) and reduction in area (about 70 per cent) indicates a high ductility. A metal showing less than 20 per cent elongation would have low ductility.

Malleability

The ability of a metal to deform permanently when loaded in compression is called malleability. Metals that can be hammered or rolled into sheets are malleable. Most ductile metals are also malleable, but some very malleable metals such as lead are not very ductile and cannot be drawn into wire easily. Metals with low ductility, such as lead, can be extruded

or pushed out of a die to form wire and other shapes. Some very malleable metals are lead, tin, gold, silver, iron and copper.

Brittleness

A material that will not deform plastically under load is said to be brittle. Excessive cold working causes brittleness and loss of ductility. Cast iron does not deform plastically under a breaking load and is therefore brittle.

A very sharp 'notch' that concentrates the load in a small area can also reduce plasticity. Notches are common causes of premature failure in parts. Weld undercut, sharp shoulders on machined shafts, and sharp angles on forgings and castings are examples of unwanted notches (stress raisers).

Notch toughness

Notch toughness (impact strength) is the ability of a metal to resist rupture from impact loading when there is a notch or stress raiser present. A metal may show high ductility or strength when tensile tested or be hard or soft when hardness tested, but often the behaviour of metals under shock loads is not seemingly related to those properties. Of course, as a rule, a brittle metal such as grey cast iron will fail under low shock loads; that is, its shock resistance is low, and soft wrought iron or mild steel has a high shock resistance. But soft, coarse-grained metals will have lower shock resistance than fine-grained metals. A notch or groove in a part will lower the shock resistance of a metal, so a specific notch shape and dimension is machined on the test specimen in order to give uniform results.

In general, the tensile strength of a metal changes in proportion to hardness. However, this relationship does not always hold true at high hardness levels or with brittle materials because these materials are more sensitive to stress concentrations, or notches, and may fracture prematurely when stressed in tension.

Conductivity

Conductivity is a measure of the ability of a material to conduct electric current. It is the reciprocal of resistivity. Conductivity is commonly expressed as mhos per metre since the unit of resistivity is the ohm. The conductivity of metallic elements varies inversely with absolute temperature over the normal range of temperatures but at temperatures approaching absolute zero the imperfections and impurities in the lattice structure of a material make the relationship more complicated. Metals and materials exhibit a wide range of conductivity. Between the most conductive substances (silver and copper) and the most resistive (polystyrene for example) the difference amounts to 23 orders of magnitude.

Non-metallic materials

Ceramics

Ceramics offer unique properties as engineering materials, notably exceptionally high hardness and resistance to abrasion and corrosion as well as high temperature properties considerably superior to those of any metals. However, they are less ductile, intrinsically brittle and susceptible to thermal shock which can limit their maximum service temperature on applications involving thermal cycling. Resistance to thermal shock is directly dependent

on a low coefficient of thermal expansion and high thermal conductivity, which properties differ appreciably between different ceramic materials.

The fabrication of ceramics does not set particular problems since they can be formed by traditional techniques such as slip casting wet pressing and extrusion; and by such modern methods as injection moulding, iso-static pressing, tape casting and dry pressing.

Ceramics which can be classified (or are usable or potentially usable) as engineering materials currently embrace: (i) alumina, (ii) beryllia (beryllium oxide) and boron nitride, (iii) porcelain (aluminium silicates), (iv) steatite and forsterite (magnesium silicates), (v) silicon nitride and silicon carbide, (vi) titanium diboride and (vii) vitreous carbon.

Ceramics are finding an increasing use in the fabrication of electronic components, engineering components, medicine and dentistry and jewellery.

Cermets

The use of ceramic-coated metals and ceramic-metal combinations has now assumed significant proportions, particularly in the fields of practical nuclear physics (e.g. parts for nuclear reactors) and jet engine manufacture. Metal ceramic combinations are of two types: a ceramic coating on the metal, or a chemical and mechanical combination of metals and ceramics in a cermet material. Both are essentially attempts to produce satisfactory high-temperature materials, either with reduced costs and better availability or with an overall performance superior to existing metal or ceramic materials on their own. Broadly speaking the mechanical properties of these two types of materials represent extremes. Metals have high tensile strength and shock resistance, but lose these properties rapidly with increasing temperature. Ceramics of the refractory kind have extremely high melting points and excellent general stability, but are low in tensile strength and both mechanical and thermal shock resistance. The demand for materials combining the favourable features of both metals and ceramics is increasing; hence the development of combinations of ceramics with metals over the past few years.

Normally cermets are formed by techniques similar to those employed in powder metallurgy. The ceramic content usually comprises refractory oxides, carbides or nitrides whilst the metal powder component is usually chromium, nickel, molybdenum or titanium. The resulting properties are different from those of either of the separate constituents. A number of cermets have particularly high melting points, best realized in an open flame.

Composites

A composite is a material in which a stronger, sometimes fibrous material is usually combined with another to reinforce or strengthen the resultant mass. The needs of the aerospace industry led to the development and acceptance of composite materials. Low weight, high strength and great rigidity were of paramount interest of military aviation. These same qualities are also in demand in many non-military applications.

The most common forms of composites are based on a plastic matrix. The fibrous reinforcing material may be in sheet form, as in thermoset plastic laminates; filament form, woven or random, as in glass reinforced plastics; or short fibre form as in filled or reinforced thermoplastics. These materials are well established and widely available.

In the case of thermoset laminate composites, phenolic, melamine and epoxide are the main resin systems used with paper, cotton fabric, glass fabric and asbestos as the main alternative reinforcing materials.

Ceramic and metal composites have remained relatively undeveloped as general engineering and constructional materials, largely on account of high cost. There are, however, numerous applications of 'filled' and 'laminated' metal forms which qualify as composites under the general description.

Concrete

Concrete is a mixture of stone and sand held together by a hardened paste of hydraulic cement and water. When the ingredients are thoroughly mixed, they make a plastic mass which can be cast or moulded into a predetermined size and shape. When the cement paste hardens, the concrete becomes very hard like a rock. It has great durability and has the ability to carry high loads especially in compression.

The required strength and properties of concrete can be obtained by careful selection of its ingredients, correct grading of ingredients, accurate water additions and adopting a good workmanship in mixing, transportation, placing, compaction, finishing, and curing of concrete in the construction work.

The main ingredients of concrete are cement, coarse aggregate (i.e. screenings, gravel, etc.), fine aggregate (i.e. sand), chemical admixtures (if necessary) and fibrous materials (as necessary). Aggregates in concrete constitute by far the bulk of the mass.

2.2.3 *Discontinuities and defects in metallic materials*

Whenever there is a change in the homogeneity and uniformity of properties within a material, it can invariably be attributed to the presence of discontinuities or imperfections (lack of material) within the material. Starting from the dislocations and atomic structure irregularities, the discontinuities can take various shapes and forms such as gas inclusions (micro-porosity, porosity, blowholes, pipes, voids), cracks, metallic inclusions, lack of penetration, lack of fusion, shrinkage, laps and seams, etc.

Discontinuities can be divided into three general categories inherent, processing, and service.

- (a) Inherent discontinuities are usually formed when the metal is molten. There are two further sub classifications. Inherent wrought discontinuities relate to the melting and solidification of the original ingot before it is formed into slabs, blooms, and billets. Inherent cast discontinuities relate to the melting, casting and solidification of a cast article.
- (b) Processing discontinuities are usually related to the various manufacturing processes such as machining, forming, extruding, rolling, welding, heat treating, and plating. During the manufacturing process, many discontinuities that were subsurface will be made open to the surface by machining, grinding, etc.
- (c) Service discontinuities are related to the various service conditions, such as stress, corrosion, fatigue and erosion. The discontinuities may alter the local stress distribution and, in addition, may affect the mechanical or chemical (corrosion resistance) properties.

Discontinuities should be characterized not only by their nature, but also by their shape. Planar type discontinuities, such as cracks, laminations, incomplete fusion, and inadequate

joint penetration, create serious notch effects. Three-dimensional discontinuities create almost no notch effect, but amplify stresses by reducing the weldment area. Therefore, the characteristics of discontinuities which should always be considered, include the size, acuity or sharpness, orientation with respect to the principal working stress and residual stress, location with respect to the exterior surfaces and the critical sections of the structure.

All the above discontinuities are described under the individual processes in Sections 1.3 and 1.4.

1.3. Processing and defects

1.3.1 Primary processes and related defects

Ingot casting and related defects

A casting suitable for working or re-melting is called ingot. The moulds into which molten metal is poured to form ingots are made of grey cast iron, meehanite with large graphite flakes, and anodized aluminium alloys. The inside surface of the mould is frequently coated with suitable materials to help form a smooth ingot surface. The slab or billet is normally the starting point for actual forming of articles or materials. Typical discontinuities found in ingot FIG. 1.15 are non-metallic inclusions, porosity and pipe. Most of these discontinuities in the ingot are in the upper portion and can be easily eliminated by cropping off the top of the ingot. The ingot after the hot top is cropped off is called a bloom. The blooms then can be further processed to form slabs and billets as shown in FIG. 1.16.

Casting processes

A commonly used method of forming metal objects of complex shapes is by pouring molten metal into a mould in which it sets to the required shape. The mould is then broken away to expose the casting, or the design of the mould is such that it can be separated without damage and re-used. The moulds are usually formed from patterns which can be used many times over, if necessary, and their design is critical in that 'feed' and 'vent' holes must be carefully positioned in the mould to permit the metal to flow freely into all parts FIG. 1.17. Problems that can occur are interaction on cooling. It is also unlikely that the crystal structure of a casting will be optimum in all parts so that its strength may be less than with other methods of fabrication. Various casting processes include sand casting, permanent mould casting, die casting, centrifugal casting and shell mould casting etc. Since the casting process is complex and a large number of variables need to be controlled to get a good quality product and since

it is not possible to give all the details here, only the principles and salient features of the above mentioned processes of casting are briefly presented.

Sand casting

In this case a sand mould is used for casting the desired shape of the required alloy. A sand mould may be defined as a pre-formed sand container into which molten metal is poured and allowed to solidify. In general sand moulds are destroyed as the casting is removed from them. Sand moulds make it possible to cast complex shapes that might not be possible otherwise.

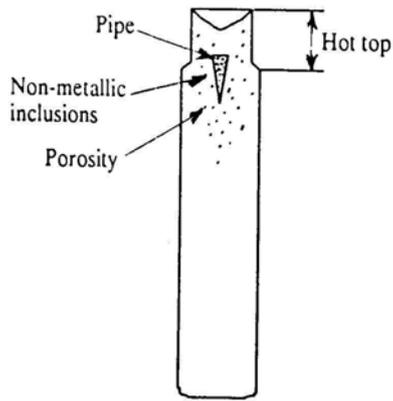


FIG. 1.15. Typical defects in an ingot.

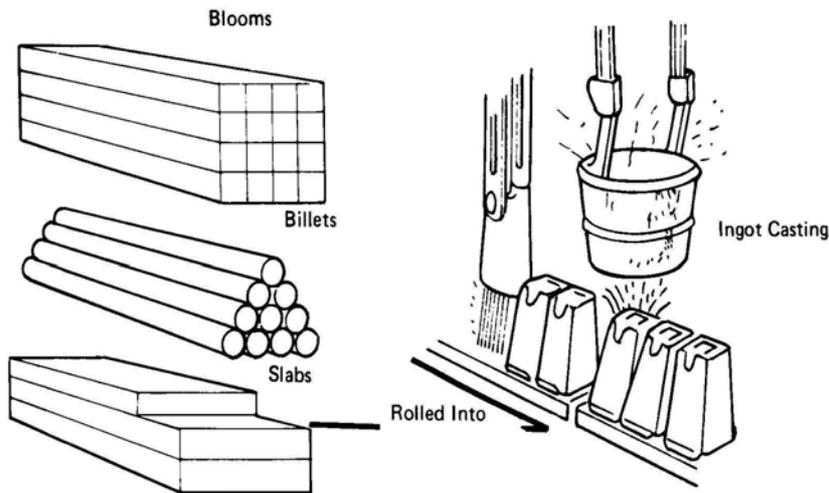


FIG. 1.16. Typical primary material processes.

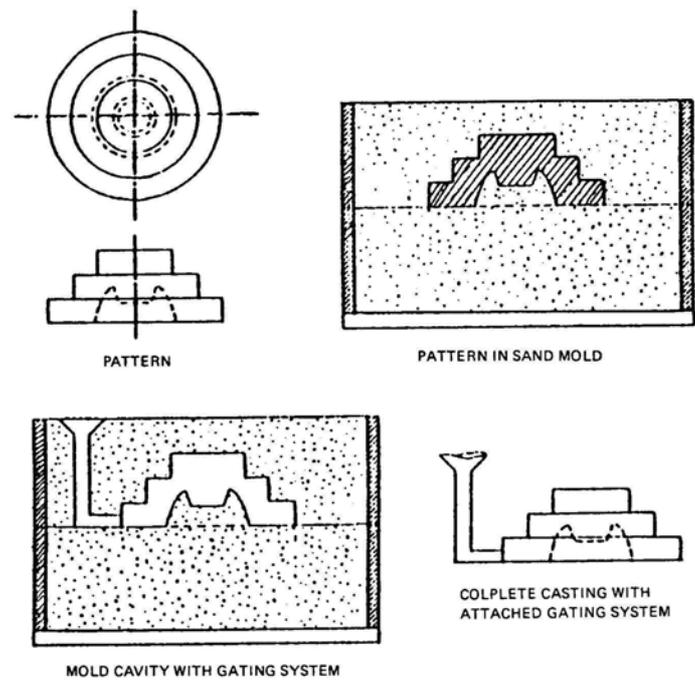


FIG. 1.17. Typical casting steps

Different types of sand moulds can be made for making different castings. Green sand moulds are made from moist sand and are used for practically all ferrous and non-ferrous castings. They have the disadvantage of not being very strong as well as requiring moisture during manufacture which may cause certain defects in the casting. Green sand moulds may be provided with a dry sand on the surface to give skin-dry moulds. Purely dry-sand moulds can also be made by adding to the sand a binder instead of moisture.

Methods of preparing sand moulds include bench moulding, machine moulding, floor moulding' and pit moulding. Bench moulding is used for small castings. This is usually a slow and laborious process since hand ramming with loose pattern is usually used. Small and medium moulds may be made even with the aid of a variety of machines which are usually faster and more uniform than bench moulding. Medium to large moulds are made directly on the foundry floor. Very large moulds made in a pit constructed for the purpose are called pit moulds.

The sands most commonly used in sand die casting contain silica sand which is usually from 50 to 95% of the total material in any moulding sand, zirconate and olivine, etc. The most important properties and characteristics of such sands are permeability, cohesiveness and refractoriness. Permeability is a condition of porosity and is related to the passage of gaseous material through the sand as well as to the density of sand grains. Cohesiveness can be defined as the holding together of sand grains or strength of moulding sand and depends upon the size and shape of the sand grains.

The property of cohesiveness may be improved by adding to the sand some binders such as clay, resins and gums and drying oil. The third important characteristic of the moulding sand is refractoriness which is its ability to withstand a high temperature without fusing. Pure silica sand can withstand a temperature as high as 3148°F. The property of refractoriness can be affected by impurities like metallic oxides.

Mould cavities may be produced by packing the moulding material around what are called patterns. The patterns may be made from wood, metal or other suitable materials. There are a variety of these patterns used in the manufacture of castings. Another important part of the casting process is the core box which is a structure made of wood, metal or other suitable material, containing a cavity with the shape of a desired core. Making a sand mould involves the proper packing of moulding sand around a pattern. After the pattern is removed from the sand and the gating arrangement completed, the mould cavity is filled with molten metal to form the casting.

Permanent mould casting

A casting made by pouring molten metal into a mould made of some metallic alloy or other material of permanence is known as a permanent mould casting.

Grey cast iron and meehanite with large graphite flakes are the most commonly used materials in the construction of permanent moulds. This common use is partly due to the ease with which they may be machined. Certain steels, particularly special alloy steels that are heat treated, often have especially good resistance to erosion. They have excellent refractory properties. Some aluminium alloys on which the surface has been anodized, are also used as moulding materials. Anodizing produces Al_2O_3 which is very refractory and resistant to abrasion. These alloys are very easy to machine and possess a good chilling capacity. The mould is not destroyed on removing the casting and therefore can be re-used many times.

Die casting

Die casting may be defined as the use of a permanent mould (die) into which molten metal is introduced by means of pressure. The term pressure die casting is another name for this method of casting. This pressure is obtained by application of compressed air or by pneumatically or hydraulically operated pistons. This process of casting can be subdivided in two types, e.g. (a) Hot chamber die casting and (b) Cold chamber die casting.

(a) Hot chamber die casting.

The melting unit is an integral part of the hot chamber machine, and molten metal is introduced directly from this melting unit, by means of plunger mechanism into the die cavity. The process is further characterized by a normal amount of superheat in the metal and the need for a commensurately lower casting pressure. Pressure on the molten metal in hot chamber die casting machines may vary from approximately 500 to 6000 psi (3.5 to 41 MPa). An average of approximately 2000 to 2500 psi (14 to 17 MPa) is common. Air injection pressures are normally limited to about 600 psi (4 MPa) FIG. 1.18.

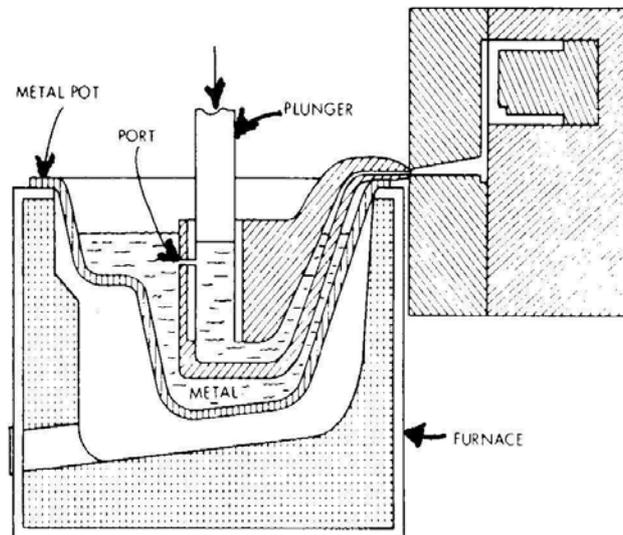


FIG. 1.18: Hot chamber die casting.

(b) Cold chamber die casting

The melting unit is usually separate in this case, and molten metal must be transferred to the injection mechanism by ladle FIG. 1.19. Further distinctive characteristics of the process are, very high metal pressures and the fact that the casting alloy may be at a temperature somewhat less than normal superheat; the melt may even be in a semimolten condition. Pressure on the casting metal in cold chamber die casting machines may vary from 3000 psi (20.5 MPa) to as high as 25 000 psi (172 MPa) and in some cases may reach 100 000 psi (690 MPa). Metallic alloys cast in a semimolten condition require greater pressure to compensate for the reduced fluidity resulting from low pouring temperatures. Lower working temperature and high pressures produce castings of dense structure, free of blow holes and porosity related to dissolved gases.

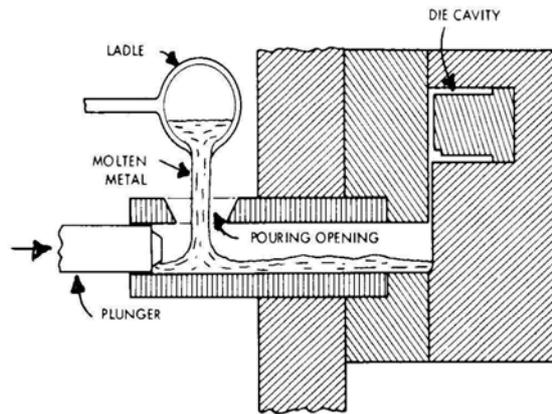


FIG. 1.19: Cold chamber die casting.

Centrifugal casting

Any process in which molten metal is poured and allowed to solidify while the mould is revolving, is a centrifugal casting process. Castings produced under this centrifugal force are called centrifugal castings. There are three recognized centrifugal processes namely true centrifugal casting, semi-centrifugal or profiled-centrifugal casting and centrifuged or pressure casting and are shown in FIG. 1.20. True centrifugal casting is that in which castings are made in a hollow, cylindrical mould rotated about an axis common to both casting and mould. Cast-iron pipe is commonly made by this method. In this process the axis of spin may be horizontal, inclined, or vertical. In the true centrifugal casting process the inside circumference is always circular. When the mould is rotated on a horizontal axis, a true cylindrical inside surface is produced. True centrifugal casting is used only on symmetrically shaped objects. Semi-centrifugal or profiled-centrifugal casting is similar to the true centrifugal method, except that a central core is used to form the inner surface or surfaces. The casting is not dependent upon centrifugal force for its shape. A good example of semi-centrifugal work is a cast wheel-like casting. The axis of spin in the semi-centrifugal process is always vertical. Although the yield is better than with static casting, it is not as high as in true centrifugal casting. With this process also only symmetrically shaped objects can be cast.

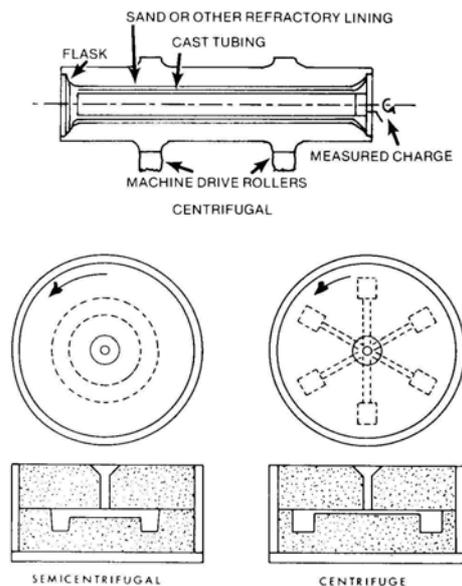


FIG. 1.20. Centrifugal casting.

Centrifugal or pressure casting is applied for non-symmetrical castings. The mould cavity is not rotated about its own axis but about the axis of a central down sprue common to the axis of spin, which feeds metal into the mould cavity under centrifugal force. This process of centrifuging can be done only about a vertical axis. Centrifugal force provides a high pressure to force the metal alloy into the mould cavity. Centrifugal casting processes can be used to produce parts made of both the ferrous and non-ferrous alloy groups. Cast-iron pipe, gun barrels, automotive cylinder walls, jet engine rings, piston rings and brake drums are common parts centrifugally cast. Advantages include the elimination of foreign inclusions and the production of sounder castings. The chief disadvantages are the shape and size limitations.

Investment casting

This process involves making a one-piece mould from which the pattern is removed by a procedure which melts the pattern. The moulds used in this process are single purpose moulds. The elimination of all parting planes provides improved dimensional tolerances. Since the pattern is removed by melting or burning out, casting precision is increased through eliminating draft, rapping, and shifts. Various other names are given to this process. It is also called precision investment casting, precision casting or the lost-wax process and is shown in FIG. 1.21.

Various types and grades of wax are the common materials for pattern making for investment casting. Certain plastics that burn without residue are also used as pattern materials. Some low melting point metallic alloys can also be used as pattern materials. In this process of casting the patterns are formed afresh each time by casting or forging the pattern material in dies made of metal, plastic, rubber or wood.

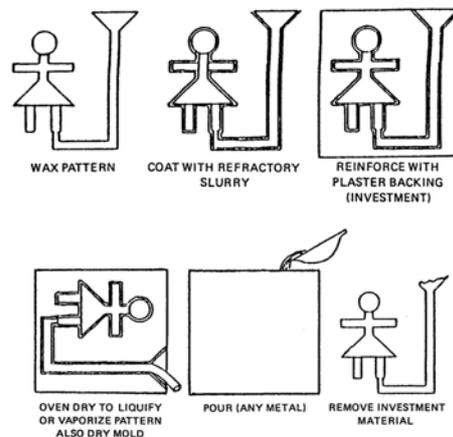


FIG. 1.21. Steps for investment casting.

Patterns are first made of wax or other pattern materials by melting and then injecting it into a metallic or non-metallic die. Then the patterns are welded or joined to gates and runners, which are also of the same material as the pattern. By this welding or joining of the pattern to gates and runners a tree like pattern is prepared. This tree is now dipped into a refractory sand, placed in a metal flask and sealed to the pallet. Then the investment or moulding material, in viscous slurry form, is poured around the pre-coated tree. When the investment has set, the mould is heated by putting it in an oven at 200°F. By this heating the mould is dried and baked and the pattern is melted and the molten pattern material is taken out of the mould. Now as a final touch to the mould before casting, the mould is placed in a furnace and is heated to a temperature of 1300–1900°F. This removes all the wax residue, if any, sticking to the investment mould. The mould is then heated to the casting temperature.

Shell mould casting

This process involves making a mould that has two or more thin, shell-like parts consisting of thermosetting resin-bonded sand. These shells are single purpose in application and are hard and easily handled and stored. Shells are made so that matching parts fit together easily, held with clamps or adhesives and poured in either a vertical or horizontal position. These moulds may be supported in racks or in a mass of bulky permeable material like sand, steel shots, or gravel.

Metallic patterns are used for the production of shells, as they are subjected to heating temperatures approaching 1,000°F. The pattern must have some provision, in the form of ejector pins, for the removal of shells from the surface of the pattern. Clean dry silica sand is the bulk material used in the making of shell moulds. Grain size and distribution can vary with use. Thermosetting synthetic resins are used as binders for sand. The resins include the phenolformaldehydes, urea formaldehydes, and others.

The sand and resin mix or coated sand is caused to fall against, or is blown against, a heated metal pattern or core box. The temperature of the pattern ranges from 350 to 600°F. Contact of the thermosetting resin with the hot pattern causes an initial set and thus an adhering layer of bonded sand is formed within 5 to 20 seconds. The pattern with this adhering layer of bonded sand is placed into the furnace and is cured by heating to the proper temperature for one to three minutes. The time of curing depends on the shell thickness and the resin type. The assembly is then removed from the furnace and the shell is stripped from the pattern by ejector devices. This stripping is sometimes a problem and can be overcome by using a silicon parting agent.

The main advantages of this process are that the 'shell' cast parts have generally a smooth surface and thereby reduce machining costs. These techniques are readily adaptable to mass production by using automatic equipment. The disadvantages can be the initial cost of metal patterns, the higher cost of the resin binders and a general size limitation.

Continuous casting

Although only a small tonnage of castings are produced by continuous casting, it is possible to produce two dimensional shapes in an elongated bar by drawing solidified metal from a water cooled mould. As shown schematically in FIG. 1.22 molten metal enters one end of the mould, and solid metal is drawn from the other. Control of the mould temperature and the speed of drawing is essential for satisfactory results. Exclusion of contact with oxygen, while molten and during solidification, produces high quality metal. Gears and other shapes in small sizes can be cast in bar form and later sliced into multiple parts.

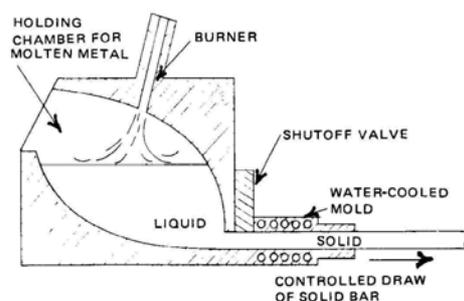


FIG. 1.22. Schematic diagram of continuous casting process.

TABLE 1.2. COMPARISON OF CASTING METHODS (APPROXIMATE)

| | Sand casting | Permanent mould casting | Die-casting | Centrifugal casting | Investment casting | Shell mould casting |
|--|--------------|--|---|---------------------|--------------------|---------------------|
| Relative cost in large quantity | Medium | Low | Lowest | High | Highest | Medium |
| Relative cost for small number | Lowest | High | Highest | Medium | Low | Low |
| Permissible weight of casting | Unlimited | 100 lb | 300 lb | Several tons | 5 lb | Limited |
| Thinnest section castable(mm) | 3.25 | 3.25 | 1 | 12.5 | 0.25 | 3.25 |
| Typical dimensional tolerance (mm) | 1.6 | 0.75 | 0.25 | 1.6 | 0.25 | 0.25 |
| Relative surface finish | Poor | Good | Best | Fair | Very good | Good |
| Relative mechanical properties | Fair | Good | Very good | Best | Fair | Good |
| Relative ease of casting complex designs | Fair | Fair | Good | Poor | Best | Fair |
| Relative ease of changing design in production | Best | Poor | Poorest | Good | Good | Good |
| Range of alloys that can be cast | Unlimited | Copper base and lower melting preferable | Aluminium base and lower melting preferable | Unlimited | Unlimited | Unlimited |

Casting defects

There are in general three broad categories of casting defects. First are the major or most severe defects which result in scraping or rejection of the casting. The second category is of intermediate defects which permit salvaging of the casting through necessary repair. The third category defects are minor ones which can be easily repaired. The elimination and control of casting defects is a problem that the foundry engineer may approach in several ways.

The common procedure is to rely upon salvaging techniques that appear to provide immediate savings. Remedial procedure in the moulding, core-making, melting or pouring areas of the foundry are frequently neglected but are highly desirable to be controlled to avoid defects. Some of the defects which usually occur in castings are given hereunder:

Porosity

Gas holes are spherical holes of varying size, with bright walls, usually fairly evenly distributed and formed by gas in the metal. The larger holes tend to be found in the heavier section (i.e. last to solidify). If the metal is correct prior to casting, the pinhole type of porosity is probably due to absorption of hydrogen from steam in the mould. The gas in the molten metal is removed by a gas scavenging technique and by keeping casting ladles and moulds dry.

Blowholes

Blowholes are mainly found in three forms: i) Elongated cavities with smooth walls, found on or just below the surface of the topmost part of a casting. These are caused by entrapped air and repetition can be avoided by venting the mould and increasing its permeability. ii) Rounded shape cavities with smooth bright walls are caused by mould or core gases, coupled with insufficient permeability, or venting. They can be avoided by using less oil binder in the mould and ensuring that cores are dry and properly baked and that the sand is properly mixed. iii) Small cavities immediately below the 'skin' of the casting surface are formed by the reaction of the molten metal with moisture in the moulding sand. This can be avoided by reducing the volatile content in mould cores and mould dressing, by ensuring that metal is deoxidized, by using more permeable sands, by ensuring that moulds and cores are properly vented and by reducing pouring temperature.

Piping

When this term is used in the foundry it refers to the gas inclusion defects encountered in risers or within the casting proper.

Inclusions

These are material discontinuities formed by the inclusion of oxides, dross, and slag in a casting. They are due to careless skimming and pouring, or the use of a dirty ladle, and to turbulence due to improper gating methods when casting alloys, such as aluminium and bronze, that are subject to surface oxide-skin formation. Faulty closing of moulds can cause 'crush' and loose pieces of sand becoming incorporated in the casting. The occurrence of inclusions can be avoided by proper use of equipment and foundry practice.

Sponginess

A defect that occurs during the early stages of solidification of a casting and has the appearance, as the name would imply, of a sponge; it may be local or general in extent. The major cause is failure to obtain directional solidification of the casting towards the desired heat centres, such as risers and in-gates; insufficiently high pouring temperature and placing of in-gates adjacent to heavy sections.

Shrinkage

It is a casting defect that occurs during the middle and later stages of solidification of the cast metal. It has a branching formation, is readily distinguishable from that of sponginess, and is a form of void FIG. 1.23. The defect can be avoided by paying particular attention to the direction of solidification and ensuring adequate risers, or other feeding aids, on the heavier sections of a casting. Modification of casting design, i.e. to make cast sections more uniform

for the flow and solidification of the metal is helpful in avoiding shrinkage. Moulds and cores are sometimes made too strong and greatly resist the contraction of the cast metal and, in this way, will cause a breakdown in the homogeneity of the metal.

Hot tears

These are discontinuities that result from stresses developed close to the solidification temperature while the metal is still weak. These, again, are attributed to resistance of the mould and core, which hinder contraction of the casting, causing thermal stress. Hot tears resemble ragged cracks. They can be avoided by making cores and moulds more collapsible, avoiding abrupt changes in section and preventing the formation of intense hot spots by designing with more uniform sections FIG. 1.24.

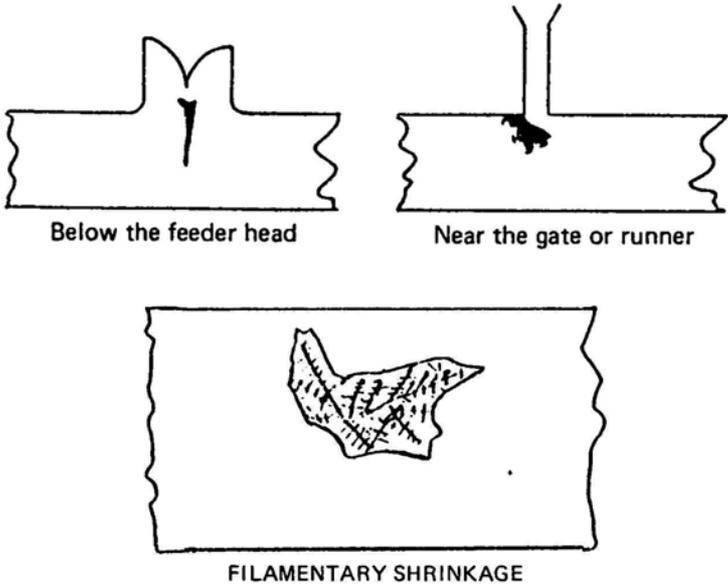


FIG. 1.23. Formation of shrinkage defects.

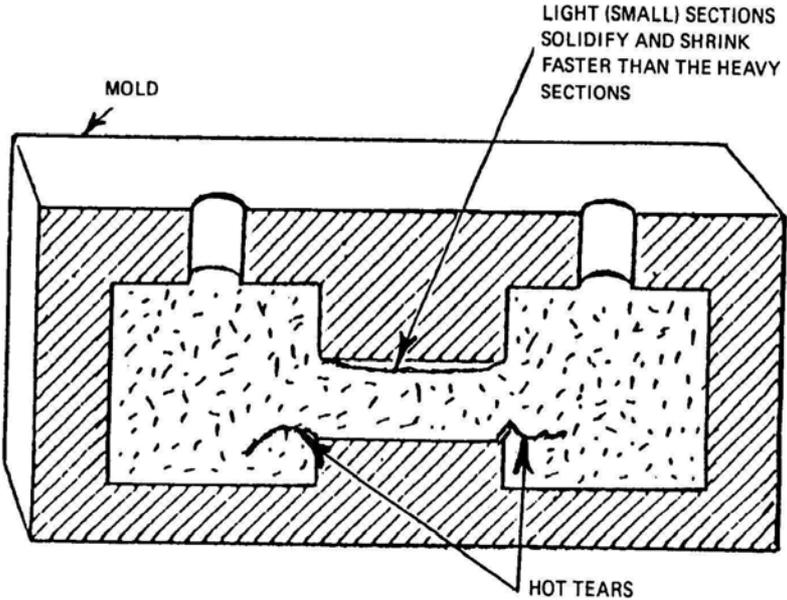


FIG. 1.24. Hot tears.

Crack

Well defined and normally straight, they are formed after the metal has become completely solid. Quite large stresses are required to cause fracture, and the walls of such cracks are discoloured according to the temperature of the casting when the cracks formed. Bad casting design coupled with restriction of contraction by the mould, core, or box bars contribute to cracking, and avoidance of these, together with the easing of mould or cores as soon as possible after solidification, will help to prevent build-up of stresses.

Cold shuts

These are discontinuities (a form of lack of fusion) caused by the failure of a stream of molten metal to unite with another stream of metal, or with a solid metal section such as a chaplet FIG. 1.25. They are linear in appearance, with perhaps a curling effect at the ends. A cold shut is caused by the fluidity of the metal being too low (i.e. surfaces too cold) or perhaps unsatisfactory methods of feeding the molten metal. Cold shuts can often be avoided by raising the pouring temperature or pouring rate or both and reviewing the position, size, and number of in-gates and the arrangements for venting the mould.

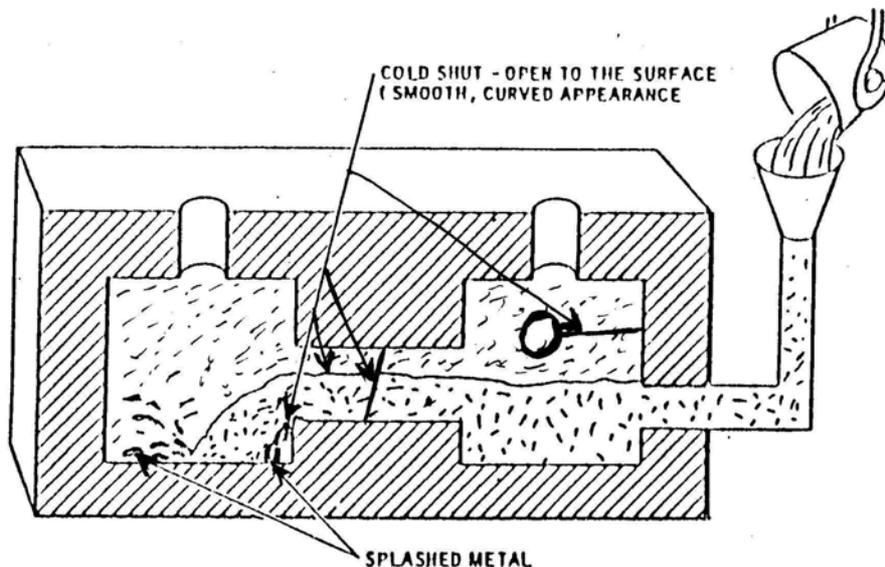


FIG. 1.25. Types of cold shuts.

Unfused chaplet

A chaplet is often used to support a section of a mould or a core within a mould and when the molten metal is poured in, the chaplets should fuse into the casting. When unfused the chaplet will cause a discontinuity in the casting. Design of chaplet and type of chaplet should be reviewed in overcoming this defect.

Misplaced core

An irregularity of wall thickness, e.g. one wall thicker than the other, can be detected by a double wall technique radiograph. It is caused by core out-of-alignment, careless coring-up and closing of mould, or rough handling after the mould is closed.

Segregation

Segregation is a condition resulting from the local concentration of any of the constituents of an alloy. The segregation can be general extending over a considerable part of a casting, local when only the shrinkage voids or hot tears are wholly or partially filled with a constituent of low melting point or 'banded' which is mainly associated with centrifugal castings but can also occasionally occur in static castings.

Powder metallurgy processes

The definition for the term powder metallurgy is 'the art of producing metal powders and objects shaped from individual, mixed, or alloyed metal powders, with or without the inclusion of non-metallic constituents, by pressing or moulding objects which may be simultaneously or subsequently heated to produce a coherent mass, either without fusion or with the fusion of a low melting constituent only'. FIG. 1.26 shows the steps ordinarily required in the production of a part by the powder metallurgy process. Suitable powder must first be produced. While theoretically any crystalline material may be fabricated by powder metallurgy, the production of suitable powder has presented restrictions in many cases, either because of difficulty in obtaining adequate purity or because of economic reasons. After selection and blending of the powder and manufacture of a die for the shape to be produced, the powder is pressed to size and shape. The application of heat results in crystalline growth and the production of a homogeneous body.

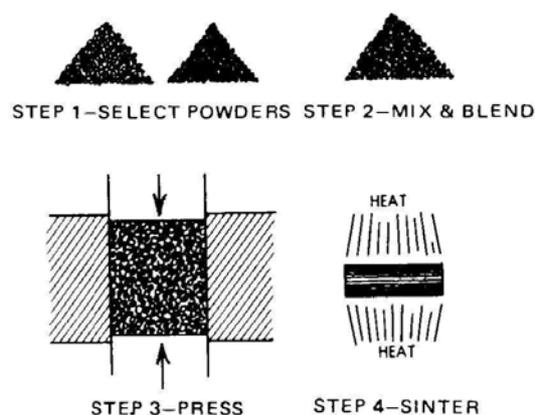


FIG. 1.26. Elements of powder metallurgy.

Mixing and blending

Mixing is required for even a single metal powder to promote homogeneity with a random dispersion of particle sizes and shapes. The mixing and blending is even more important for combinations of materials that depend on uniform alloying to develop final properties. Small amounts of organic materials may be added to reduce segregation, and other materials, both organic and inorganic, may be added to act as lubricants during pressing or sometimes in the final product.

Pressing

Compacting of metallic powders ideally would be done by applying pressure in all directions at one time. This is usually impractical for commercial use, and most compaction is done along a single axis. Pressure is sometimes applied from one direction only, but in other cases

opposing motions are used to reduce the effect of sidewall friction. The effectiveness of pressing is most often evaluated by measuring the density of the material and expressing it as a percentage of the theoretical density for solid metal of the type being treated. Densities depend on the particle size and shape, the material, the pressure, the time, and the temperature. The density variation problem is further complicated by shapes that are other than simple cylinders. Development of pressure by centrifuging may produce more uniform density because each particle of material supplies a force of its own.

Sintering

The term sintering is used to identify the mechanism by which solid particles are bonded by application of pressure or heat, or both. In its broadest sense, the process includes such procedures as welding, brazing, soldering, firing of ceramics, and union of plastic flakes or granules. Each of the procedures other than those involving metal in powder form are important enough and of such wide usage as to have developed their own language and technology. Sintering can be accomplished at room temperature with pressure alone but it is most often performed at elevated temperature, either at the same time or after pressure has been applied. The two most common sintering procedures are: (1) application of heat and pressure together, called hot pressing; and (2) application of heat after the particles have been closely packed, by cold pressing. In hot pressing, the plasticity of the particles is greater, and they re-crystallize more readily and thus permit high densities to be achieved with lower pressures than would be necessary at lower temperatures. Cold-pressed parts that are subsequently sintered may be heated in conventional manner by being placed in ordinary furnaces or salt baths.

Deformation

Because of variations of density and other factors, shrinkage of powder metallurgy products during sintering is difficult to control. Parts that require close tolerances must nearly always be finished by some dimensional treatment. Cold working may be used for minor changes of dimensions, but this procedure is limited by the lack of ductility common to powder metallurgy products. Reprising, sometimes referred to as coining, improves the density, strength, and ductility of the material. Even with this process, it is seldom that these properties are equal to those of a similar material produced by fusion. Most commercial deformation working is done by hot working or by cold working with frequent interruptions for re-crystallization.

Heat treatment

Powder metallurgy products may be heat treated in the same ways as other materials of similar chemical composition, but the treatments are usually not as effective as for the fusion produced metals, mainly because of the porous structure restricting the heat conductivity. Many of the voids within powder metallurgy products are stress concentration points that not only limit service loads but also increase the stresses arising from thermal gradients during heat treatment. The treatments include re-sintering for stabilization and homogeneity, annealing for softness, grain refinement for improved ductility, and hardening for improved wear resistance.

Machining

The machinability of sintered materials is usually poor, but machining is sometimes necessary to provide final control of dimensions or to establish shapes that are not practical for the

powder metallurgy process. With some types of products, such as the cemented carbides, grinding is the common finishing process both to control size and shape and, in many cases, to eliminate the surface produced in the sintering process.

Impregnation

One important finishing step is that of impregnation. Inorganic materials, such as oils or waxes, may be impregnated into porous metal products for purposes of lubrication. An entirely different kind of product can be produced by impregnating high melting temperature metals with low melting temperature metals. The principal use of this technique is in the production of cemented steels.

Applications of powdered metal products

Powder metallurgy occupies two rather distinct areas. It is a basic shape-producing method for practically all metals, in direct competition with other methods. In addition, for many refractory materials, both metals and non-metals, powder metallurgy is the only practical means of shape production. Tungsten is typical of the refractory metals; it has a melting point of 3400°C, and no satisfactory mould or crucible materials exist for using conventional casting techniques at this temperature. Tantalum and molybdenum are similar.

Cemented carbides form one of the most important groups of materials that can be fabricated into solid shapes by powder metallurgy only. The biggest use is for cutting tools and cutting tool tips or inserts, but the cemented carbides are also used for small dies and some applications where wear resistance is important. The principal material used is tungsten carbide, although titanium carbide and tantalum carbide are also used. Some very useful production cutting tools are manufactured by using strong, tough materials as a core and impregnating the surface with titanium carbide or another hard, wear resistant material.

A further area in which powder metallurgy produces products not practical by other means is the manufacture of materials with controlled low density. One of the first mass-produced powder metallurgy products was sintered porous bronze bearings. After cold pressing, sintering, and sizing, the bearings are impregnated with oil, which in service is made available for lubrication. Although not true fluid film bearings, they provide long service with low maintenance. Porous materials are also useful as filters.

Composite electrical materials form a group similar to the cemented carbides. Tungsten and other refractory metals in combination with silver, nickel, graphite, or copper find wide applications as electrical contacts and commutator brushes; powder metallurgy not only provides a means for producing the combination but also provides the finished shape for the parts. Many of the currently used permanent magnetic materials are as well produced by powder metallurgy.

1.3.2 Manufacturing processes and related defects

Welding processes

Welding can be defined as the metallurgical method of joining, applied to the general problem of construction and fabrication. It consists of joining two pieces of metal by establishing a metallurgical atom-to-atom bond, as distinguished from a joint held together by friction or mechanical interlocking. This metallurgical atom-to-atom bond is achieved by the application of heat and sometimes pressure.

Many welding processes require the application of heat or pressure, or both, to produce a suitable bond between the parts being joined. The physics of welding deals with the complex physical phenomena associated with welding, including heat, electricity, magnetism, light, and sound. In making a joint two parts of the same chemical composition may be welded together using no added metal to accomplish the joint. This might be termed as autogenous welding. A metal which is of the same composition as the parts being joined may be added, in which event, the process would come under the general heading 'homogenous' welding. Finally, an alloy quite different from that of which the parts are made may be used or alternatively the parts themselves may differ significantly in composition. Then this process is called heterogeneous welding. Almost every imaginable high energy density heat source has been used at one time or another in welding. Externally applied heat sources of importance include arcs, electron beams, light beams (lasers), exothermic reactions (oxyfuel gas and thermit), and electrical resistance. Welding processes that acquire heat from external sources are usually identified with the type of heat source employed. The welding processes which are commonly used for the welding of metals are described and their features are discussed in the following sections.

Weld design and positions

The loads in a welded structure are transferred from one member to another through welds placed in the joints. The types of joints used in welded construction and the applicable welds are shown in FIG. 1.27. All welds that are encountered in actual construction, except groove welds in pipe, are classified as being flat, horizontal, vertical, or overhead. Groove welds in pipe are classified as horizontal rolled, horizontal fixed, vertical, or inclined fixed. These positions are illustrated in FIGs 1.28 and 1.29 and explained below:

Flat position (1G). The test plates are placed in an approximately horizontal plane and the weld metal deposited from the upper side FIG. 1.28 (A).

Horizontal position (2G). The test plates are placed in an approximately vertical plane with the welding groove approximately horizontal FIG. 1.28 (B).

Vertical position (3G). The test plates are placed in an approximately vertical plane with the welding groove approximately vertical FIG. 1.28 (C).

Overhead position (4G). The test plates are placed in an approximately horizontal plane and the weld metal deposited from the underside FIG. 1.28 (D).

Horizontal rolled (1G). The pipe is placed with its axis in an approximately horizontal plane with the welding groove in an approximately vertical plane and the pipe is rolled during welding FIG. 1.28 (A).

Vertical (2G). The pipe is placed with its axis in an approximately vertical position with the welding groove in an approximately horizontal plane FIG. 1.28 (B).

Horizontal fixed (5G). The pipe is placed with its axis in an approximately horizontal plane with the welding groove in an approximately vertical plane and the pipe is not to be rolled or turned during welding FIG. 1.28 (E)

Inclined fixed (6G). The pipe is inclined fixed ($45^{\circ} \pm 5^{\circ}$) and not rotating during welding FIG. 1.28 (F).

For fillet welds in plates, different positions are defined as below:

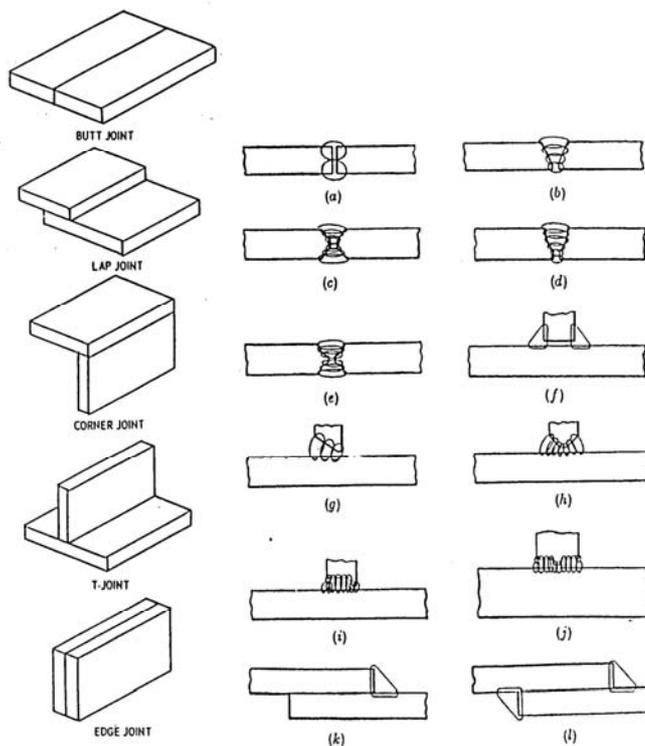
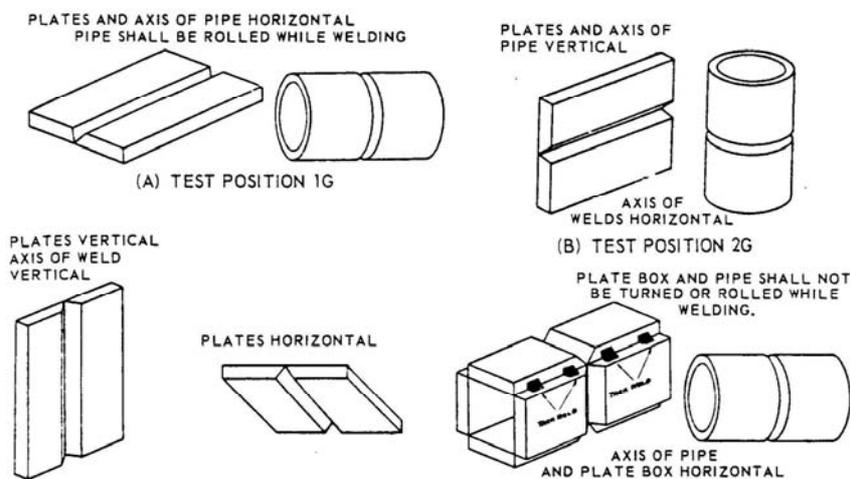


FIG. 1.27. Types of welding joints: (a) square butt , (b) single-v butt , (c) double-v butt , (d) single-u butt , (e) double-u butt , (f) square-t , (g) single-bevel t , (h) double-bevel t , (i) single-u t , (j) double-u t , (k) single-bead lap , (l) double-bead lap



(C) TEST POSITION 3G , (D) TEST POSITIONING 4G , (E) TEST POSITION 5G, (F) TEST POSITION 6G

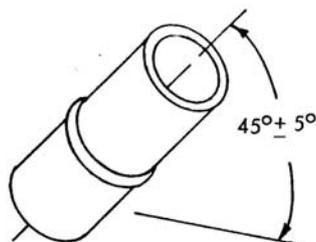


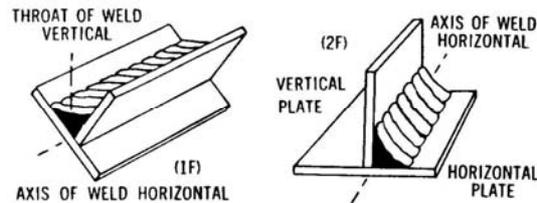
FIG. 1.28. Positions of plates and pipes for groove weld.

Flat position (1F). The test plates are so placed that each fillet weld is deposited with its axis approximately horizontal and its throat approximately vertical FIG. 1.29 (A).

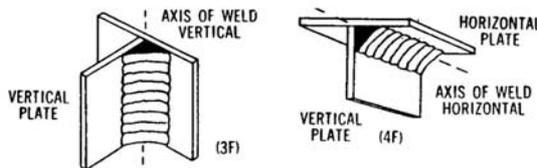
Horizontal position (2F). The test plates are so placed that each fillet weld is deposited on the upper side of the horizontal surface and against the vertical surface FIG. 1.29 (B).

Vertical position (3F). Each fillet weld is made vertically FIG. 1.29 (C).

Overhead position (4F). The test plates are so placed that each fillet weld is deposited on the underside of the horizontal surface and against the vertical surface FIG. 1.29 (D).



(A) FLAT POSITION (B) HORIZONTAL POSITION



(C) VERTICAL POSITION (D) OVERHEAD POSITION

FIG. 1.29. Positions of plates for fillet welds.

Shielded metal arc welding (SMAW)

Shielded metal arc welding is an early arc welding process. It is one of the simple and versatile processes for welding ferrous and several non-ferrous base metals. Basically, it is a manual welding process in which the heat for welding is generated by an arc established between a flux covered consumable electrode and the work. The electrode tip, welded puddle, arc and adjacent areas of the work piece are protected from atmospheric contamination by a gaseous shield obtained from the combustion and decomposition of the flux covering. The process is illustrated in FIG. 1.30.

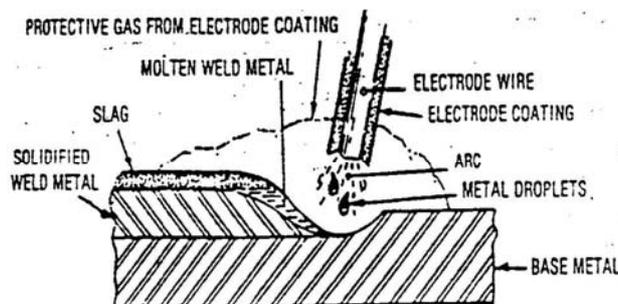


FIG. 1.30. Shielded metal arc welding process.

Covered electrodes are produced in a variety of diameters normally ranging from 1/16 to 5/16 in. (2 to 8 mm). The smaller diameters are used with low currents for joining thin sections and for welding in all positions. The large diameters are designed for conducting high currents to achieve greater deposition rates in the flat and horizontal positions. Special alloy filler metal compositions can be formulated with relative ease by the use of metal powders in the electrode coating.

The SMAW process has several advantages. Using the process, job shops can handle many welding applications with a relatively small variety of electrodes. Other advantages are the simplicity and lightness of the equipment, and its relatively low cost. Also, welds can be made in confined locations or remote from heavy power supplies.

Submerged arc welding (SAW)

In submerged arc welding the arc and molten metal are shielded by an envelope of molten flux and a layer of unfused granular flux particles as shown in FIG. 1.31. When the arc is struck, the tip of the continuously fed electrode is submerged in the flux and the arc is therefore not visible. The weld is made without the intense radiation that characterizes an open arc process and with little fumes. The SAW process is used in both mechanized and semiautomatic operations, although the former is by far more common. High welding currents can be employed to produce high metal deposition rates at substantial cost savings. Welds can only be made in the flat and horizontal positions.

The process is most widely employed for welding all grades of carbon, low alloy, and alloy steels. Stainless steel and some nickel alloys are also effectively welded or used as surfacing filler metals with the process. Various filler metal-flux combinations may be selected to provide specific weld metal properties for the intended service. The flux may contain ingredients that when melted react to contribute alloying additions to the weld metal.

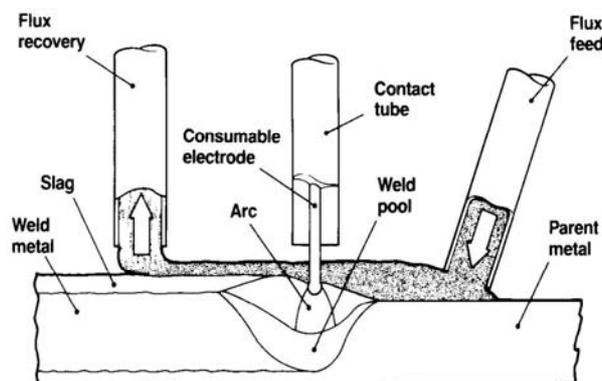


FIG. 1.31. Submerged arc welding process.

Gas metal arc and flux cored arc welding (GMAW & FCAW)

Gas metal arc welding (GMAW/ or MIG/MAG) and flux cored arc welding (FCAW) are two distinct processes, but they have many similarities in application and equipment. Both processes use a continuous solid wire or tubular electrode to provide filler metal, and both use gas to shield the arc and weld metal. In GMAW, the electrode is solid, and all of the shielding gas is (argon, helium, CO₂ or mixtures of these gases) supplied by an external source, as shown in FIG. 1.32.

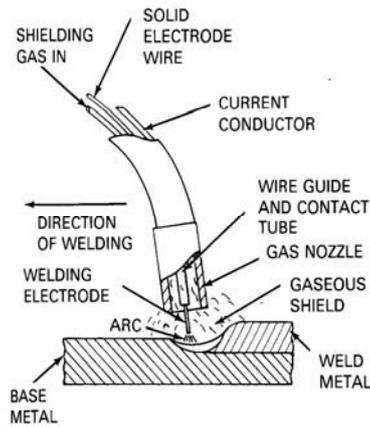


FIG. 1.32. Gas metal arc welding process.

The original gas metal arc process consisted of a continuous operation requiring high current densities to achieve a smooth transfer of molten metal.

The process permits welding with minimal spatter, uniform penetration, and good out-of-position capability. With FCAW, the electrode is tubular and contains core ingredients that may supply some or all of the shielding gas needed. This process may also use auxiliary gas shielding, depending on the type of electrode employed, the material being welded, and the nature of the welding involved. FCAW is illustrated in FIG. 1.33.

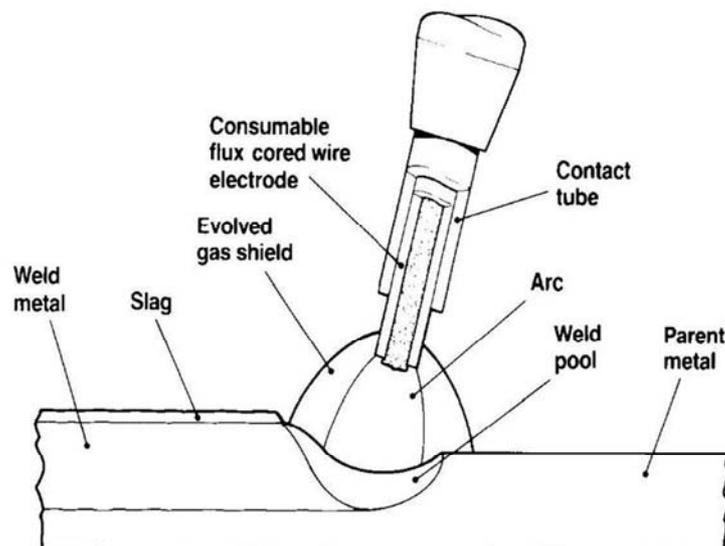


FIG. 1.33. Flux cored arc welding.

Flux cored arc welding uses cored electrodes instead of solid electrodes for joining ferrous metals. The flux core may contain minerals, ferroalloys, and materials that provide shielding gases, deoxidizers, and slag forming materials. The additions to the core promote arc stability, enhance weld metal mechanical properties, and improve weld contour. Many cored electrodes are designed to be used with additional external shielding. Carbon dioxide-rich gases are the most common. Weld metal can be deposited at higher rates, and the welds can be larger and better contoured than those made with solid electrodes, regardless of the shielding gas.

Gas tungsten arc welding (GTAW)

Gas tungsten arc welding uses a non-consumable tungsten electrode which must be shielded with an inert gas. The arc is initiated between the tip of the electrode and work to melt the metal being welded, as well as the filler metal, when used. A gas shield protects the electrode and the molten weld pool, and provides the required arc characteristics. This process is illustrated in FIG. 1.34 and is also sometimes called TIG welding.

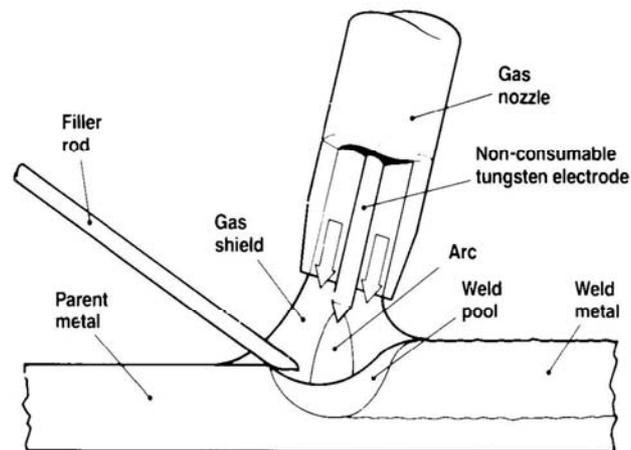


FIG. 1.34. Gas tungsten arc welding.

Several types of tungsten electrodes are used with this process. Thoriated and zirconiated electrodes have better electron emission characteristics than pure tungsten, making them more suitable for dc operations.

Thorium (Th) is slightly radioactive with a long half life and emits mainly alpha (α) particles. Thorium oxide (thoria) is, therefore, a low level radioactive material which may give rise to both a small external radiation hazard and an internal hazard from ingestion or inhalation. There is almost no release of radioactive material during arcing. However, to achieve maximum arc stability the electrode tip is ground to a conical point before use. During the grinding process, particles of tungsten with thoria on the surface may be produced. The dust particles that create the hazard, as they may be inhaled, and the thoria may release alpha particles. However, the risk of cancer in TIG welders due to thoria exposure is very low, since the exposure times to individuals are invariably small. It is recommended that thoriated electrodes are stored in steel boxes, clearly labeled with the radiation trefoil. When stored in closed boxes, there is no significant hazard in handling and storage. Small numbers (1 day's supply) of electrodes can be handled by welders safely without any special precautions. Generally there are no regulatory restriction on disposal of used thoriated electrodes by conventional means. However, if large disposals are anticipated it would be worthwhile to have some preliminary discussions with the local landfill operator and the regulatory body concerned.

Electro-slag welding (ESW)

Electroslag welding is a specialized adaptation of submerged arc welding and it is used for joining thick materials in the vertical position. This process is illustrated in FIG. 1.35. Strictly speaking it is not an arc welding process at all, because it actually depends on the electrical receptivity of a molten flux bath to produce the heat necessary to melt the filler and base metal.

The process is, however, initiated by an arc, which heats a layer of granular welding flux contained within water cooled moulding shoes or dams and the edges of the joint, thus turning it to a bath of molten slag. The arc is then extinguished, and the conductive slag maintained in a molten condition by its resistance to the electric current passing through from a consumable electrode to the work. The principal application of electroslog welding is welding of thick steel plate heavy forgings and large steel castings in the fabrication of machine bases and in the structural steel industry. Its main features are: (i) Extremely high metal deposition rates, (ii) Ability to weld very thick materials in one pass, (iii) Minimal joint preparation and fit-up requirements, (iv) Little or no distortion and (v) Low flux consumption.

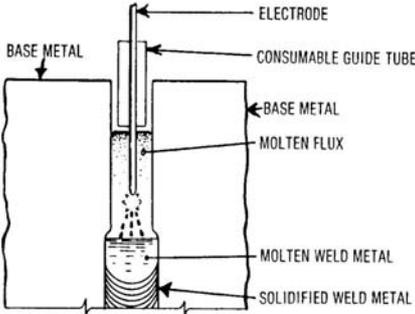


FIG. 1.35. Electroslog welding process.

Stud arc welding (SAW)

In stud welding, basically an arc welding process, the welding arc is generated between a metal stud or similar part and the part to which it is ultimately fused by the welding heat so generated FIG. 1.36. In a way it is also a variation of the shielded metal arc process, the stud representing the electrode. But only the end of the electrode is melted and it becomes a permanent part of the final assembly.

In operation the stud is retained in a hand held or bench mounted gun and is positioned over the spot where it is to be attached. Upon initiation, current flows through the stud, which, at the same time, is lifted slightly, creating an arc. After a very short arcing period, the stud is plunged into the molten pool created on the base plate, and the gun is withdrawn.

Typical applications of stud welding include securing special lining in tanks, studding boiler tubes, assembling electrical panels, securing water, hydraulic, and electrical lines to buildings, vehicles and large appliances, and securing feet and handles to large appliances.

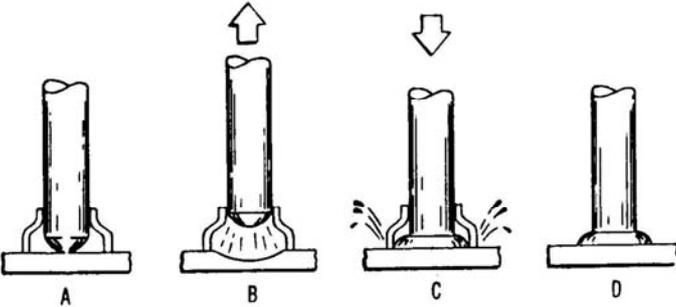


FIG. 1.36. Stud welding sequence.

Plasma arc welding (PAW)

The plasma arc welding process provides a very stable heat source for welding most metals from 0.001 to 0.25 in. (0.02 to 6 mm). This process has advantages over other open arc welding processes, such as SMAW, GMAW, and GTAW, because it has greater energy concentration, improved arc stability, higher heat content, and higher welding speeds. As a result, PAW has greater penetration capabilities than SMAW, GMAW, and GTAW.

The basic elements of the plasma arc torch, illustrated in FIG. 1.37, are the tungsten electrode and the orifice. A small flow of argon is supplied through the orifice to form the arc plasma. Shielding of the arc and weld zone is provided by gas flowing through an encircling outer nozzle assembly. The shielding gas can be argon, helium, or mixtures of argon with either hydrogen or helium. The plasma is initiated by an internal low current pilot arc between the electrode and the orifice. The pilot arc ionizes the orifice gas to ignite the primary arc between the electrode and the base metal. The arc plasma is constricted in size by the orifice around the electrode, and is called a transferred arc. If filler metal is used, it is fed into the arc as in the GTAW process.

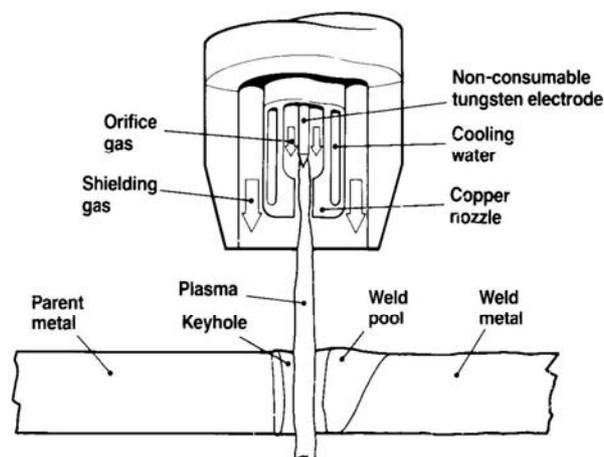


FIG. 1.37. Plasma arc welding.

Resistance welding (RW)

Resistance welding incorporates a group of processes in which the heat for welding is generated by the resistance to the flow of electrical current through the parts being joined. It is most commonly used to weld two overlapping sheets or plates which may have different thicknesses. A pair of electrodes conducts electrical current to the joint. Resistance to the flow of current heats the facing surfaces, forming a weld. These electrodes clamp the sheets under pressure to provide good electrical contact and to contain the molten metal in the joint. The joint surfaces must be clean to obtain consistent electrical contact resistance to obtain uniform weld size and soundness. The main process variables are welding current, welding time, electrode force, and electrode material and design. High welding currents are required to resistance heat and melt the base metal in a very short time. The time to make a single resistance heat and melt the base metal is very short usually less than one second.

There are four major resistance welding processes, namely, spot welding (RSW), projection welding (RPW), flash welding (RFW), and seam welding (RSEW). These processes are illustrated in FIG. 1.38. In RSW, the welding current is concentrated at the point of joining using cylindrical electrodes. Spot welds are usually made one at a time. In RPW, a projection

or dimple is formed in one part prior to welding. The projection concentrates the current at the facing surfaces. Large, flat electrodes are used on both sides of the components to produce several welds simultaneously. As an example, a stamped bracket may have three or four projections formed in it so that it can be welded to a sheet with one welding cycle. In seam welding, electrodes in the form of rolls are used to transmit pressure and to send current through the overlapping sheet being moved between them. Flash welding is usually an automatic process. Parts are clamped in place by a welding operator who simply presses a button to start the welding sequence. The usual flash weld joins rods or bars end to end or edge to edge. The flashing action is continued until a molten layer forms on both surfaces. Then the components are forced together rapidly to squeeze out the molten metal. This produces a hot worked joint free of weld metal. The mechanical properties of flash welds are often superior to other types of welds.

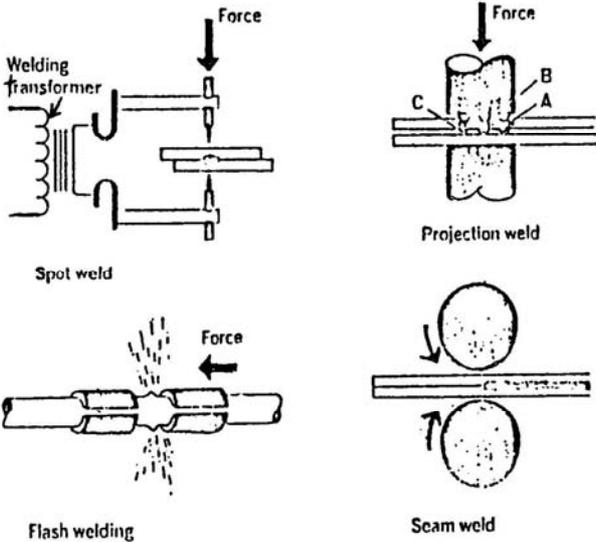


FIG. 1.38. Basic resistance welding methods.

Oxyfuel gas welding (OFW)

Oxyfuel gas welding includes a group of welding processes that use the heat produced by a gas flame or flames for melting the base metal and, if used, the filler metal. Oxyfuel gas welding is an inclusive term used to describe any welding process that uses a fuel gas combined with oxygen to produce a flame having sufficient energy to melt the base metal. The fuel gas and oxygen are mixed in the proper proportions in a chamber which is generally a part of the welding torch assembly. The torch is designed to give the welder complete control of the welding flame to melt the base metal and the filler metal in the joint. This process is illustrated in FIG. 1.39.

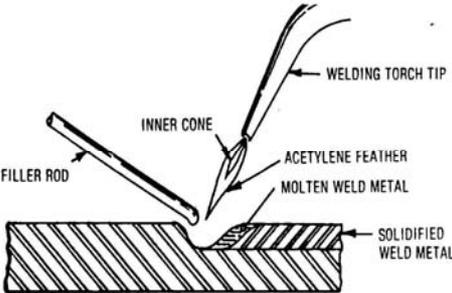


FIG. 1.39. Oxyfuel gas welding process.

Oxyfuel gas welding is normally done with acetylene fuel gas. Other fuel gases, such as methyl acetylene propadiene and hydrogen, are sometimes used for oxyfuel gas welding of low melting metals. The welding flame must provide high localized energy to produce and sustain a molten weld pool. With proper adjustment, the flames can also supply a protective reducing atmosphere over the molten weld pool.

Oxyfuel gas welding can be used for joining thick plates, but welding is slow and high heat input is required. Welding speed is adequate to produce economical welds in sheet metal and thin-wall and small diameter piping. Thus, OFW is best applied on material of approximately ¼ inches (6 mm) maximum thickness.

Brazing process

Brazing is a metal joining process where the base metal is heated to a temperature of about 425°C. Non-ferrous filler metals, such as brass or silver alloys, are melted by the heat of the base metal and flow by capillary attraction between the closely fitted surfaces of the joint. Heat for brazing is usually applied by flame torches, furnaces, electric induction, electric resistance or dropping the work into a hot salt bath. Filler and flux are either applied manually or are replaced in the form of powder, metallic rings or strips.

Miscellaneous welding processes

There are number of other welding processes sometimes encountered. Some of the important ones of these processes are briefly discussed below:

Electron beam and laser welding

These methods are generally utilized for precision assemblies requiring high-quality welds. The procedure is conducted by focusing an electron beam or laser beam on the joint interface and causing melting and fusion of the metal. Beam welds require that the mating of the components to be welded be fitted closely since there is no filler metal. The weld joint is created by the fusion of the material penetrated by the beam, therefore, the mating surface should be geometrically prepared so that they are in intimate contact over the entire joint surface. Electron beam welds are usually made in a vacuum while laser welding is conducted using an inert gas surrounding the laser beam. At the present time, electron beam has the capability for welding thicker specimens (up to 200 mm in steel), but is limited by the size of the vacuum chamber.

The devices use an intense beam of electrons to heat and melt the base metals to be welded and any filler metal. The heat comes from the absorption of the electrons in the metal. Since electrons can be stopped by all matter, including air, the welding process is almost always conducted in a vacuum chamber. X rays are generated when the accelerated electrons strike a material. The maximum energy of the x rays produced will be determined by the voltage used to accelerate the electrons and the metals involved. Assuming 1.5~2 cm thick steel chamber walls, the calculated exposure rate outside the device would be from 0.1 to 1mR/hr. Actual measurements made around e-beam welders do not usually exceed 0.05 to 0.1mR/hr at the surface of the chamber.

Friction welding (FW)

In friction welding the heat for coalescence is produced by direct conversion of mechanical energy to thermal energy at the joint interface. The mechanical energy is generated by the

sliding action between rotating or rubbing surfaces. The basic process involves holding a non-rotating work piece in contact with a rotating work piece under constant or gradually increasing pressure until the interface reaches welding temperature. The rotation is then stopped. It is a solid state process in which coalescence occurs at a temperature below the melting point of the metals being joined. Many ferrous and non-ferrous alloys can be friction welded, and the method can be used to join metals of widely differing thermal and mechanical properties.

Ultrasonic welding (USW)

Ultrasonic welding is a form of friction welding that has long been used to join plastics. Recently, such high frequency vibration has been successfully applied to the welding of metals, mostly non-ferrous metals.

It is known as a cold bonding process, because atomic combination and diffusion occurs while materials are in a semisolid or solid state. Although some heating occurs, welding depends more on the cleaning action of the process than on material heating.

In practice the parts to be welded are clamped under pressure between an anvil and a tip connected to a horn that vibrates at a high frequency. The welding tip and anvil may be contoured to the shape of the parts. The part in direct contact with the tip is rubbed at a high frequency against the stationary part. This vibratory action first erodes oxides and other contaminants on the interface surfaces. Once they are clean the surfaces come into intimate contact, and solid state bonding takes place.

Ultrasonic welding is best suited for joining small parts, sheet and foil. The process is fast, requires no consumables, and, because of its low heat, the result of the processing eliminates the need for further cleaning. In some instances, even coated, painted and badly rusted surfaces can be effectively joined without surface preparation.

Weld defects and discontinuities

During the process of welding, discontinuities of various types may occur. These may be classified under the headings of procedure and process, design, and metallurgical behaviour. The groups should be applied loosely because discontinuities listed in each group may have secondary origins in other groups. Discontinuities related to process, procedure, and design are, for the most part, those that alter stresses in a weld or heat-affected zone. Metallurgical discontinuities may also alter the local stress distribution, and in addition, may affect the mechanical or chemical (corrosion resistance) properties of the weld and heat-affected zone.

Porosity

Molten weld metal has a considerable capacity for dissolving gases which come into contact with it, such as hydrogen, oxygen and nitrogen. As the metal cools its ability to retain the gases diminishes. For instance, in steel the oxygen reacts with the carbon to form carbon monoxide, which is given off as a gas. With the change from the liquid to the solid state, there is reduced solubility with falling temperature. This causes an additional volume of gas to be evolved at a time when the metal is becoming mushy and therefore incapable of permitting the gas to escape freely. Entrapment of the gas causes gas pockets and porosity in the final weld. The type of porosity within a weld is usually designated by the amount and distribution of the pores. Some of the types are classified as follows: FIG. 1.40.

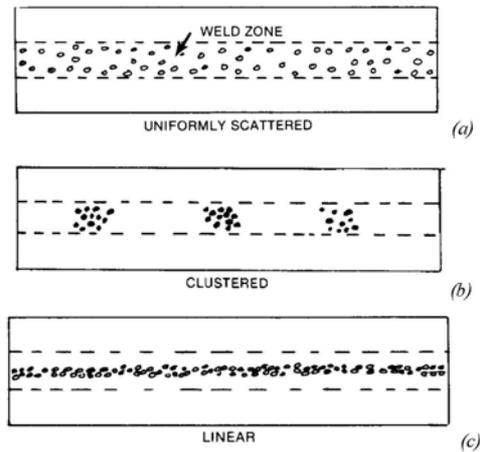


FIG. 1.40 Three types of weld porosity (a) Uniformly scattered porosity (b) Clustered porosity (c) Linear porosity.

Pipe or wormholes

Some gas inclusions have an elongated form known as pipes or wormholes. They are usually almost perpendicular to the weld surface. They can result from the use of wet powdered flux or from inadequate welding current. Another typical form of pipe has appearance of a branch of a tree FIG. 1.41. These can be caused by use of wet welding electrodes.

The common causes of porosity, and suggested methods of preventing it, are summarized in Table 1.3.

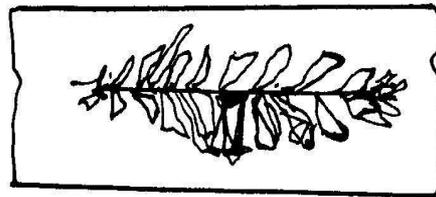


FIG. 1.41: Piping in weld.

TABLE 1.3. COMMON CAUSES AND REMEDIES OF POROSITY

| Causes | Remedies |
|---|---|
| Excessive hydrogen, nitrogen, or oxygen in welding atmosphere | Use low-hydrogen welding process, filler metals high in deoxidizers; increase shielding gas flow |
| High solidification rate | Use preheat or increase heat input |
| Dirty base metal | Clean joint faces and adjacent surfaces |
| Dirty filler wire | Use specially cleaned and packaged filler wire, and store it in clean area |
| Improper arc length, welding current, or electrode manipulation | Change welding conditions and techniques |
| Volatilization of zinc from brass | Use copper-silicon filler metal; reduce heat input |
| Galvanized steel | Use E6010 electrodes and manipulate the arc heat to volatilize the zinc ahead of the molten weld pool |
| Excessive moisture in electrode covering or on joint surfaces | Use recommended procedures for baking and storing electrodes. Preheat the base metal |
| High sulphur base metal | Use electrodes with basic slagging reactions |

Non-metallic inclusions

These may be the result of weld-metal contamination by substances on the surface of the joint or by the atmosphere. But the usual source is the slag formed by the electrode covering or flux used in the welding process. Some slag may be trapped in the deposited metal during its solidification, particularly if the metal fails to remain molten for a sufficient period to permit the slag to rise to its surface. In multi-pass welding, insufficient cleaning between weld passes can leave a portion of the slag coating in place to be covered by subsequent passes. A particular characteristic of slag inclusions is the slag line, intermittent or continuous. Such slag lines are often accompanied by a pronounced lack of fusion to the base metal. In general inclusions may be due to any one of several reasons which include failure to clean the surface of the joint, failure to remove slag from a previous deposit, incorrect edge preparation, incorrect manipulation of the electrode and insufficient arc shielding. The common causes and remedies of inclusion-type discontinuities are shown in Table 1.4.

TABLE 1.4. COMMON CAUSES AND REMEDIES OF SLAG INCLUSIONS

| <u>Causes</u> | <u>Remedies</u> |
|--|--|
| Failure to remove slag | Clean the surface and previous weld bead |
| Entrapment of refractory oxides | Power wire brush the previous weld bead |
| Improper joint design | Increase groove angle of joint |
| Oxide inclusions | Provide proper gas shielding |
| Slag flooding ahead of the welding | Reposition work to prevent loss of slag control |
| Poor electrode manipulative technique | Change electrode or flux to improve slag control |
| Entrapped pieces of electrode covering | Use undamaged electrodes |

Tungsten inclusions

Tungsten inclusions are particles of metallic tungsten embedded in the weld metal which originate from the tungsten electrode used in tungsten arc welding. Causes are excessive welding current allowing the melting and deposition of tungsten in the weld and incorrect polarity of electrode using a d.c. source. Tungsten inclusions can also be caused from dipping the electrode into the molten weld metal or by touching the filler rod to the electrode during welding. Tungsten inclusions frequently occur at the start of welds when the electrode may be cold. Small globular and widely scattered tungsten inclusions are sometimes permissible, but sharp edged inclusions are dangerous.

Lack of fusion

This is due to the lack of union in a weld between the weld metal and parent metal or between parent metal and parent metal or between weld metal and weld metal. Consequently the lack of fusion can be of three types namely lack of side fusion, lack of root fusion and lack of inter-run fusion. The defect results mainly from the presence of slag, oxides, scale, or other non-metallic substances, too low a welding current or incorrect edge preparation. Incomplete fusion can also arise from too high a welding current when the high melt rate encourages the welder to use excessive welding speed. The defect reduces considerably the strength of a joint subjected to static loading, and under cyclic or shock loading it is quite serious. The causes and remedies for incomplete fusion are summarized in Table 1.5.

TABLE 1.5. COMMON CAUSES AND REMEDIES OF INCOMPLETE FUSION

| Causes | Remedies |
|--|---|
| Insufficient heat input, wrong type or size of electrode, improper joint design, or inadequate gas shielding | Follow correct welding procedure specification |
| Incorrect electrode position | Maintain proper electrode position |
| Weld metal running ahead of the arc | Reposition work, lower current, or increase weld travel speed |
| Trapped oxides or slag on weld groove or weld face | Clean weld surface prior to welding |

Incomplete root penetration

In butt welding, a root opening is usually left at the bottom of the groove (in one-side welding) or at the centre of the weld (in two-side welding). If the opening between the two plates is narrow, it is difficult to achieve complete penetration and fusion at the root of the weld. Therefore there can be a lack of fusion in the root of the weld or a gap left by the failure of the weld metal to fill the root of a butt weld FIG. 1.42. It is caused by the electrode held at an incorrect angle, an electrode too large in diameter, a rate of travel too fast, an insufficient welding current, or an improper joint preparation (e.g. joint misalignment).



FIG. 1.42. Incomplete root penetration.

Cracks

Cracks are linear ruptures of metal under stress. Although sometimes wide, they are often very narrow separations in the weld or adjacent base metal.

Cracks can occur in a wide variety of shapes and types and can be located in numerous positions in and around a welded joint FIG. 1.43.

Cracks associated with welding may be categorized according to whether they originate in the weld itself or in the base metal. Four types commonly occur in the weld metal, i.e. transverse, longitudinal, crater and hat cracks. Base-metal cracks can be divided into seven categories, namely, transverse cracks, lamellar tearing, delaminations and fusion-line cracks.

(a) Transverse cracks

In the weld metal, these are formed when the predominant contraction stresses are in the direction of the weld axis (No. 2 in FIG. 1.43). They can be hot cracks, which separate intergranularly as a result of hot shortness or localized planar shrinkage, or they can be transgranular separations produced by stresses exceeding the strength of the material. Transverse cracks lie in a plane normal to the axis of the weld and are usually open to the surface. They usually extend across the entire face of the weld and sometimes propagate into the base metal.

Transverse cracks in base metal (No. 3 in FIG. 1.43) occur on the surface in or near the heat-affected zone. They are the result of the high residual stresses induced by thermal cycling during welding. High hardness, excessive restraint, and the presence of hydrogen promote their formation. Such cracks propagate into the weld metal or beyond the heat affected zone into the base metal.

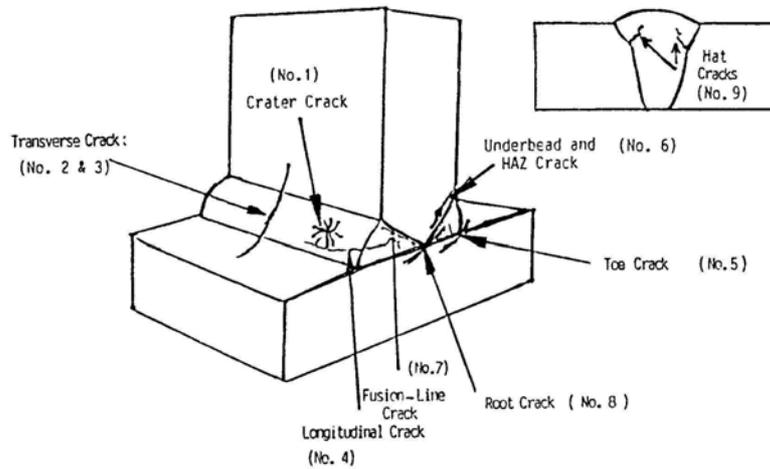


FIG. 1.43. Different types of cracks located in and around a welded joint.

(b) Underbead cracks

These are similar to transverse cracks in that they form in the heat-affected zone because of high hardness, excessive restraint, and the presence of hydrogen. Their orientation follows the contour of the heat-affected zone (No. 6 in FIG. 1.43).

(c) Longitudinal cracks

These cracks may exist in three forms, depending on their position in the weld (No. 4 in FIG. 1.43). Check cracks are open to the surface and extend only partway through the weld. Root cracks extend from the root to some point within the weld. Full centreline cracks may extend from the root to the face of the weld metal. Check cracks are caused either by high contraction stresses in the final passes applied to a weld joint or by a hot-cracking mechanism.

Root cracks are the most common form of longitudinal weld-metal cracks because of the relatively small thickness and size of the root pass. If such cracks are not removed, they can propagate through the weld as subsequent passes are applied. This is the usual mechanism by which full centreline cracks are formed.

Centreline cracks may occur at either high or low temperatures. At low temperatures, cracking generally is the result of poor fit-up, overly rigid fit-up, or a small ratio of weld metal to base metal.

All three types of longitudinal cracks usually are oriented perpendicular to the weld face and run along the plane that bisects the welded joint. Seldom are they open at the edge of the joint face, because this requires a fillet weld with an extremely convex bead.

(d) Crater cracks

As the name implies, crater cracks occur in the weld crater formed at the end of a welding pass (No. 1 in FIG. 1.43). Generally, this type of crack is caused by failure to fill the crater before breaking the arc. When this happens, the outer edges of the crater cool rapidly, producing stresses sufficient to crack the interior of the crater. This type of crack may be oriented longitudinally or transversely, or may occur as a number of intersecting cracks forming the shape of a star. Longitudinal crater cracks can propagate along axis of the weld to form a centreline crack. In addition, such cracks may propagate upward through the weld if they are not removed before subsequent passes are applied.

(e) Hat cracks

These cracks derive their name from the shape of the weld cross section with which they are usually associated. This type of weld flares out near the weld face, resembling an inverted top hat (No. 9 in FIG. 1.43). Hat cracks are the result of using excessive voltage or too low a welding speed. The cracks are located about halfway up through the weld and extend into the weld metal from the fusion line of the joint.

(f) Toe and root cracks

These cracks occur in the root area of the weld or near the boundary between the weld metal and the parent metal (Nos 5 and 8 in FIG. 1.43).

Undercut

During the final or cover pass the exposed upper edges of the bevelled weld preparation tend to melt and to run down into the deposited metal in the weld groove. The result is a groove which may be either intermittent or continuous, with more or less sharp edges along the weld reinforcement FIG. 1.44.



FIG. 1.44. Undercut.

Concavity at the root of the weld

A concave surface at the root of the weld can occur specially in pipe welding (without a cover pass on the root side). Root concavity is commonly produced by the flux cored arc welding (FCAW) process. In overhead welding this condition is a consequence of gravity which causes the molten metal to sag away from the inaccessible upper surface of the weld. It can also occur in downhand welding with a backing strip at the root of the weld groove if slag is trapped between the molten metal and the backing strip FIG. 1.45.



FIG. 1.45. Root concavity.

TABLE 1.7: COMMON CAUSES AND REMEDIES OF CRACKING

| Causes | Remedies |
|--------------------------------------|--|
| Highly rigid joint | Preheat; relieve residual stresses mechanically; minimize shrinkage stresses using backstep or block welding sequence |
| Excessive dilution | Change welding current and travel speed; weld with covered electrode negative, butter the joint faces prior to welding |
| Defective electrodes | Change to new electrode; bake electrodes to remove moisture |
| Poor fit-up | Reduce root opening; build up the edges with weld metal |
| Small weld bead | Increase electrode size; raise welding current; reduce travel speed |
| High sulphur base metal | Use filler metal low in sulphur |
| Angular distortion | Change to balanced welding on both sides of joint |
| Crater cracking | Fill crater before extinguishing the arc; use a welding current decay device when terminating the weld bead |
| Hydrogen in welding atmosphere | Use low-hydrogen welding process; preheat and hold for 2 h after welding or postweld heat treat immediately |
| Hot cracking | Use low heat input; deposit thin layers; change base metal |
| Low ductility | Use preheat; anneal the base metal |
| High residual stresses | Redesign the weldment; change welding sequence; apply intermediate stress-relief heat treatment |
| High hardenability | Preheat; increase heat input; heat treat without cooling to room temperature |
| Brittle phases in the microstructure | Solution heat treat prior to welding |

Excessive penetration

In welds molten metal sometimes runs through the root of the weld groove producing an excessive reinforcement at the back side of the weld. In general this is not continuous but has an irregular shape with characteristic hanging drops of excess metal FIG. 1.46.

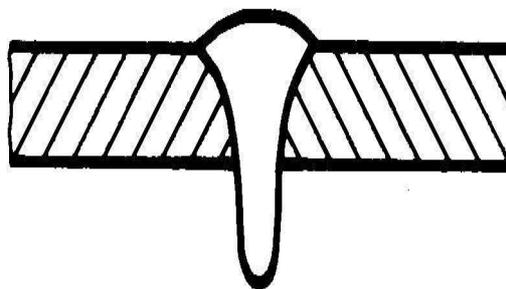


FIG. 1.46. Excessive penetration.

Overlap

Overlap is an imperfection at the toe or root of a weld caused by an overflow of weld metal onto the surface of the parent metal, without fusing with the latter FIG. 1.47. It is caused when the welding rod has been used at an incorrect angle, the electrode has travelled too slowly, or the current was too low.

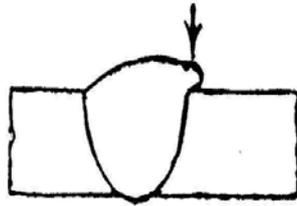


FIG. 1.47. Overlap.

Lamellar tearing

This is a phenomenon that occurs in T-joints where the web plate is welded on both sides with usually full penetration welds. The stresses developed by this configuration result in a separation that takes place in the base metal between the roots of the two welds extending in a plane parallel to the surface of the base metal. Such a discontinuity is often associated with laminations or other planes of weakness in the metal. It is characterized by a step-like tear and caused by the shrinkage of the weld bead stressing the base metal through its thickness. This results initially in de-cohesion of non-metallic inclusions and then ductile tearing at about 45° between adjacent non-metallic inclusions to produce the step-like tears. Lamellar tearing can occur outside the heat affected zone 5–10 mm below the fusion face FIG. 1.48.

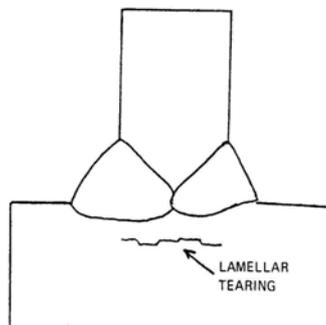


FIG. 1.48. Lamellar tearing.

Burn through

A burn through area is that portion of the weld bead where excessive penetration has caused the weld pool to be blown into the pipe or vessel. It is caused by the factors, such as high current, slow rod speed, incorrect rod manipulation, etc., that produce excessive heat in one area. It is often accompanied by excessive drop through of the metal on the inside of the pipe. FIG. 1.49.



FIG. 1.49. Burn through.

Root pass oxidation

Oxidation is the result of insufficient protection of the weld and heat affected zone from the atmosphere. Severe oxidation will occur on stainless steels, for example, reducing corrosion resistance, if the joint is not purged with an inert gas.

Forging processes

Forging is the working of metal into a useful shape by hammering or pressing and is the oldest of the metal forming processes. Most forging operations are carried out hot, although some metals are cold-forged. The hot working of metals in the forging process results in an improvement in the mechanical properties. This method of shaping is therefore used in the manufacture of parts requiring good mechanical properties. Improvement in the mechanical properties results from a general consolidation of the metal and closing of gas and contraction cavities by means of mechanical pressure, a refinement of the crystal structure and a destruction of the continuity of inter-granular concentrations of impurities and inclusions.

Forging is done on either a hammer or a press. A horizontal press (forging machine) is used in certain instances for forging small parts; otherwise forging machines are vertical, the lower die of which is fixed while the upper die is moveable, being carried on a vertical ram. In the case of hammers the die is raised mechanically and the blow is struck by the die falling freely FIG. 1.50.

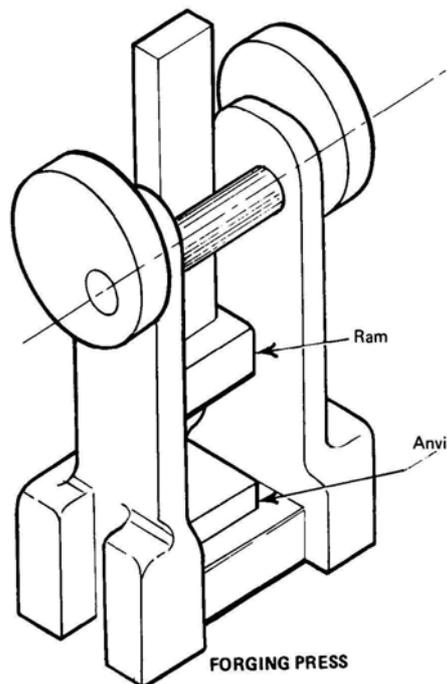


FIG. 1.50. Vertical forging press.

Forging may be considered under two categories. First where the working surface of the dies is flat or of uniform curved contour and shaping is done by manipulation using tools of simple shape. This is called open-die forging. The second is where impression dies are used and the metal is shaped by being forced into the die impressions. This is called closed-die forging. In the first category are forgings of simple, round or rectangular cross-section and forgings of more complicated shapes which are so large that sinking of closed dies would be impractical

or too costly. Small forgings of complicated final shape may be rough forged on simple dies and then machined to final form if the number required is too small to justify the cost of an impression die. In this category also are hollow forged parts. For these, the centre metal of the rough piece of proper size is either machined out cold (trepanned), or is punched out hot using suitable dies on a press. The part is then forged on a mandrel passing through the centre hole and supported at both ends so that the mandrel acts as the bottom die. In closed die forging on a hammer or vertical press the lower die has an impression corresponding to one half of the part to be made while the upper die has an impression corresponding to the other half. For relatively simple shapes the dies may have only one impression but more commonly they incorporate a series of impressions in which the part is successively shaped to the final form. Closed die forging is commonly known as 'drop forging'. Around the impressions the dies are shaped to provide space for the excess stock, as it is not practical to have exactly the amount of metal required to fill the impressions. The excess metal that is forced into this space is referred to as flashing or flash. After forging this is trimmed off in suitable dies. The closed die forging business FIG. 1.51 is so competitive that the losses in trim scrap provide one of the most important areas for economy.

The hot forging process whereby bolts, for example, are headed is referred to as hot upset forging or hot heading. In this process, a bar of uniform cross section is gripped between grooved dies and pressure is applied on the end in the direction of the axis of the bar by means of a heading tool. The metal flows under the applied pressure and fills the cavity between the dies.

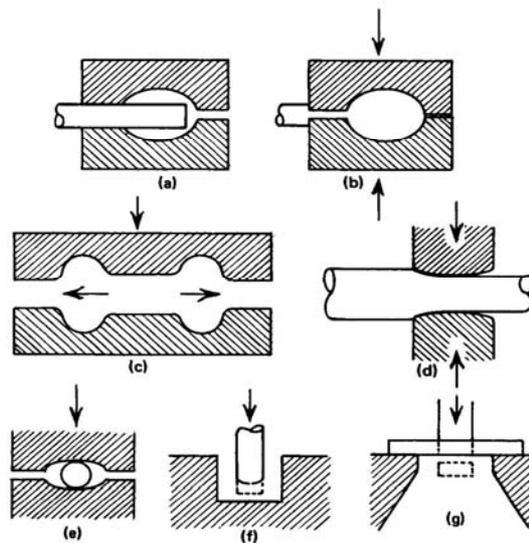


FIG. 1.51. Forging operations; (a, b) edging; (c) fullering; (d) drawing, (e) swaging (f) back extruding; (g) punching.

Rolling processes

The flattening of metal between rollers is used for the production of strip, sheet, plate, bar and sections. Since the metal is formed by a squeezing action, rolling can be considered as a continuous forging process with the rolls acting as hammers and the metal being drawn down.

Rolling may be performed above the temperature of re-crystallization (hot rolling) or below the temperature of re-crystallization (cold rolling). Hot rolling is always used for the initial rolling of the cast ingot. Not only is it easier to break down the ingot to size quickly when it is hot and plastic, but the hot-rolling process closes any casting discontinuities and forge welds

their surfaces together. This prevents any faults, which could lead to lamination, being carried forward into subsequent rolling operations. In hot rolling the coarse grains are first elongated and distorted and then formed into equi-axed crystals due to re-crystallization. The crystals elongated and distorted by cold rolling do not re-crystallize and the metal therefore remains work-hardened.

Rolling mills are described according to the arrangement of the rolls. The simplest is the two-high reversing mill FIG. 1.52 (b). In this the metal is passed through from one side, the rolls are then lowered and their direction of rotation is reversed, and the metal is passed back through them. This cycle is repeated until the metal is of the required thickness. In the three-high mill FIG. 1.52 (c) the rolls rotate continuously in one direction. The roller beds rise and fall to pass the metal between the lower two rolls first and then back again between the upper two rolls. The cycle is repeated until the metal is of the required thickness. In the four-high mill FIG. 1.52 (d) and the cluster mill FIG. 1.52 (e) the additional rolls 'back-up' the working rolls and allow them to apply greater pressure on the metal being rolled without deflection. Four-high and cluster mills operate in the same manner as the two-high reversing mill, and are widely used for cold rolling bright finished strip. Some typical rolling-mill processes are slabbing, cogging and re-rolling. Slabbing is the process of breaking down the ingot into slabs ready for re-rolling into strip, sheet and plate. The process is carried out at 1300°C and casting discontinuities in the ingot are welded by the process thus making the slab homogeneous. Cogging is similar to slabbing except that the ingot is rolled into 'blooms' ready for re-rolling into bars and sections. Two-high and four-high reversing mills are usually used for rolling both slabs and blooms. The re-rolling of slabs into strip is usually performed in a continuous strip mill. The slab is reheated to 1300°C and passed through a water spray and scale-breaking rolls to remove the scale left on the surface of the slab from previous processing. It is then roughed down, and finally passed to the finishing train of rolls. The strip is finally coiled ready for further processing. The re-rolling of sections and bars is usually performed in two-high reversing mills fitted with grooved rolls. Some modern plants handling large quantities of standard section beams and joists are often laid out to provide a continuous train FIG. 1.53.

Whilst materials that are forged into wire and tube require the property of malleability, materials that are drawn into wire and tube require the property of ductility, combined with a relatively high tensile strength and a low work-hardening capacity as the process is performed cold. The reduction in size of the drawn section is provided by the material being pulled through a die. Rods and bars are drawn using draw-benches FIG. 1.54.

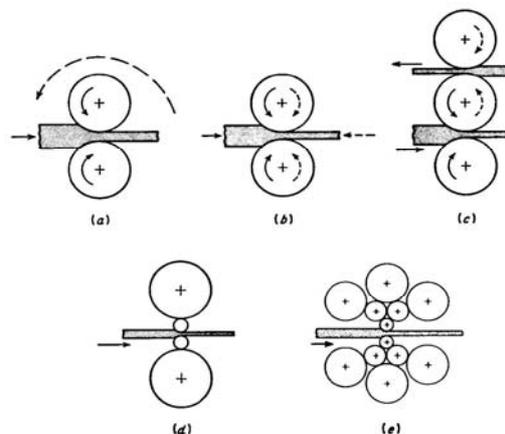


FIG. 1.52. Typical arrangements of rolls for rolling mills; (a) Two-high pullover, two-high reversing, (c) three-high, (d) four-high, (e) cluster.

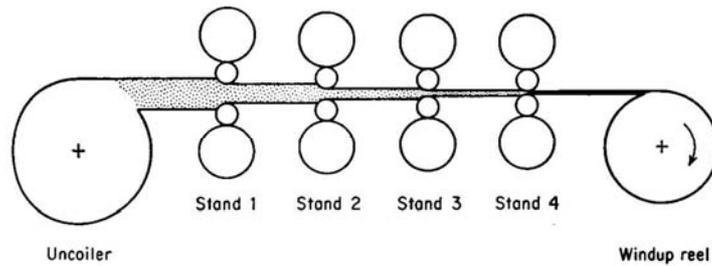


FIG. 1.53. Schematic drawing of strip rolling on a four-stand continuous mill.

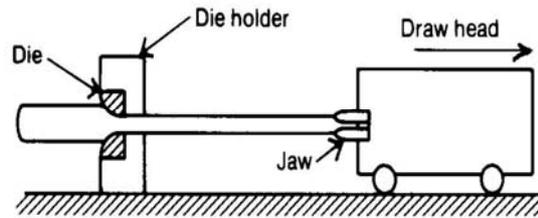


FIG. 1.54. Schematic drawing of a drawbench.

Fine wire, especially the copper wire used for electrical conductors, is drawn on multiple die machines. A capstan block pulls the wire through each die and passes it onto the next stage in the machine. As the wire becomes finer its length increases and the speed of the last capstan has to be very much higher than the first FIG. 1.55.

Tube drawing is similar to rod drawing using a draw bench. However, the billet is pierced to start the hole and the tube is drawn over a mandrel. Where longer lengths of tube are required, the stock and the drawn tube have to be coiled. This prohibits the use of a fixed mandrel, and a floating mandrel or plug is used.

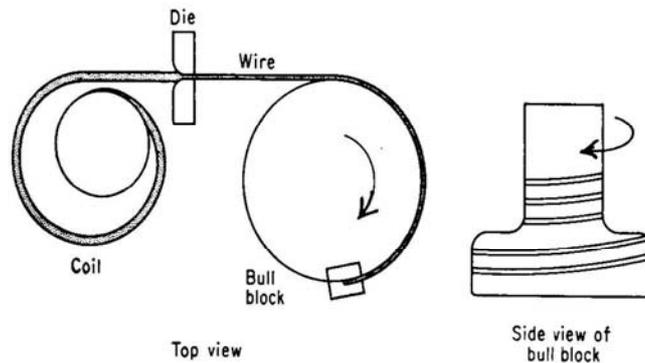


FIG. 1.55. Schematic wiredrawing equipment.

Extrusion processes

Another process which is similar to rolling is extrusion. In principle, extrusion is similar to squeezing toothpaste from a toothpaste tube. The raw material is a heated cast billet of the required metal. Usually this is either a copper alloy, an aluminium alloy or lead. The pressure necessary to force the metal through the die is provided by the hydraulic ram. Since the billet is reduced to the size of the finished section in one pass through the die, extrusion is a highly productive process. However, the plant is extremely costly and so is its operation and

maintenance. Like most hot processes the finish and dimensional accuracy of the section is lower than that associated with cold drawing. Therefore, where greater accuracy is required, the extruded section is given a light draw to strengthen the section and finish, and improve its dimensional accuracy FIG. 1.56 (a, b).

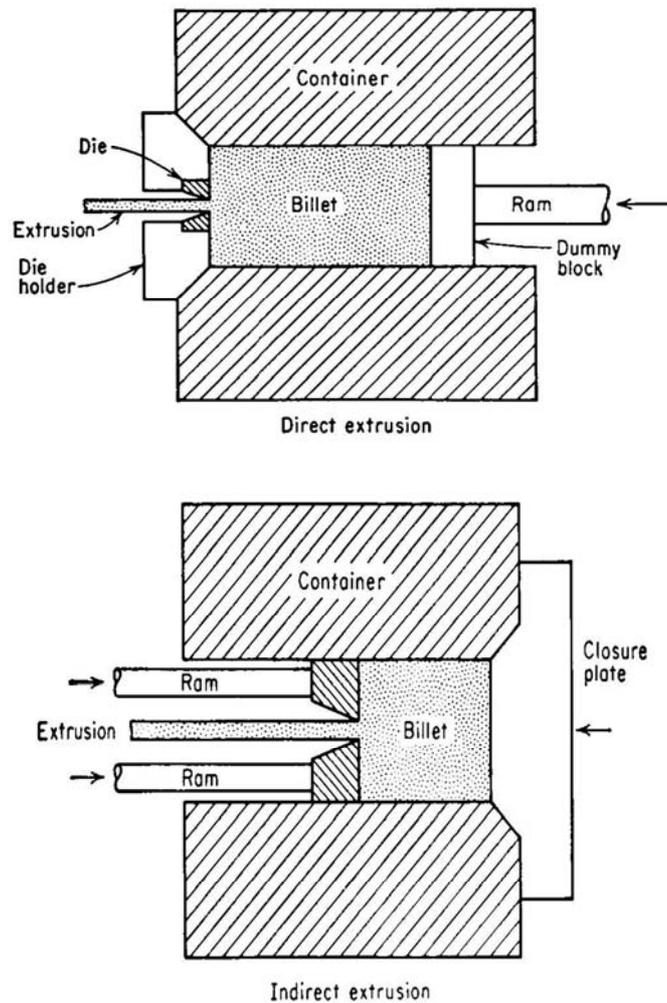


FIG. 1.56. Types of extrusion.

The Mannesmann mills, plug rolling mills, three-roll piercing mills, and reeling mills are also used for producing seamless pipe and tubing FIG. 1.57. The Mannesmann mill FIG. 1.57 (a) is used extensively for the rotary piercing of steel and copper billets. The process employs two barrel-shaped driven rolls which are set at an angle to each other. An axial thrust is developed as well as rotation to the billet. Because of the low arc of contact with the billet, tensile stresses develop along the axis of the billet. This assists in opening up the center of the billet as it flows around the piercing point to create the tube cavity. Piercing is the most severe hot-working operation customarily applied to metals. The Mannesmann mill does not provide sufficiently large wall reduction and elongation to produce finished hot-worked tubes. Various types of plug rolling mills which drive the tube over a long mandrel containing a plug FIG. 1.57 (b) have been widely adopted. This has led to the development of three-roll piercing machines FIG. 1.57 (c) which produce more concentric tubes with smoother inside and outside surfaces than the older Mannesmann design. A reeling mill FIG. 1.57 (d) which burnishes the outside and inside surfaces and removes the slight oval shape is usually one of the last steps in the production of pipe or tubing.

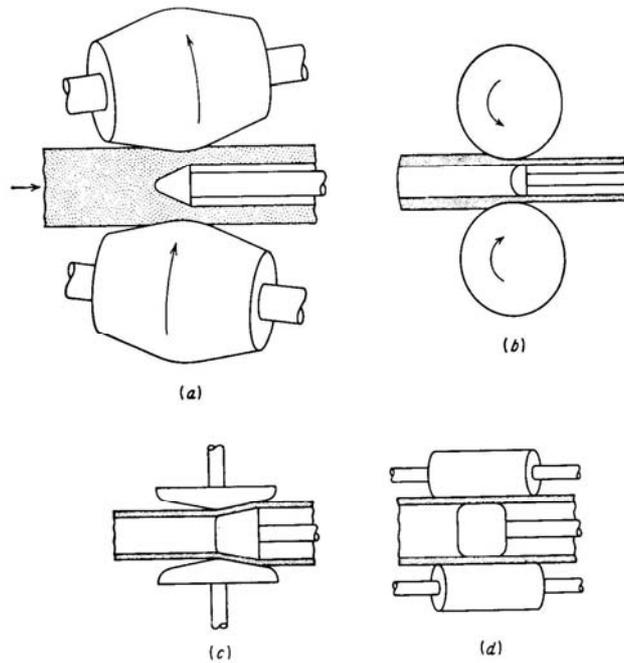


FIG. 1.57. (a) Mannesmann mill, (b) plug rolling mill, (c) three-roll piercing mill, (d) reeling mill.

Spinning processes

A method of making tank heads, television cones, and other deep parts of circular symmetry is called spinning FIG. 1.58 (a). The metal blank is clamped against a form block which is rotated at high speed. The blank is progressively formed against the block, either with a manual tool or by means of small diameter work rolls. In the spinning process the blank thickness does not change but its diameter is decreased. The shear spinning process FIG. 1.58 (b) is a variant of conventional spinning. In this process the part diameter is the same as the blank diameter but the thickness of the spun part is reduced according to equation, $t = t_0 \sin \alpha$. This process is also known as power spinning, flow-turning, and hydro-spinning. It is used for large axi-symmetrical conical or curvilinear shapes such as rocket-motor casings and missile nose cones.

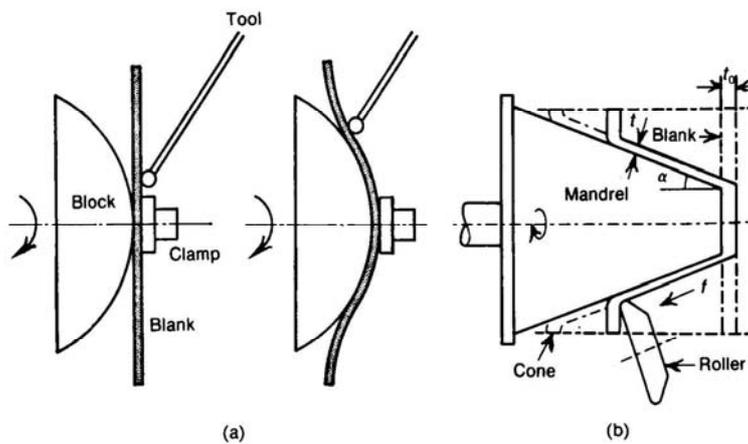


FIG. 1.58. Schematic representation of spinning processes; (a) manual spinning, (b) shear spinning.

Shearing and blanking

Shearing is the separation of metal by two blades moving as shown in FIG. 1.59. In shearing, a narrow strip of metal is severely plastically deformed to the point where it fractures at the surfaces in contact with the blades. The fracture then propagates inward to provide complete separation. The depth to which the punch must penetrate to produce complete shearing is directly related to the ductility of the metal. The penetration is only a small fraction of the sheet thickness for brittle materials, while for very ductile materials it may be slightly greater than the thickness.

The clearance between the blades is an important variable in shearing operations. With the proper clearance the cracks that initiate at the edges of the blades will propagate through the metal and meet near the centre of the thickness to provide a clean fracture surface FIG. 1.59 (a), (b). Note that even with proper clearance there is still distortion at a sheared edge. Insufficient clearance will produce a ragged fracture and also will require more energy to shear the metal than when there is proper clearance. With excessive clearance there is greater distortion of the edge, and more energy is required because more metal must plastically deform before it fractures. Furthermore, with too large a clearance burrs or sharp projections are likely to form on the sheared edge. A dull cutting edge also increases the tendency for the formation of burrs. The height of the burr increases with increasing clearance and increasing ductility of the metal. Because the quality of the sheared edge influences the formability of the part the control of clearance is important. Clearances generally range between 2 and 10 per cent of the thickness of the sheet; the thicker the sheet the larger the clearance.

A whole group of press operations are based on the process of shearing. The shearing of closed contours, when the metal inside the contour is the desired part, is called blanking. If the material inside the contour is discarded, then the operation is known as punching, or piercing. Punching indentations into the edge of the sheet is called notching. Parting is the simultaneous cutting along at least two lines which balance each other from the standpoint of side thrust on the parting tool. Slitting is a shearing cut which does not remove any metal from the sheet. Trimming is a secondary operation in which previously formed parts are finished to size, usually by shearing excess metal around the periphery. The removal of flash in a press is a trimming operation. When the sheared edges of part are trimmed or squared up by removing a thin shaving of metal, the operation is called shaving.

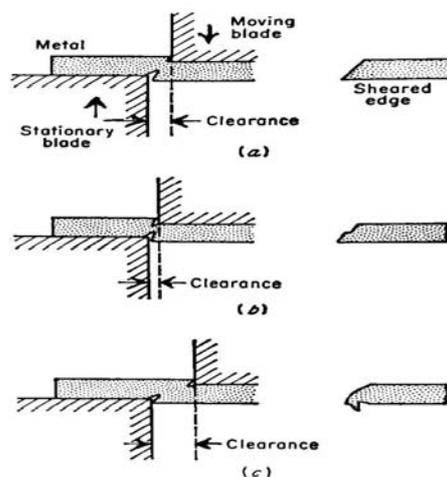


FIG. 1.59. Shearing of metal; (a) proper clearance, (b) insufficient clearance, (c) excessive clearance.

Bending processes

Bending is the process by which a straight length is transformed into a curved length. It is a very common forming process for changing sheet and plate into channel, drums, tanks, etc. In addition, bending is part of the deformation in many other forming operations. The definition of the terms used in bending processes are illustrated in FIG. 1.60. The bend radius R is defined as the radius of curvature on the concave, or inside, surface of the bend. For elastic bending below the elastic limit the strain passes through zero halfway through the thickness of the sheet at the neutral axis. In plastic bending beyond the elastic limit the neutral axis moves closer to the inside surface of the bend as the bending proceeds.

Deep drawing processes

Deep drawing is the metalworking process used for shaping of flat sheets into cup-shaped articles such as bathtubs, shell cases, and automobile panels. This is done by placing a blank of appropriate size over a shaped die and pressing the metal into the die with a punch FIG. 1.61. Generally a clamping or hold-down pressure is required to press the blank against the die to prevent wrinkling. This is best done by means of a blank holder or hold-down ring in a double action press.

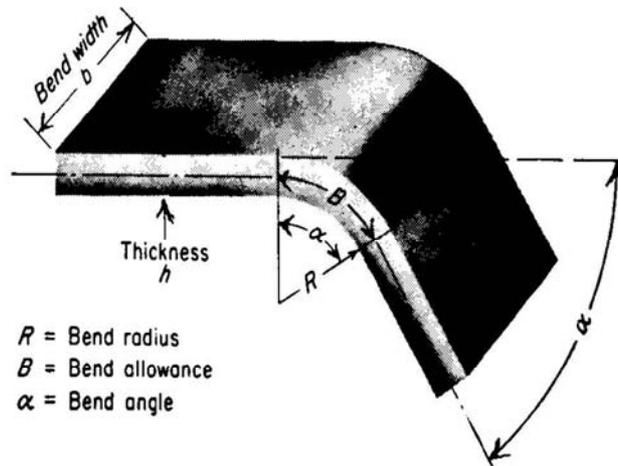


FIG. 1.60. Definition of terms used in bending.

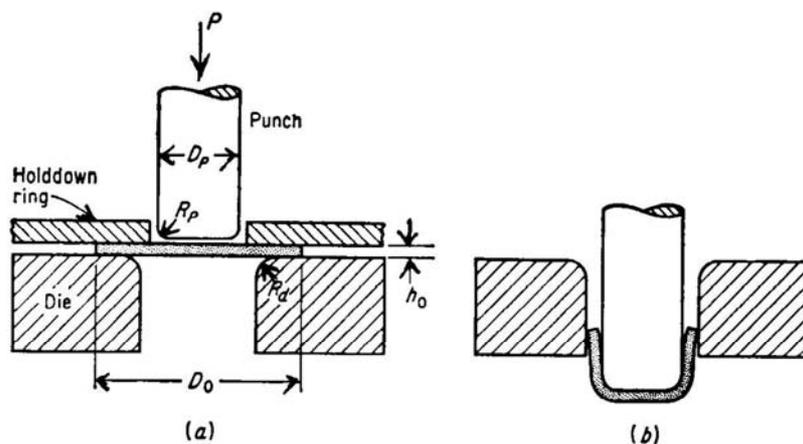


FIG. 1.61. Deep-drawing of a cylindrical cup; (a) before bending, (b) after drawing.

Forging and rolling defects

Discontinuities in forgings may originate in the slab or billet and be modified by the rolling and forging of the material, or may result from the forging process itself. Some of the defects that can occur in forgings are similar to those in castings since most forgings originate from some form of cast ingot. Given below are some of the more specific defects.

Laminations

Large porosity, pipe and non-metallic inclusions in slabs or billets are flattened and spread out during the rolling and forging processes. These flattened discontinuities are known as laminations FIG. 1.62.

Seams

Surface irregularities, such as cracks, on the slab or billet are stretched out and lengthened during rolling and are then called seams. Seams may also be caused by folding of the metal due to improper rolling. Seams are surface discontinuities and on finished bars will appear as either continuous or broken straight lines. On round bar stock they will appear as straight or slightly spiral lines, either continuous or broken.

Forging laps

Forging laps are the discontinuities caused by the folding of metal in a thin plate on the surface of the forging. They are irregular in contour FIG. 1.62.

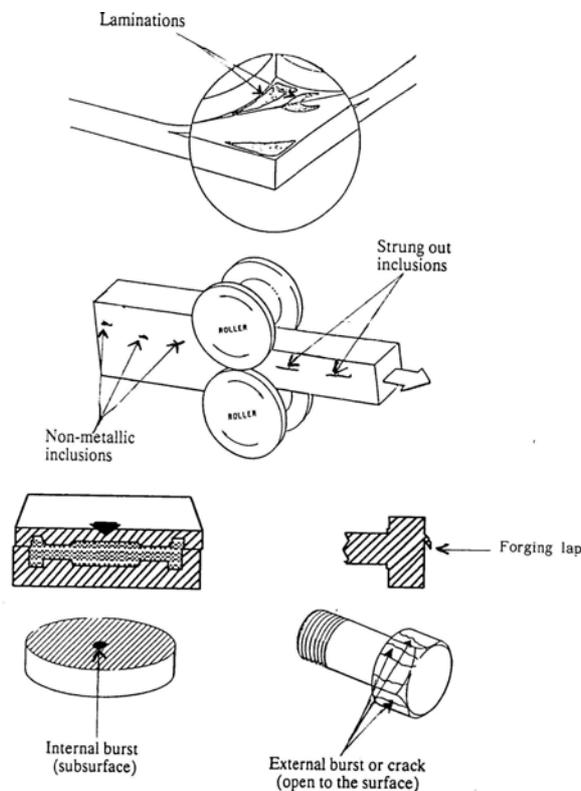


FIG. 1.62. Forging and rolling defects.

Centre bursts

Ruptures that occur in the central region of a forging are called centre bursts. They can arise because of an incorrect forging procedure (e.g. too low a temperature or too drastic a reduction) or from the presence of segregation or brittle phase in the metal being forged FIG. 1.62.

Clinks (thermal cracks)

Clinks are cracks due to stresses arising from excessively high temperature gradients within the material. Cracks formed during too rapid cooling originate at the surface and extend into the body of the forging; those formed during too rapid heating occur internally and can be opened up to become diamond-shaped cavities, during subsequent forging.

Hairline cracks (flakes)

Flakes are very fine internal cracks of circular shape that develop and extend with time and are associated with the presence of hydrogen in steel. There is greater susceptibility in larger forgings than in smaller and in certain grades of alloy steel than in carbon steel; they can be avoided by correct treatment.

Hot tears

Surface defects due to metal being ruptured and pulled apart during forging. They may be associated with the presence of local segregation, seams, or brittle phases.

Stringers

Non-metallic inclusions in slabs or billets, that are thinned and lengthened in the direction of rolling by the rolling process are called stringers FIG. 1.62.

Overheating

Normally identified by the facets seen on the fractured surfaces of a test-piece, but in extreme cases can manifest itself as a severely broken-up surface.

Pipe

If there has been insufficient discard from the original ingot, remnant primary pipe will normally show up axially. Secondary pipe that has never been exposed to the atmosphere will be welded-up if there has been sufficient forging.

Finishing processes and related defects

Machining process

Machining is a shape-producing process in which a power-driven device causes material to be removed in chip form. Most machining is done with equipment that supports both the work piece and the cutting tool. Although there are many kinds of machines used in manufacturing industry, the term machine tools has been assigned to that group of equipment designed to hold a cutting tool and a work piece and establish a suitable set of motions between them to remove materials from the work in chip form. The common combination of motions is shown in FIG. 1.63.

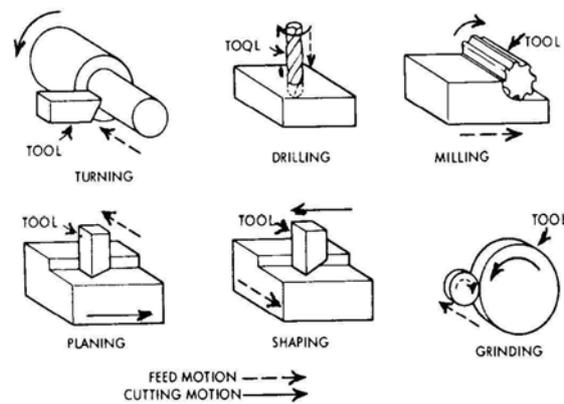


FIG. 1.63. Feed and cutting motions.

Turning and boring

These machines normally rotate the work piece to produce the cutting motion and feed a single point tool parallel to the work axis or at some angle to it. External cylindrical machining is called turning, internal cylindrical machining is called boring, and making a flat surface by feeding the tool perpendicular to the axis of revolution is termed as facing.

Drilling

A special fluted tool with two or more cutting lips on its exposed end is called a drill and is rotated and advanced axially into the work piece by use of a drill press. The principal work is the making of, or enlarging of, cylindrical holes.

Milling

There are a great variety of milling machines which like the drill press employ special multi-edge cutters. Except for some special production type milling machines, this equipment permits multi-direction feeding and the cutters perform their principal cutting on their periphery edges.

Straight line machines

One group of machine tools provide straight line cutting motion for its cutting action. This includes the shaper (straight line motion of the cutter), the planer (straight line motion of the work piece), and the broach (straight line motion of a special multi-tooth cutter). Because of the high cost of the special cutter, broaching is used only for production quantity machining but the shaper and planer are more commonly used.

Machine tears are caused by dull machine tools. They will show up as short irregular lines at right angle to the direction of machining. They are the result of tool removing the metal more through a tearing action than through a cutting action.

Grinding processes

Grinding processes employ an abrasive wheel containing many grains of hard material bonded in a matrix. The action of a grinding wheel may be considered as a multiple-edge cutting tool except that the cutting edges are irregularly shaped and randomly spaced around the face of the wheel. Each grain removes a short chip of gradually increasing thickness, but

because of the irregular shape of the grain there is considerable ploughing action between each grain and the work-piece.

The depth of cut in grinding usually is very small (a few μm), and this results in very small chips that adhere readily to the wheel or the work-piece. The net effect is that the specific cutting energy for grinding is about 10 times greater than for turning or milling. In grinding, greater than 70 per cent of the energy goes into the finished surface. This results in considerable temperature rise and generation of residual stresses.

Grinding cracks are a processing type discontinuity caused by stresses which are built up from excess heat created between grinding wheel and metal. Grinding cracks are fine sharp type cracks and will usually occur at right angles to the rotation of the grinding wheel.

Heat treatment of steel

A number of heat treatment cycles have been developed to alter the structure and hence the properties of iron and steel. Some of usual treatments and the specific properties they develop in iron and steel are discussed in the following FIG. 1.64. The first is annealing. Steel is annealed to soften it for easy machining and to release internal stresses that might have been caused by working of the metal or by unequal contraction in casting. For annealing the steel is heated slowly to a temperature between 800°C and 1000°C . It is then held at this temperature for sufficient time so as to enable the internal changes to take place. It is then cooled slowly. For slow cooling, which is very essential, the heated steel is taken out of the furnace and embedded in sand, ash, lime or some other non-conducting material.

Normalizing is another heat treatment process. This treatment is done to refine the structure and to remove strains that might have been caused by cold working. When steel is cold worked its crystalline structure may get upset and the metal may become brittle and unreliable. Also when the metal is heated to very high temperatures as for forging then it may lose its toughness. To remedy these effects steel is slowly heated to about 1000°C and allowed to cool in air.

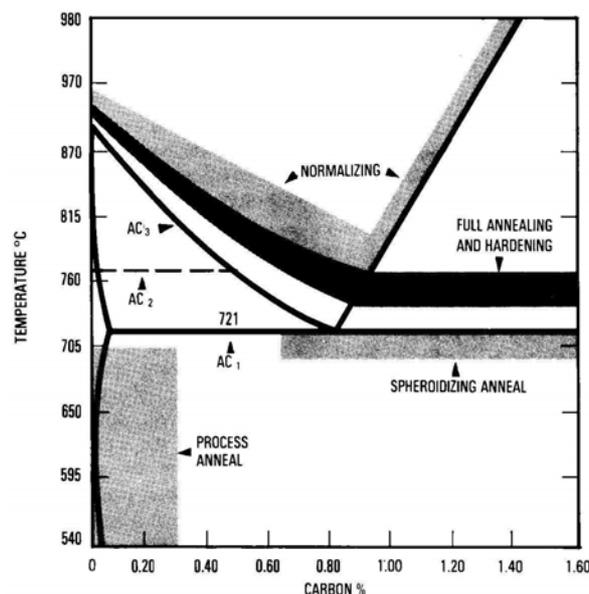


FIG. 1.64. Temperature ranges for various heat treating processes.

Hardening or quenching of steel consists of heating the steel to above the transformation temperature and then suddenly cooling it by dipping it in a bath of cold water or oil. This way of cooling of hot steel is known as quenching or hardening. The steel after quenching is known as quenched steel. This type of steel is hard and brittle because of martensitic crystal structure. The hardness of quenched steel depends upon the medium used for quenching and the rate of cooling.

When steel is heated to or above its critical temperature (transformation temperature range the value of which is dependent upon the alloy percentages) and held at this temperature for some period of time carbon unites in solid solution with iron in the gamma or face centred cubic lattice form. In this phase, as much as 2% carbon can dissolve at the eutectic temperature of 1148°C at which the widest range of gamma composition exists. This is called the process of austenitization.

Tempering involves heating of hardened steel to a suitable temperature between 230°C and 600°C. This causes a particle transformation of the martensitic back to pearlite again thereby taking away some of the hardness of the steel to make it tougher.

Minimum hardness and maximum ductility of steel can be produced by a process called spheroidizing, which causes the iron carbide to form in small spheres or nodules in a ferrite matrix. In order to start with small grains that spheroids more readily, the process is usually performed on normalized steel. Several variations of processing are used, but all require the holding of the steel near the A1 temperature (usually slightly below) for a number of hours to allow the iron carbide to form in its more stable and lower energy state of small, rounded globules.

Heat treating cracks are often caused by stresses built up during heating and cooling. Unequal cooling between light and heavy sections may cause heat treatment cracks. Heat treatment cracks have no specific direction and usually start at sharp corners which act as stress concentration points (stress raisers).

Surface finishing

Products that have been completed to their proper shape and size frequently require some type of surface finishing to enable them to satisfactorily fulfil their function. In some cases, it is necessary to improve the physical properties of the surface material for resistance to penetration or abrasion. In many manufacturing processes, the product surface is left with dirt, metal chips, grease or other harmful material on it. Assemblies that are made of different materials or from the same materials processed in different manners, may require some special surface treatment to provide uniformity of appearance.

Surface finishing may sometimes become an intermediate step in processing. For instance, cleaning and polishing are usually essential before any kind of plating process. Some of the cleaning procedures are also used for improving surface smoothness on mating parts and for removing burrs and sharp corners, which might be harmful in later use. Another important need for surface finishing is for corrosion protection in variety of environments. The type of protection provided will depend largely upon the anticipated exposure, with due consideration to the material being protected and the economic factors involved.

Satisfying the above objectives necessitates the use of many surface finishing methods that involve chemical change of the surface, mechanical work affecting surface properties,

cleaning by a variety of methods and the application of protective coatings, organic and metallic.

Case hardening of steels

Case hardening results in a hard, shell like surface. Some product applications require surface properties of hardness and strength to resist penetration under high pressure and to provide maximum wear properties. Where through hardness and the maximum strength associated with it are not necessary, it may be more economical to gain the needed surface properties by a case hardening process. Case hardening involves a change of surface properties to produce a hard, wear resistant shell with a tough fracture resistant core. This is usually accomplished by a change of surface material chemistry. With some materials, a similar condition can be produced by a phase change of the material already present.

Case depth measurement is sometimes checked by destructive methods, cutting the object, etching the cut surface and checking the cut depth with a measuring microscope. A faster and more useable method when knowledge is needed directly for service parts, is to use eddy current tests.

Carburizing

Case hardening of steel may be accomplished by a number of methods. The choice between them is dependent on the material to be treated, the application and the desired properties. One of the more common methods is carburizing which consists of an increase or addition of carbon to the surface of the part. Carburizing is usually performed on a low alloy or plain low carbon steel. If an alloy steel is used, it usually contains small quantities of nickel or some other elements that act as grain growth retarder during the heating cycle. Low carbon steels are commonly used to minimize the effect of subsequent heat treatment on the core material. It is possible to carburize any steel containing less than the 0.7% to 1.2% carbon that is produced in the surface material. The complete cycle for case hardening by carburizing is illustrated in FIG. 1.65.

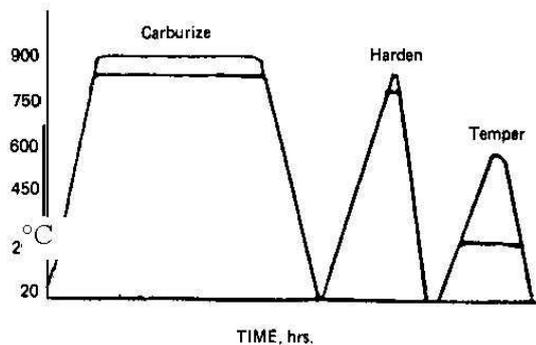


FIG. 1.65. Typical heat treatment cycle for carburizing.

Flame hardening

Another case hardening process that does not require a change of composition in the surface material is flame hardening. This method can be used only on steels that contain sufficient carbon to be hardenable by standard heat treating procedures. The case is produced by selectively heating part or all of the surface with special high capacity gas burners or oxy-acetylene torches at a rate sufficiently high that only a small depth from the surface goes

above the critical temperature. Following immediately behind the torch is a water quenching head that floods the surface to reduce the temperature fast enough to produce a martensitic structure. As in the case of carburizing, the surface may be then reheated to temper it for toughness improvement. The depth of hardness is controlled by the temperature to which the metal is raised, by the rate of heating, and by the time that passes before quenching.

Cleaning

Few, if any, shaping and sizing processes produce products that are suitable without some type of cleaning unless special precautions are taken. Hot working, heat treating, and welding cause oxidation and scale formation in the presence of oxygen. For the same reason, castings are usually coated with oxide scale. If they are made in sand moulds they may have sand grains fused or adhering to the surface. Residue from coolants, lubricants and other processing materials is common on many manufactured parts. In addition to greasy films from processing, protective coatings of greases, oils, or waxes are frequently used intentionally to prevent rust or corrosion on parts that are stored for some period of time before being put to use. Even if parts are clean at the completion of manufacturing, they seldom remain that way for long. After only short storage periods, corrosion and dust from atmospheric exposure necessitate cleaning particularly if further processing is required.

When using NDT methods such as penetrant testing and ultrasonic testing good pre-cleaning may be necessary to get accurate results and post-cleaning is often needed to leave the surface in a suitable condition. In some applications such as on stainless steels and nickel based alloys, ultrasonic couplants and penetrant materials must be made of only certain materials so that they do not cause stress-corrosion failure.

Cleaning sometimes has finish improvement associated with it. Some shape producing methods produce unsatisfactory surface characteristics such as sharp corners, burrs and tool marks which may affect the function, handling ease, and appearance of the product. Some cleaning processes at least partially blend together surface irregularities to produce uniform light reflection. Improvement of surface qualities may be accomplished by removal of high spots by cutting or by plastic flow as cleaning is performed.

Many different cleaning methods are available. The most commonly used ones are briefly mentioned here: the most widely used cleaning methods use a cleaning medium in liquid form, which are applied to the object to be cleaned in different ways such as spraying, brushing or dipping the object in a bath of the cleaning liquid. Cleaning may be carried out through the process of blasting wherein the cleaning medium which may be a liquid or a solid (e.g. sand, glass or steel beads, etc.) is accelerated to high velocity and impinged against the surface to be cleaned. A number of cleaning operations can be quickly and easily performed by use of wire brushes either manually or by rotating them at high speeds. The cleaned surface may be given a final polishing touch using a flexible abrasive wheel. Buffing is a kind of polishing process.

Coatings

Many products, in particular those exposed to view and those subject to change by the environment with which they are in contact, need some type of coating for improved appearance or for protecting from chemical attack. All newly created surfaces are subject to corrosion, although the rate of occurrence varies greatly with the material, the environment, and the conditions. For all practical purposes, some materials are highly corrosion resistant because the products of corrosion resist further corrosion. For example, a newly machined

surface on an aluminium alloy will immediately be attacked by oxygen in the air. The initial aluminium oxide coating protects the remaining metal and practically stops corrosion unless an environmental change occurs. Corrosion rates are closely dependent on environment. Rates increase with rise of temperature and greater concentration of the attacking chemical. The need for corrosion protection for maintenance of appearance is obvious. Unless protected, an object made of bright steel will begin to show rust in a few hours of exposure to ordinary atmosphere. In addition to change of appearance, loss of actual material, change of dimensions, and decrease of strength, corrosion may be the cause of eventual loss of service or failure of a product.

Hardness and wear resistance can, however, be provided on a surface by plating with hard metals. Chromium plating of gauges subject to abrasion is frequently used to increase their wear life. Coatings of plastic materials and asphaltic mixture are sometimes placed on surfaces to provide sound deadening. The additional benefit of protection from corrosion is usually acquired at the same time.

Metallizing

Metal spraying, or metallizing, is a process in which metal wire or powder is fed into an oxy-acetylene heating flame and the same after melting, is carried by high velocity air to be impinged against the work surface. The small droplets adhere to the surface and bond together to build up a coating. The nature of the bond is dependent largely on the materials. The droplets are relatively cool when they make contact and in fact can be sprayed on wood, leather, and other flammable materials. Little, if any, liquid flow aids the bonding action. If, however, sufficient affinity exists between the metals, a type of weld involving atomic bonds may be established. The bond is largely mechanical in most cases and metal spraying is usually done on surfaces that have been intentionally roughened to aid the mechanical attachment. Zinc, aluminium, and cadmium, which are anodic to steel and therefore provide preferential corrosion protection, are usually sprayed in thin layers, averaging about 0.25 millimetre (0.010 inch) in thickness, as protective coatings. Because sprayed coatings tend to be porous, coatings of two or more times this thickness are used for cathodic materials such as tin, lead, and nickel. The cathodic materials protect only by isolating the base material from its environment.

Several metals, mainly zinc, tin, and lead, are applied to steel for corrosion protection by a hot dip process. Steel in sheet, rod, pipe, or fabricated form, properly cleansed and fluxed, is immersed in molten plating metal. As the work is withdrawn the molten metal that adheres solidifies to form a protective coat.

Coating of many metals can be deposited on other metals, and on non-metals by electroplating, when suitably prepared. This is based on the principle that when direct current power of high enough voltage is applied to two electrodes immersed in a water solution of metallic salt, current will flow through the circuit causing changes at the electrodes FIG. 1.66. At the negative electrode, or cathode (the work), excess electrons supplied from the power source neutralize positively charged metallic ions in the salt solution to cause dissolved metal to be deposited in the solid state. At the positive electrode, or anode (plating metal), metal goes into solution to replace that removed at the other electrode. The rate of deposition and the properties of the plated material are dependent on the metals being worked with, the current density, the solution temperature, and other factors.

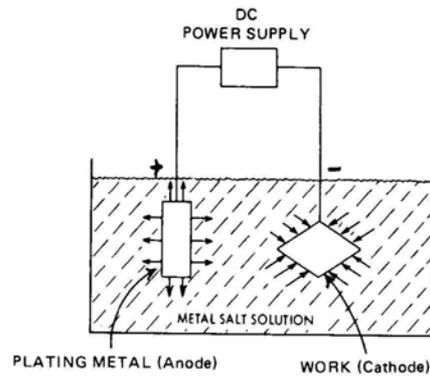


FIG. 1.66. Electroplating.

Chemical treatment

A relatively simple and often fully satisfactory method for protection from corrosion is by conversion of some of the surface material to a chemical composition that resists attack from the environment. These converted metal surfaces consist of relatively thin (seldom more than 0.025 millimetre, or 0.001 inch thick) inorganic films that are formed by chemical reaction with the base material. One important feature of the conversion process is that the coatings have little effect on the product dimensions. However, when severe conditions are to be encountered, the converted surface may give only partial protection, and coatings of entirely different types may be applied over them.

Aluminium, magnesium, and zinc can be treated electrically in a suitable electrolyte to produce a corrosion-resistant oxide coating. The metal being treated is connected to the anode in the circuit, which provides the name anodizing for the process.

Phosphate coatings, used mostly on steel, result from a chemical reaction of phosphoric acid with the metal to form a non-metallic coating that is essentially phosphate salts. The coating is produced by immersing small items or spraying large items with the phosphating solution. A number of proprietary blackening processes, used mainly on steel, produce attractive black oxide coatings. Most of the processes involve the immersing of steel in a caustic soda solution heated to about 150°C (300°F) and made strongly oxidizing by the addition of nitrites or nitrates. Corrosion resistance is rather poor unless improved by application of oil, lacquer, or wax. As in the case of most of the other chemical conversion procedures this procedure also finds use as a base for paint finishes.

1.4. Materials in service

1.4.1 Behaviour of materials in service

Materials have to operate and perform in widely varied environments and situations. The requirements of safety and reliability demand that the materials and components should perform well in their environments and situations without premature failure. There are a number of factors and processes which can cause the failure of materials. As premature failure of critical components can be disastrous in many situations apart from being a cause for lost production and bad reputation, it is essential to understand and control these causes of failure.

1.4.2 Conditions leading to defects and failures

Due to advances in technology and the understanding of materials and their design, and due to sophisticated inspection and testing methods, such as the non-destructive testing methods,

metal failures occur only in an extremely low percentage of the millions of tons of metals fabricated every year. Those that do occur fall mainly into three categories. Operational failures can be caused by overload, wear, corrosion and stress-corrosion, brittle fracture and metal fatigue. In the second category fall the failures due to improper design. In this it is necessary to consider whether sharp corners or high-stress areas exist in the design, has sufficient safety stress factor been considered and whether the material selected is suitable for particular application. The third type of failure is caused by thermal treatments such as forging, hardening, tempering and welding, and by surface cracks caused by the heat of grinding. These aspects and especially those related to operational or in-service conditions will be described here in more detail.

Corrosion

With the exception of some noble metals, all metals are subject to the deterioration caused by ordinary corrosion. Iron, for example, tends to revert back to its natural state of iron oxide. Other metals revert to sulphides and oxides or carbonates. Buildings, ships, machines and automobiles are all subject to attack by the environment. The corrosion that results often renders them useless and they have to be scrapped. Billions of dollars a year are lost as a result of corrosion. Corrosion can also cause dangerous conditions to prevail, such as on bridges, where the supporting structures have been eaten away, or in aircraft in which an insidious corrosion called inter-granular corrosion can weaken the structural members of the aircraft and cause a sudden failure.

Corrosion in metals is the result of their desire to unite with oxygen in the atmosphere or in other environments to return to a more stable compound, usually called ore. Iron ore, for example, is in some cases simply iron rust. Corrosion may be classified by the two different processes by which it can take place; direct oxidation corrosion, which usually happens at high temperature, and galvanic corrosion, which takes place at normal temperatures in the presence of moisture or an electrolyte. Direct oxidation corrosion is often seen in the scaling that takes place when a piece of metal is left in a furnace for a length of time. The black scale is actually a form of iron oxide, called magnetite (Fe_3O_4). Galvanic corrosion is essentially an electrochemical process that causes a deterioration of metals by a very slow but persistent action. In this process, part or all of the metal becomes transformed from the metallic state to the ionic state and often forms a chemical compound in the electrolyte. On the surface of some metals such as copper or aluminium, the corrosion product sometimes exists as a thin film that resists further corrosion. In other metals such as iron, the film of oxide that forms is so porous that it does not resist further corrosive action, and corrosion continues until the whole piece has been converted to the oxide.

Corrosion requires the presence of an electrolyte to allow metal ions to go into solution. The electrolyte may be fresh or salt water and acid or alkaline solutions of any concentration. Even a finger print on metal can form an electrolyte and produce corrosion. When corrosion of a metal occurs, positively charged atoms are released or detached from the solid surface and enter into solution as metallic ions while the corresponding negative charges in the form of electrons are left behind in the metal. The detached positive ions bear one or more positive charges. In the corrosion of iron, each iron atom releases two electrons and then becomes a ferrous iron carrying two positive charges. Two electrons must then pass through a conductor to the cathode area. The electrons reach the surface of the cathode material and neutralize positively charged hydrogen ions that have become attached to the cathode surface. Two of these ions will now become neutral atoms, and are released generally in the form of hydrogen gas. This release of the positively charged hydrogen ions leaves an accumulation and a concentration of OH negative ions that increases the alkalinity at the cathode. When this

process is taking place, it can be observed that hydrogen bubbles are forming at the cathode only. When cathodes and anodes are formed on a single piece of metal, their particular locations are determined by, for example, the lack of homogeneity in the metal, surface imperfections, stresses, inclusions in the metal, or any thing that can form a crevice such as a washer.

Corrosion can also take the form of erosion in which the protective film, usually an oxide film, is removed by a rapidly moving atmosphere or medium. Depolarization can also take place, for example, on the propellers of ships because of the movement through the water, which is the electrolyte. This causes an increased corrosion rate of the anodic steel ship's hull. Impellers of pumps are often corroded by this form of erosion corrosion in which metal ions are rapidly removed at the periphery of the impeller but are concentrated near the centre where the velocity is lower. Another form of corrosion is inter-granular corrosion. This takes place internally. Often the grain boundaries form anodes and the grains themselves form cathodes, causing a complete deterioration of the metal in which it simply crumbles when it fails. This often occurs in stainless steels in which chromium carbides precipitate at the grain boundaries. This lowers the chromium content adjacent to the grain boundaries, thus creating a galvanic cell. Differences in environment can cause a high concentration of oxygen ions. This is called cell concentration corrosion. Pitting corrosion is localized and results in small holes on the surface of a metal caused by a concentration cell at that point. When high stresses are applied to metals in a corrosive environment, cracking can also be accelerated in the form of stress-corrosion failure. It is a very localized phenomenon and results in a cracking type of failure. Cathodic protection is often used to protect steel ships hulls and buried steel pipelines. This is done by using zinc and magnesium sacrificial anodes that are bolted to the ship's hull or buried in the ground at intervals and electrically connected to the metal to be protected. In the case of the ship, the bronze propeller acts as a cathode, the steel hull as an anode and the seawater as an electrolyte. Severe corrosion can occur on the hull as a result of galvanic action. The sacrificial anodes are very near the anodic end of the galvanic series and have a large potential difference between both the steel hull of the ship and the bronze propeller. Both the hull and propeller become cathodic and consequently do not deteriorate. The zinc or magnesium anodes are replaced from time to time. Selection of materials is of foremost importance. Even though a material may be normally resistant to corrosion, it may fail in a particular environment or if coupled with a more cathodic metal. Coatings are extensively used to prevent corrosion. There are different types of such coatings, for example; anodic coatings, cathodic coatings, organic and inorganic coatings, inhibitive coatings, etc.

Fatigue

When metal parts are subjected to repeated loading and unloading over prolonged periods they may fail at stresses far below their yield strength with no sign of plastic deformation. This is called a fatigue failure. When designing machine parts that are subject to vibration or cyclic loads, fatigue strength may be more important than ultimate tensile or yield strength. Fatigue is a universal phenomenon observed in most solids. Cyclic loading leads to a continuous accumulation of damage which, as in the case of static fracture, eventually results in rupture. Fatigue limit, or endurance limit, is the maximum load that can be applied an infinite number of times without causing failure FIG. 1.67. But 10 million loading cycles are usually considered enough to establish fatigue limits. The number of cycles leading to fracture at a given stress is often referred to as the fatigue strength or endurance. This phenomenon of failure of a material when subjected to a number of varying stress cycles is known as fatigue since it was once thought that fracture occurred due to the metal weakening or becoming tired.

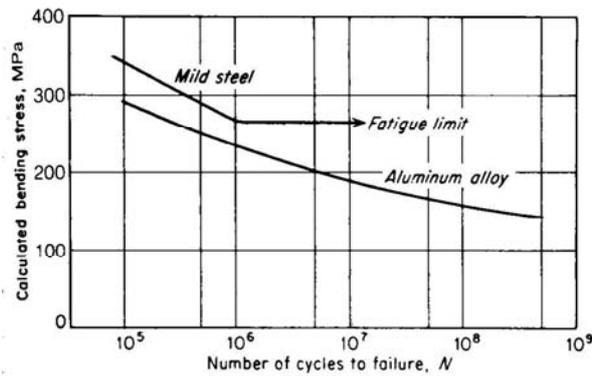


FIG. 1.67. Typical fatigue curves for ferrous and non-ferrous metals.

Failures caused by fatigue are found in many of the materials of industry. Some plastics and most metals are subject to fatigue in varying degrees as these are widely used in dynamically loaded structures and machines. It has been estimated that at least 75% of all machine and structure failures have been caused by some form of fatigue. Fatigue failure is caused by a crack that is initiated by a notch, bend, or scratch that continues to grow gradually as a result of stress reversals on the part. The crack growth continues until the cross-sectional area of the part is reduced sufficiently to weaken the part to the point of failure. In welding, even spatter on a sensitive surface such as a steel spring can initiate fatigue failure. Fatigue is greatly influenced by the kind of material, grain structure and the kind of loading. Some metals are more sensitive to sharp changes in section (notch sensitive) than others.

There are various types of fatigue failure. In the case of one-way bending load a small elliptically shaped fatigue crack usually starts at a surface flaw such as a scratch or tool mark. The crack tends to flatten out as it grows. It is caused by the stress at the base of the crack being lower because of the decrease in distance from the edge of the crack to the neutral axis. If a distinct stress raiser such as a notch is present, the stress at the base of the crack would be high, causing the crack to progress rapidly near the surface, and the crack tends to flatten out sooner. In a two-way bending load cracks start almost simultaneously at opposite surfaces when the surfaces are equally stressed. The cracks proceed toward the centre at similar rates and result in a fracture that is rather symmetrical.

In the early stages of fatigue testing, specimens will generally evolve an appreciable amount of heat. Later fissures develop at the surface eventually leading to failure. The surface of the specimen is a preferential seat of damage initiation. Corrosive effects may also assist in degradation of the structure at the surface. Corrosion is essentially a process of oxidation and under static conditions a protective oxide film is formed which tends to retard further corrosion attack. In the presence of cyclic stress the situation is quite different, since the partly protective oxide film is ruptured in every cycle allowing further attack. It is a rather simplified explanation that the microstructure at the surface of the metal is attacked by the corrosive environment causing, an easier and more rapid initiation of cracks. One of the important aspects of corrosion fatigue is that a metal having a fatigue limit in air no longer possesses one in the corrosive environment and therefore fracture can occur at relatively very low stress levels.

In commercial alloys the technical fatigue limit generally lies between 0.3 and 0.5 of the ultimate tensile stress. The fatigue strength of metals can often be enhanced by treatments which render the surface more resistant to deformation. Fracture then tends to start at the interface between the hard surface layer and the softer core. Stress raisers, such as sharp

notches, corners, key ways, rivet holes and scratches can lead to an appreciable lowering of the fatigue strength of metal components. Good surface finish and corrosion protection are desirable to enhance fatigue resistance. Fatigue is basically a low temperature problem and at temperatures relatively high with respect to the melting point, fracture and hence specimen life are governed by creep.

Fractured surfaces of fatigued metals generally show a smooth and lustrous region due to the polishing effects arising from attrition at fissures. The remaining parts of the fracture surface, over which failure occurred through weakening of the specimen by the reduction of its load bearing cross-section by surface cracks and fissures, may look duller and coarser, as it is essentially caused by static fracture.

Fatigue cracks are service type discontinuities that are usually open to the surface where they start from stress concentration points (FIG. 1.68).

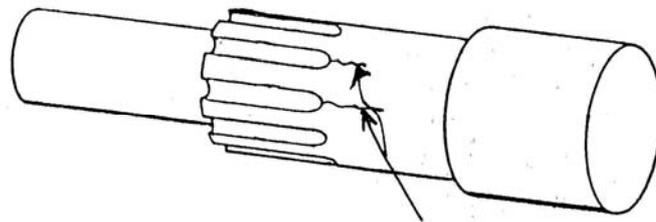


FIG. 1.68. Fatigue cracks.

Creep

The progressive deformation of a material at constant stress is called creep. To determine the engineering creep curve of a metal, a constant load is applied to a tensile specimen maintained at a constant temperature, and the strain (extension) of the specimen is determined as a function of time. Although the measurement of creep resistance is quite simple in principle, in practice it requires considerable laboratory equipment. The elapsed time of such tests may extend to several months, while some tests have been run for more than 10 years.

Curve A in FIG. 1.69 illustrates the idealized shape of a creep curve. The slope of this curve ($d\varepsilon/dt$) is referred to as the creep rate. Following an initial rapid elongation of the specimen, ε_0 , the creep rate, decreases with time, then reaches essentially a steady state in which the creep rate changes little with time, and finally the creep rate increases rapidly with time until fracture occurs. Thus, it is natural to discuss the creep curve in terms of its three stages. It should be noted, however, that the degree to which these three stages are readily distinguishable depends strongly on the applied stress and temperature.

In making an engineering creep test, it is usual practice to maintain the load constant throughout the test. Thus, as the specimen elongates and decreases in cross-sectional area, the axial stress increases. The initial stress which was applied to the specimen is usually the reported value of stress. Methods of compensating for the change in dimensions of the specimen so as to carry out the creep test under constant-stress conditions of the specimen have been developed. When constant-stress tests are made it is found that the onset of stage III is greatly delayed. The dashed line (curve B) shows the shape of a constant-stress creep curve. In engineering situations it is usually the load not the stress that is maintained constant, so a constant-load creep test is more important. However, fundamental studies of the mechanism of creep should be carried out under constant-stress conditions.

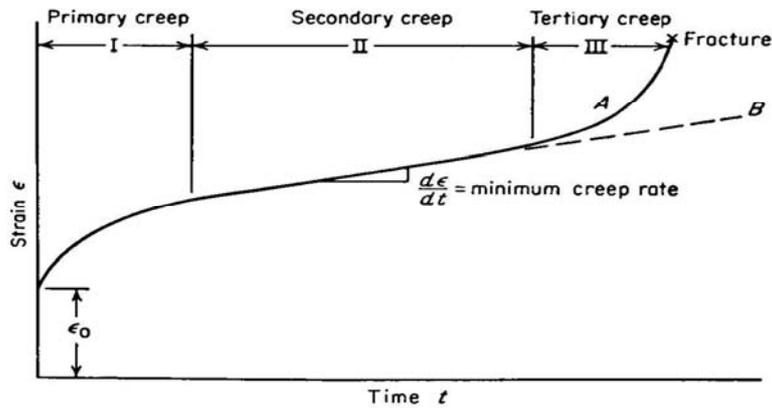


FIG. 1.69. Typical creep curve showing the three steps of creep curve A, constant-load test; curve B, constant-stress test.

The first stage of creep, known as primary creep, represents a region of decreasing creep rate. Primary creep is a period of predominantly transient creep in which the creep resistance of the material increases by virtue of its own deformation. For low temperatures and stresses, as in the creep of lead at room temperature, primary creep is the predominant creep process. The second stage of creep, known also as secondary creep, is a period of nearly constant creep rate which results from a balance between the competing processes of strain hardening and recovery. For this reason, secondary creep is usually referred to as steady-state creep. The average value of the creep rate during secondary creep is called the minimum creep rate. Third-stage or tertiary creep mainly occurs in constant-load creep tests at high stresses at high temperatures. Tertiary creep occurs when there is an effective reduction in cross-sectional area either because of necking or internal void formation. Third-stage creep is often associated with metallurgical changes such as coarsening of precipitate particles, recrystallization, or diffusional changes in the phases that are present.

Wear

Wear may be defined as undesired removal of material from contacting surfaces by mechanical action. Excessive wear can be caused by continuous overload, but wear is ordinarily a slow process that is related to the friction between two surfaces. Rapid wear can often be attributed to lack of lubrication or the improper selection of material for the wear surface. Some wear is to be expected, however, and could be called normal wear. Wear is one of the most frequent causes of failure. We find normal wear in machine tooling such as carbide and high speed tools that wear and have to be replaced or re-sharpened. Parts of automobiles ultimately wear until an overhaul is required. Machines are regularly inspected for worn parts, which when found are replaced; this is called preventive maintenance. Often normal wear cannot be prevented; it is simply accepted, but it can be kept to a minimum by the proper use of lubricants. Rapid wear can occur if the load distribution is concentrated in a small area because of the part design or shape. This can be altered by redesign to offer more wear surface. Speeds that are too high can increase friction considerably and cause rapid wear.

Metallic wear is a surface phenomenon, which is caused by the displacement and detachment of surface particles. All surfaces subjected to either rolling or sliding contact show some wear. In some severe cases the wear surface can become cold welded to the other surface. In fact, some metals are pressure welded together in machines, taking advantage of their tendency to be cold welded. This happens when tiny projections of metal make a direct contact on the

other surface and produce friction and heat, causing them to be welded to the opposite surface if the material is soft. Metal is torn off if the material is brittle. Insufficient lubrication is usually the cause of this problem. High pressure lubricants are often used while pressing two parts together in order to prevent this sort of welding. Two steel parts such as a steel shaft and a steel bore in a gear or sprocket, if pressed together dry, will virtually always seize or weld and cause the two parts to be ruined for further use. In general, soft metals, when forced together, have a greater tendency to 'cold weld' than harder metals. Two extremely hard metals even when dry will have very little tendency to weld together. For this reason, hardened steel bushings and hardened pins, are often used in earth moving machinery to avoid wear. Some soft metals when used together for bearing surfaces (for example, aluminium to aluminium) have a very great tendency to weld or seize. Among these metals there are aluminium, copper and austenitic stainless steel.

Different types of wear include abrasive wear, erosive wear, corrosive wear and surface fatigue. In abrasive wear small particles are torn off the surfaces of the metal, creating friction. Friction involving abrasive wear is sometimes used or even required in a mechanism such as on the brakes of an automobile. The materials are designed to minimize wear with the greatest amount of friction in this case. Where friction is not desired, a lubricant is normally used to provide a barrier between the two surfaces. This can be done by heavy lubricating films or lighter boundary lubrication in which there is a residual film. Erosive wear is often found in areas that are subjected to a flow of particles or gases that impinge on the metal at high velocities. Sand blasting, which is sometimes used to clean parts, utilizes this principle. Corrosive wear takes place as a result of an acid, caustic, or other corrosive medium in contact with metal parts. When lubricants become contaminated with corrosive materials, pitting can occur in such areas as machine bearings. Surface fatigue is often found on roll or ball bearing or sleeve bearings where excessive side thrust has been applied to the bearing. It is seen as a fine crack or as small pieces falling out of the surface.

Various methods are used to limit the amount of wear in the part. One of the most commonly used methods is simply to harden the part. Also, the part can be surface hardened by diffusion of a material, such as carbon or chrome, into the surface of the part. Parts can also be metallized, hard faced, or heat treated. Other methods of limiting wear are electroplating (especially the use of hard industrial chromium) and anodizing of aluminium. Some nickel plate is used, as well as rhodium, which is very hard and has high heat resistance. The oxide coating that is formed by anodizing on certain metal such as magnesium, zinc, aluminium, and their alloys is very hard and wear resistant. These oxides are porous enough to form a base for paint or stain to give it further resistance to corrosion. Some of the types of diffusion surfacing are carburizing, carbo-nitriding, cyaniding, nitriding, chromizing, and siliconizing. Chromizing consists of the introduction of chromium into the surface layers of the base metal. This is sometimes done by the use of chromium powder and lead baths in which the part is immersed at a relatively high temperature. This, of course, produces a stainless steel on the surface of low carbon steel or an iron base metal, but it may also be applied to non-ferrous material such as Tungsten, molybdenum, cobalt, or nickel to improve corrosion and wear resistance. The fusion of silicon, which is called ihrigizing, consists of impregnating an iron base material with silicon. This also greatly increases wear resistance.

Hard facing is put on a metal by the use of several types of welding operations, and it is simply a hard type of metal alloy such as alloying cobalt and tungsten or tungsten carbide that produces an extremely hard surface that is very wear resistant. Metal spraying is used for the purpose of making hard wear resistant surfaces and for repairing worn surfaces.

Overload

Overload failures are usually attributed to faulty design, extra loads applied, or an unforeseen machine movement. Shock loads or loads applied above the design limit are quite often the cause of the breakdown of machinery. Although mechanical engineers always plan for a high safety factor in designs (for instance the 10 to 1 safety factor above the yield strength that is sometimes used in fasteners), the operators of machinery often tend to use machines above their design limit. Of course, this kind of over-stress is due to operator error. Inadequate design can sometimes play a part in overload failures. Improper material selection in the design of the part or improper heat treatment can cause some failures when overload is a factor. Often a machinist or welder will select a metal bar or piece for a job based upon its ultimate tensile strength rather than upon its yield point. In effect this is a design error and can ultimately result in breakdown.

Basically there are only two modes or ways in which metals can fracture under single or monotonic loads. These two modes are shear and cleavage and they differ primarily in the way the basic metal crystal structure behaves under load. Almost all commercial solid metals are polycrystalline. Each individual crystal or grain is a structure composed of a very large number of atoms of the constituent elements. These atoms are arranged in cells within each crystal in a regular, repetitive three-dimensional pattern. Adjacent cells share the corner atoms and their positions are balanced by electrical forces of attraction and repulsion. Applied forces can cause distortion of the cells. Shear deformation represents a sliding action on planes of atoms in crystals. In a polycrystalline metal slight deformation causes no permanent change in shape, it is called elastic deformation. That is, the metal returns to its original size and shape, like a spring, after being unloaded. If a greater load is imposed, permanent or plastic deformation occurs because of irreversible slip between certain planes of atoms that make up the crystal structure. If the applied load or force is continued, the shear deformation causes tiny microvoids to form in the most highly stressed region. These tiny voids soon interconnect and form fracture surfaces. The cleavage mode of separation of the cell is different. In this case separation occurs suddenly between one face of the cell and the mating face of the adjacent cell without any deformation being present.

Fracture will originate whenever the local stress, i.e. load per unit cross-sectional area, first exceeds the local strength. This location will vary depending upon the strength of the metal and the applied stress. When a shaft or similar shape is pulled by tensile force it becomes longer and narrower. For ductile metals the shear strength is the weak link and these metals fail through the shear mode. These metals fail when shear stress exceeds the shear strength. In the case of brittle metals, these fail because the tensile stress exceeds the tensile strength. Brittle metals always have a fracture that is perpendicular to the tensile stress and little or no deformation because fracture takes place before the metal can deform plastically as ductile metals do.

When a cylinder is loaded in axial compression, a ductile metal becomes shorter and thicker. In short it bulges when squeezed by the compressive force and there is no fracture. A brittle metal in pure compression will fracture parallel to the length of the cylinder.

Brittle and ductile fracture

Fracture preceded by a significant amount of plastic deformation is known as ductile fracture, otherwise it is brittle fracture. Brittle fracture occurs, when plastic flow is inhibited either by the effective locking of atomic dislocations by precipitates or elements or by the pre-existence or formation of cracks and imperfections acting as local stress raisers in the material. All

materials can be embrittled if the temperature is lowered sufficiently. Glass, sealing wax, germanium, silicon and other materials though ductile at temperatures close to their melting point are brittle at ordinary temperatures. In most materials the brittle strength, defined as the maximum tensile stress withstood without the occurrence of brittle fracture, is low compared with the ideal strength the fault-free material would be expected to exhibit. The source of brittle fracture is therefore to be sought in the presence of structural defects.

As has already been mentioned brittle metals always have a fracture that is perpendicular to the tensile stress and have little or no deformation because fracture takes place before the metal can deform plastically. Thus a tensile fracture of a brittle metal has a fracture plane that is essentially straight across. It also usually has a characteristic bright sparkling appearance when freshly fractured.

The pattern of a break can often reveal how the failure was precipitated. For example, if the break was caused by a sudden shock load such as an explosion, there are usually chevron-shaped formations present that point to the origin of fracture. When a stress concentration is present, such as a weld on a structure that is subject to a sudden overload, the fracture is usually brittle across the entire break, showing crystals, striations, and wave fronts. Brittle fractures are often inter granular (along the grain boundaries); this gives the fracture surface a rock candy appearance at high magnification. When grain boundaries are weakened by corrosion, hydrogen, heat damage, or impurities, the brittle fracture may be inter-granular. Brittle failures can also be transgranular (through the grains): this is called cleavage.

Cleavage fracture is confined to certain crystallographic planes that are found in body centred cubic or hexagonal close-packed crystal structures. For the most part, metals having other crystalline unit structures do not fail by cleavage unless it is by stress-corrosion cracking or by corrosion fatigue. Cleavage should normally have a flat, smooth surface; however, because metals are polycrystalline with the fracture path randomly oriented through the grains and because of certain imperfections, certain patterns are formed on the surface.

Small quantities of hydrogen have a great effect on the ductility of some metals. Hydrogen can get into steels when they are heated in an atmosphere or a material containing hydrogen, such as during pickling or cleaning operations, electroplating, cold working, welding in the presence of hydrogen-bearing compounds, or the steel-making process itself. There is a noticeable embrittling effect in steels containing hydrogen. This can be detected in tensile tests and seen in the plastic region of the stress-strain diagram showing a loss in ductility. Electroplating of many parts is required because of their service environment to prevent corrosion failure. Steel may be contaminated by electroplating materials that are commonly used for cleaning or pickling operations. These materials cause hydrogen embrittlement by charging the material with hydrogen. Mono-atomic hydrogen is produced by most pickling or plating operations at the metal-liquid interface, and it seems that single hydrogen atoms can readily diffuse into the metal. Preventive measures can be taken to reduce this accumulation of hydrogen gas on the surface of the metal.

A frequent source of hydrogen embrittlement is found in the welding process. Welding operations in which hydrogen-bearing compounds such as oil, grease, paint, or water are present, are capable of infusing hydrogen into the molten metal, thus embrittling the weld zone. Special shielding methods are often used that help to reduce the amount of hydrogen absorption. One effective method of removing hydrogen is a baking treatment in which the part, or in some cases the welding rod, is heated for long periods of time at temperatures of 121 to 204°C. This treatment promotes the escape of hydrogen from the metal and restores the ductility.

Stress raisers such as notches on the surface of a material have a weakening effect and cause embrittlement. A classical example is provided by the internal notches due to graphite flakes in cast irons. The flakes embrittle the irons in tension. Therefore in structural applications cast irons are most usefully employed under compressive loads. Their brittle strength and toughness can, however, be increased appreciably if the graphite is allowed to form in spheroidal rather than flaky form. This can be done by alloying the melt, for example, with magnesium.

1.4.3 Concepts of rupture development in metals

Most of the ideas related to the development of defects in materials have already been discussed in Section 1.4.2. Rupture occurs when the size of these defects, specially cracks, reaches a certain critical size.

1.5. Quality and standardization

1.5.1 Quality

Quality of an industrial product does not mean the best or excellent. On the other hand it is defined as the fitness of the product to do the job required of it by the user. It may also be said to be the ability of the product to meet the design specifications which usually are set keeping in view the purpose and the use to which the product is expected or intended to be put. As stated earlier it would be better to set or define an optimum quality level for a product rather than trying to make it of best possible quality which will unnecessarily make the product more expensive which may not be acceptable to the customer.

In a generalized way, the typical characteristics of industrial products which help in defining and fixing its specifications and quality are chemical composition, metallurgical structure, shape and design, physical properties of strength and toughness, appearance, environmental properties, i.e. response to service conditions and presence or otherwise of internal defects. These requirements should be met within the specified tolerances. The cost, of course, is an important component. The ability of an organization to meet quality criteria in production of goods or services will ultimately bear on the profitability and survivability of that organization. If it cannot produce goods to the customer's requirements, it cannot compete except under very abnormal and short-term circumstances. However, if the customer's requirements are impossible to meet, or difficult to meet within the financial constraints imposed, the solution may very well be to redefine the requirement. Insistence on an unnecessarily high performance requirement may be completely impractical. In every industry, in every corner of the world, striving for quality has become a popular activity, applied with more or less success depending on the organization and its level of commitment. It should be recognized that quality is not an accident, rather, it should be planned. Quality cannot be inspected into a product after it is made. Instead, the inspection criteria are only to verify that quality criteria are being achieved. The complexity of management of quality within an organization depends on the complexity of the product and the process as well as on the performance criterion. Once a customer's requirement is accepted, quality is the producer's responsibility.

1.5.2 Quality control

Quality control can be defined as the controls applied at each manufacturing stage to consistently produce a quality product or in another way it is said to be the applications of operational techniques and activities which sustain quality of a product or service that will

satisfy given needs, also the use of such techniques and activities. The concept of total quality control is defined as a system for defining, controlling and integrating all company activities which enable economic production of goods or services that will give full customer satisfaction. The word 'control' represents a management tool with four basic steps, namely, setting quality standards, checking conformance with the standards, acting when the standards are not met and assessing the need for changes in the standards.

1.5.3 Quality assurance

As the name suggests quality assurance is the taking of all those planned and systematic actions necessary to assure that the item is being produced to optimum quality level and it will, with adequate confidence, perform satisfactorily in service. Quality assurance is aimed at doing things right the first time and involves a continuing evaluation of the adequacy and effectiveness of the overall quality control programme with a view to having corrective measures initiated where necessary. For a specific product or service this involves verification audits and evaluation of quality factors that affect the production or use of the product or service. Quality assurance is quality control of the quality control system.

1.5.4 Examination and testing

Examination and testing are those quality control functions which are carried out, during the fabrication of an industrial product, by quality persons who are employees of the manufacturer. Testing may also be defined as the physical performance of operations (tests) to determine quantitative measures of certain properties. Most of the non-destructive testing is performed under this heading.

1.5.5 Inspection

Inspections are the quality control functions which are carried out, during the fabrication of an industrial product by an authorized inspector. They include measuring, examining, testing, gauging or otherwise comparing the findings with applicable requirements. An authorized inspector is a person who is not the employee of the manufacturer of an industrial product but who is properly qualified and has the authority to verify to his satisfaction that all examinations specified in the construction code of the product have been made to the requirements of the referencing section of the construction code.

1.5.6 Process of standardization

The objective of most non-destructive testing methods is to detect internal defects with respect to their nature, size and location. This is done by different methods depending upon their inherent capability or sensitivity to flaw detection. A method is said to have a good or high sensitivity of flaw detection when it can detect relatively smaller flaws and vice versa. The sensitivity of flaw detection for different NDT methods depends upon a number of variable factors. Now imagine that someone is to perform, say, ultrasonic testing of circumferential welds in steel pipes of 50 cm diameter having a 10 cm wall thickness. He will undertake extensive experimentation to establish the values of different variable factors to evolve a method which gives reliable and reproducible results of desired sensitivity. This person is wise enough to carefully write down his procedure for testing of pipe welds. If someone else anywhere had a problem of ultrasonically inspecting pipe welds of similar specifications, there would be two options open to him. First he could undertake all the extensive experimentation involving lot of time, effort and money, and second he could request the first person and use his procedure which was known to be giving reliable and

reproducible results of desired sensitivity. Many persons in one city, country or different countries could use this method as a guide or recommended procedure or practice. These many persons might sometimes get together in a meeting, conference or a committee to exchange their views and experience related to this procedure. They might mutually agree on a standard procedure for ultrasonic testing of circumferential welds in steel pipes of 50 cm diameter and 10 cm wall thickness and recommend it to the standard issuing authority of their country to issue this as a national standard. Some such standards issued by the standard issuing authority of the country could be taken up by the legislature or parliament of the country and their use made obligatory by law. This briefly explains in very simple terms the otherwise complex and time consuming process of formulation and issuance of codes and standards.

1.5.7 Guides and recommended practices

Guides and recommended practices are standards that are offered primarily as aids to the user. They use verbs such as ‘should’ and ‘may’ because their use is usually optional. However, if these documents are referenced by codes or contractual agreements, their use may become mandatory. If the codes or agreements contain non-mandatory sections or appendices, the use of referenced guides and recommended practices by them, are at the user’s discretion.

1.5.8 Standards

Standards are documents that govern and guide the various activities occurring during the production of an industrial product. Standards describe the technical requirements for a material, process, product, system or service. They also indicate as appropriate, the procedures, methods, equipment or tests to determine that the requirements have been met.

1.5.9 Codes and specifications

Codes and specifications are similar types of standards that use the verbs ‘shall’ or ‘will’ to indicate the mandatory use of certain materials or actions or both. Codes differ from specifications in that their use is mandated with the force of law by governmental jurisdiction. The use of specifications becomes mandatory only when they are referenced by codes or contractual documents. A prime example of codes is the ASME boiler and pressure vessel code which is a set of standards that assure the safe design, construction and testing of boilers and pressure vessels.

1.5.10 Procedure

In non-destructive testing, a procedure is an orderly sequence of rules or instructions which describe in detailed terms where, how and in which sequence an NDT method should be applied to a production.

1.5.11 Protocols

The rules, formalities, etc., of any procedure, group, etc. (The Concise Oxford Dictionary 8th Edition).

1.5.12 Report

A report of a non-destructive examination or of testing is a document which includes all the necessary information required to be able to:

- (a) Take decisions on the acceptance of the defects by the examination.
- (b) Facilitate repairs of unacceptable defects.
- (c) Permit the examination or testing to be repeated.

1.5.13 Records

Records are documents which will give, at any time in the future, the following information about a non-destructive testing examination, (i) the procedure used to carry out the examination, (ii) the data recording and data analyzing techniques used, and (iii) the results of the examination.

1.5.14 Development of a quality system

Quality system, also called quality assurance system, has already been defined in Section 1.5.3. It is an effective method of attaining and maintaining the desired quality standards. It is based on the fact that quality is the responsibility of the entire organization and that inspection alone does not assure quality or more precisely, does not assure conformance to requirements of the control or customer order. This applies not only to complex products such as satellites or nuclear submarines, but also to simple products such as nails or pipe fittings. Regardless of the product or service involved, the essentials of an effective quality assurance system include:

- (a) Independence of the quality assurance department from the design and production departments.
- (b) Standards of quality that reflect both the needs of the customer and the characteristics of the manufacturing process.
- (c) Written procedures that cover all phases of design, production, inspection, installation and service, with a programme for continuous review and update of these procedures.
- (d) Control of the flow of documents such as order entry, order changes, specifications, drawings, route slips, inspection tickets and shipping papers.
- (e) Methods for maintenance of part identity which must establish traceability through the process.
- (f) Methods for timely detection and segregation of non-conforming material which must also include programmes for corrective action.
- (g) Schedules for periodic calibration of inspection equipment.
- (h) Schedules for retaining important records.
- (i) Programmes for training and qualification of key production and inspection personnel.
- (j) Systems for control of specifications incorporated into purchase order; for control of the quality of purchased goods and for appropriate inspection of purchased goods.
- (k) Systems for control of manufacturing, assembly and packaging processes, including inspection at key points in the process flow.
- (l) A system for periodic audit of any or all of the above by persons having no direct responsibility in the area being audited.

The quality assurance system is an evaluation or audit of each one of these subsystems to determine how effectively the functions are being performed. Evaluations are usually conducted each year to determine which elements and subsystems need improvement. The

overall rating provides a comparison with past performance or with other plants of a multi-plant corporation. These subsystems are briefly described in the following sections.

Independence of quality assurance department

Responsibility for the development, operation and monitoring of an effective quality assurance programme in a plant usually rests with the quality assurance manager. Companies having several plants may have a corporate quality assurance department that reviews and coordinates the system for the entire organization. To be effective this should be an independently staffed department that reports directly to an upper level manager such as general manager, vice president or president. The quality assurance department should be free to devise and recommend specific systems and procedures and require corrective action at their discretion.

Establishment of quality standards

No single quality level is necessary or economically desirable for universal use; the quality requirements of a paper clip are obviously quite different from those of a nuclear reactor. Many professional groups, trade associations and government agencies have established national codes and standards. However these codes and standards generally cover broad requirements, whereas a set of detailed rules for each product or class of products is required for the control of quality. In most plants it is the responsibility of the quality assurance manager to interpret national codes and standards in terms of the purchase order and from these to devise process rules uniquely suited to the specific products and manufacturing methods used in that particular plant. The set of process rules thus devised may be known by various names: in these training notes it will be called an 'operating practice description'. There may be thousands of operating plant descriptions in plant files, each varying from the others as dictated by code or customer requirements, limits on chemical composition or mechanical properties, or other special characteristics. Large plants may have computerized storage systems permitting immediate retrieval of part or all of the operating practice descriptions at key locations throughout the plant.

Written procedures

Written procedures are of prime importance in quality assurance. Oral instructions can be inadequately or incorrectly given and thus misunderstood and incorrectly followed. Clear and concise written instructions minimize the likelihood of misinterpretation. Vague generalizations that do neither assign specific responsibilities nor determine accountability in case of error must be avoided. For instance, procedures should be specific regarding the type and form of inspection records, the identity of the individual who keeps the records and where the records are kept. Similarly, a calibration procedure should not call for calibration at 'periodic intervals' but should specify maximum intervals between calibrations. Depending on the type of equipment, calibration may be performed at intervals ranging from a few hours to a year or more.

Control of document flow

The original purchase order, which is often less than one page in length, may generate hundreds of other working papers before the ordered material or part is shipped. All paperwork must be accurate and must reach each work station on time. In some industries where there may be an average of two or more specifications or drawing changes per order, an effective system of material tracking that is separate and distinct from material identification

is necessary. Control of document flow places direct responsibility on departments not usually associated with quality control. The sales office (which is responsible for entry of the customer order), the production planning group (which is responsible for scheduling work and tracking material) and the accounting department (which is responsible for billing and shipping) are all involved. Many large plants have computerized order systems, the heart of which is an 'active order file'. This computer file receives periodic inputs to update information on specifications, drawings, material sizes, shop operations, shipping and routing. In turn this file may be accessible from various terminals in the sales office, home office or plant, when information is needed on material location, order status and the like.

Maintaining identity and traceability of materials

In high speed manufacturing operations, particularly those involving hot work, identity markings on the raw material (such as paint mark, stencils or stamps) are usually destroyed during processing. In such instances, procedures must be devised for maintaining identity not by marking alone but also by location and count. These procedures sometimes must provide for traceability of individual units of products by a method suitable for the product and process and must include any additional identity that the customer may require. Ultimately both producer and customer must be confident that the goods actually delivered are described accurately in the shipping papers, test reports and certificates of compliance. This confidence is of great importance in certain applications in the aerospace and nuclear industries.

Non-conforming material and corrective action

A system for detection and segregation of non-conforming material requires:

- (a) Written inspection instructions that can be clearly understood.
- (b) Identified, segregated holding areas for parts that have been rejected.
- (c) A structured group (sometimes called a materials review board) to evaluate rejected material, make final judgement on its fitness for use, decide what is to be done with nonconforming material and prescribe action for the cause of rejection.

In many instances rejected parts are only slightly out of tolerance and their usefulness is not impaired. Even so, all decisions of a materials review board to accept non-conforming material must be unanimous. In the absence of unanimity, the problem may be referred to top management for a decision based on overall business judgement. In some companies, the authority of the materials review board is limited to merely deciding whether or not non-conforming material is fit for use. However, in many companies the board also determines what is to be done with nonconforming lots; whether they are to be shipped 'as is', sorted, repaired or scrapped, and fixes the accountability for incurred losses. When corrective action is recommended by a materials review board, it is usually systems oriented, that is, intended to prevent recurrence of the non-conformity by avoiding its cause. In instances where a lot has been rejected because the acceptance number for a sampling plan has been exceeded, decisions concerning disposition of the lot often are made on the basis of costs, the solution that results in the least total cost to both producer and customer is adopted. Sometimes, material that is slightly out of tolerance and therefore not fit for use by one customer may meet the specifications of another customer.

Calibration of equipment

The quality assurance system must recognize that the accuracy and repeatability of measuring and testing equipment may be affected by continued use; maximum intervals between

calibrations should be specified in the written quality assurance procedures. Except perhaps for small hand instruments such as micrometers, each testing machine or instrument should be plainly labelled with the last date of calibration. Calibration standards should be traceable to recognized industry or national standards of measurement. It is also desirable to maintain a central file of calibration records for each plant or department.

Retention of records

A quality assurance system must designate which records are to be retained and must set down minimum time periods for retention of such records. It is usual for important documents to be retained for 25 years or more; the nuclear industry is required to maintain records for 40 years. Retention time, however, should be consistent with real needs as dictated by projected lifetime of products or by legal requirements. Besides satisfying certain contractual or other legal requirements, retained records can provide important cost benefits to both producer and customer. In one instance, extensive and costly testing of a 50 years old structure prior to repair was avoided when the fabricator was able to produce original drawing and material test reports.

Personnel training and qualification

National codes exist for the qualification of certain specialized workers, for instance welders and inspectors. When applicable, codes should be incorporated as minimum requirements for training and qualification of key personnel. All of these, however, must be supplemented by local written procedures for both on-the-job and classroom training. Quality assurance management must reduce complex procedures to the simplest form that will permit a trainee to understand exactly what the job is and how it is to be performed.

Control of purchased material

All specifications and orders for outside purchases of material whose performance may affect product quality should be subject to approval by quality assurance management. Inspection of incoming material should be subject to approval by quality assurance management. Inspection of incoming material should be incorporated into the quality assurance programme. The main purpose of receiving inspection is to check for failures of vendor quality programmes, but receiving inspection should not be expected to compensate for poor quality control by vendors. The purchaser should evaluate and periodically audit the quality assurance system of each major supplier to make sure that the purchased material can be expected to have the specified level of quality.

Manufacturing, assembly and packaging

All manufacturing, assembly and packaging processes should be controlled to ensure attainment of the finished product of the right quality at the time of its reaching the customer. Design drawings and the processes of manufacturing and assembly should be assessed whether appropriate methods of adequate capability and sensitivity are being applied and whether the results being obtained are reliable and reproducible or not. The tests should be applied at appropriate stages during manufacture and all test reports should be properly signed by authorized persons. All manufacturing, testing, assembly and packing should be done according to verifiable written procedures.

Quality audit

Quality audit is an independent evaluation of various aspects of quality performance to provide information with respect to that performance. Quality audits are usually made by companies to evaluate their own quality performance, by buyers to evaluate the performance of their vendors, by regulatory agencies to evaluate the performance of organizations which they are assigned to regulate.

Purpose of audit is to provide assurance that:

- (a) Procedures for attaining quality are such that, if followed, the intended quality will be obtained.
- (b) Products are fit for use and safe for the user.
- (c) Laws and regulations are being followed.
- (d) There is conformance to specifications.
- (e) Written procedures are adequate and being followed.
- (f) The data system is able to provide adequate information on quality.
- (g) Corrective action is being taken with respect to deficiencies.
- (h) Opportunities for improvements are identified.

For an internal quality audit typically the organization is divided up into its component parts and each area is audited. The time taken depends on the size of the organization. For a small NDT organization one could audit the following:

- (a) Documentation of NDT procedures.
- (b) Control of stores.
- (c) Receipt of job instructions.
- (d) Purchasing of equipment and accessories.
- (e) Maintenance of equipment and accessories.
- (f) Calibration of equipment.
- (g) Contract administration.
- (h) Safety.
- (i) Accounting.
- (j) Office administration, e.g. wages, leave, superannuation.
- (k) Organizational structure.
- (l) Research and development.
- (m) Reports and records.

A periodic audit of quality of the system performance against written standard is needed to detect corner-cutting, non-compliance and intentional violations of established quality procedures. To be as unbiased as possible, such audits should be performed by persons not having responsibility in the area being audited. In companies having multiple plants, each individual plant may conduct its own internal audit, but in addition should be subject to audit by corporate staff personnel. The most important activities of corporate staff aside from auditing are review of the quality system with the highest level of plant management and follow up to approve corrective action for any discrepancies found during an audit. Periodic review of the quality assurance system and reaffirmation of quality objectives by top management should be part of company policy. This will in part ensure long range viability of the business enterprise.

2. PHYSICAL PRINCIPLES

2.1. Electricity

The study of charges in motion is called electricity and the rate of flow of charge is called electric current. When potential difference between two charges force a third charge to move, the charge in motion is an electric current. Therefore to produce current, the charge must be moved by a potential difference. In the case of a conductor the current is defined as the flow of electrons through the conductor. Electrons are negatively charged particles that are part of the atom, which is the basic building block of any material. Some materials are conductor while others are not. A material is called a conductor if it is capable of carrying the electric current. A conducting material has free charges, which move under the influence of an external field. The free charges in a metallic conductor are negative electrons. The free charges in an electrolyte are ions, both positive and negative. A gas under proper conditions, as in a neon sign or fluorescent lamp is also a conductor and its free charges are positive and negative ions and negative electrons.

2.1.1 Direct current (DC)

An electric current flowing continuously in one direction through a conductor is called the direct current (DC). The dry cell is a DC voltage source because it has only one polarity of the output voltage which produces direct current in the external circuit

Amperage and Voltage

When there is an electric field in a conductor the free charges within it are set in motion. Positive charges moving in the same direction as the field and negative charges move in the opposite direction. FIG. 2.1 shows a portion of a conductor within which there is an electric field of intensity E . In a metallic conductor negative charges crossing a section from right to left are equivalent to positive charges crossing from left to right. The entire current is due to the motion of the free charges. The electrons move in the opposite direction to the conventional current in a metallic conductor. The value of current, I , is given by the relation

$$I = Q/t \quad (2.1)$$

where

I = current

Q = charge

t = time

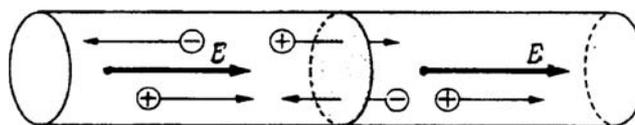


FIG. 2.1. Positive charges move in the direction of the field in a conductor

The unit of current in MKS system of units is an Ampere, which represents a quantity of one Coulomb of charge flowing per second. Quantitatively it is equal to the flow of 6.25×10^{18} electrons per second through a given point in a circuit. The basic unit of potential in an electrostatic field is a Volt which is equal to the potential difference between two points for

which one Coulomb of charge will do one Joule of work in going from one point to the other, i.e.

$$1 \text{ Volt} = 1 \text{ Joule/Coulomb} \quad (2.2)$$

The above relation helps us to define potential difference. The potential difference between two (arbitrary) points is said to be one Volt if the work done in bringing one unit of charge from one point to another is one joule. If the points are lettered A and B, the potential difference between them is simply $V_A - V_B$ or $V_B - V_A$. The potential difference between the terminals of a lead storage battery is about 12 volts with the terminal marked + at higher potential. If we call this terminal A and other terminal (negative) as B, then $V_{AB} = 12$ Volts and $V_{BA} = -12$ Volts

There is an electric field in the space between the battery terminals. If the positive charge moves from terminal A (+) to terminal B (-) its potential energy decreases by 12 Joules/Coulomb. This energy appears in some other form such as heat in the filament of a head light or work in starting the motor. The electrical energy, derived from mechanical, chemical or other form of energy that must be applied across the material to force the electrons to move, is called the Electromotive Force (EMF). The potential difference between the terminals of the battery when it is not supplying current to an external circuit is called its EMF. When an EMF is applied across a conductive material, flow of electrical current results. The unit of EMF is also a Volt.

Ohm's law and resistance

If a voltage V is applied across a conductor, a current I flows through it. George Ohm discovered that the magnitude of the current in metals is proportional to the applied voltage provided there is no change in the physical state of the conductor. This is known as the Ohm's law. The relationship is exact within the accuracy of the measurements. Mathematically, it can be written as

$$I = V / R \quad (2.3)$$

where

- I = current
- V = voltage
- R = resistance

Resistance in any conducting material is the measure of the opposition to the motion of free electrons due to their continuous collisions against the atoms of the lattice. Resistance depends on the nature, dimension and physical state of the conductor. The unit of electrical resistance is Ohm (Ω). The Ohm is defined as the resistance of a conductor through which a current of one Ampere is flowing when the potential difference across it is one Volt i.e.

$$1 \text{ Ohm} = 1 \text{ Volt /1Ampere}$$

The amount of resistance in a material is a factor that limits the amount of current that flows through the material for a given applied electromotive force (EMF). Since the resistance in a circuit results in the expenditure of energy, the result is the dissipation of that energy in the form of heat. For a pure conductor resistance is directly proportional to its length L and inversely proportional to its cross section area A i.e.

$$R \propto L/A$$

or

$$R = \rho L/A, \tag{2.4}$$

where

R = resistance

ρ = resistivity

L = length

A = area

Conductivity and resistivity.

Conductivity is defined as the ability of a material to conduct electric current. It is denoted by σ . The unit of conductivity is Siemens per meter or mho per meter. The conductivity of a conductor decreases with the increase in the temperature. Each element has a unique value of conductivity. Copper, silver and gold have high conductivities where as, carbon has a very low conductivity.

An eddy current is a flow of electrons. The amount of electron flow through an electrically conductive material is directly related to the conductivity of the material. If the conductivity increases, the flow of eddy current increases.

Resistivity is reciprocal of the conductivity. Therefore the materials that have high resistivity have poor conductivity and vice versa. The resistivity is denoted by ρ and is defined as the 'ratio of electrical intensity (emf) to the current per unit cross-section area.'

Mathematically it can be written as

$$\rho = E/I/A$$

or

$$\rho = EA/I \tag{2.5}$$

where

ρ = resistivity

E = emf

L = length

A = area

The value of resistivity can also be derived from relation (2.4), i.e. $\rho = RA/L$.

The unit of resistivity is Ohm-meter (Ω -m). The Ohm-meter is a bigger unit, the smaller unit is the micro Ohm-centimeter ($\mu\Omega$ -cm).

Resistivity of a material changes with the change in temperature. As the temperature of the conductor rises, the amplitude of the vibration of the atoms in the lattice increases and hence the probability of their collision with the free electrons also increases. It can also be said, that at high temperatures, the atoms offer bigger target area, i.e. the collision cross-section of the atoms increases. This makes the collision between free electrons and the atoms in the lattice more frequent and hence the resistance of the conductor increases.

Experimentally the change in resistivity of a metallic conductor with temperature is found to be nearly linear over a wide range of temperatures below and above 0°C. Over such a range, the fractional change in resistivity per Kelvin is known as the temperature coefficient of resistivity.

In eddy current testing, conductivity is frequently given as a percentage of the international annealed copper standard (%IACS). In this system conductivity of pure annealed copper at 20 °C is set to 100% and conductivity of other materials is given as a percentage of copper. Conductivity of a material can be calculated from its resistivity.

$$\% IACS = 172.41 / \rho \quad (2.6)$$

Where IACS = international annealed copper standard
 ρ = resistivity

Conductivity is a one of main variables in eddy current inspection. It makes possible the screening of certain materials based upon their conductivity, the detection of changes in chemistry, lattice distortion, heat treat, hardness, discontinuities, etc. The resistivity and conductivity of various materials are given in Table 2.1.

TABLE 2.1. THE RESISTIVITY AND CONDUCTIVITY VALUES OF VARIOUS MATERIALS

| Material | Resistivity ($\mu\Omega$ -cm), $\times 10^{-7}$ | Conductivity (mho/m), $\times 10^7$ | Conductivity (%IACS) |
|-------------------|---|--|-------------------------|
| Silver | 1.6 | 6.14 | 105 |
| Copper | 1.7 | 5.81 | 100 |
| Gold | 2.4 | 4.10 | 70 |
| Aluminium | 2.8 | 3.55 | 61 |
| 7075-T6(AI Alloy) | 5.3 | 1.89 | 32 |
| Zinc | 5.9 | 1.70 | 29 |
| Magnesium | 4.6 | 2.17 | 37 |
| Admiralty Brass | 7.0 | 1.43 | 24 |
| Iron | 9.7 | 1.03 | 18 |
| Phosphor Bronze | 16 | 0.63 | 11 |
| Lead | 20.6 | 0.49 | 8.4 |
| 70 Cu-30 Ni | 37.4 | 0.27 | 4.5 |
| Monel | 48.2 | 0.21 | 3.6 |
| Zirconium | 50 | 0.20 | 3.4 |
| Titanium | 54.8 | 0.18 | 3.1 |
| 304 SST | 70 | 0.14 | 2.5 |
| Sircalloy-2 | 72 | 0.14 | 2.5 |
| Inconel 600 | 98 | 0.10 | 1.7 |
| Hastelloy X | 115 | 0.087 | 1.5 |
| Waspalloy | 123 | 0.081 | 1.4 |
| Ti-6A I-4V | 172 | 0.058 | 1.0 |

2.1.2 Alternating current (AC)

An electric current that reverses its direction of flow at regular intervals is called an alternating current (AC). The AC circuits are of major importance in applied electricity. The alternating current is positive as much as it is negative. A typical sine wave showing AC voltage is shown in FIG. 2.2 below. Alternating voltage periodically reverses in polarity, causing alternating current that periodically reverses its direction.

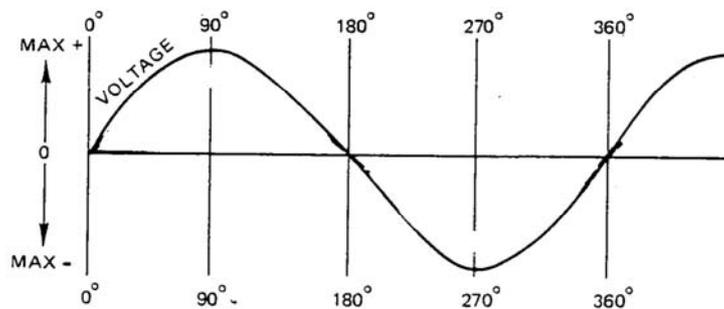


FIG. 2.2. Sine wave curve showing AC voltage.

Amplitude and Phase

The systems that vary periodically with time are called sinusoidal time variation systems. Electric circuits tend to develop sinusoidally varying currents and voltages, or have particularly simple responses to sinusoidal signals. To maintain a continuous current in a conductor, the electric field has to be maintained i.e. the potential difference across the conductor has to be maintained. If the field reverses its direction periodically, the flow of charge reverses and the current is thus alternating between the two constant maximum positive and maximum negative values. This is illustrated in FIG. 2.3. The maximum vertical height of the wave is called its amplitude. The voltage changes its amplitude every half cycle and an equal time to reach maximum of negative amplitude value.

The time taken to complete one cycle is termed as the time period and the number of cycles per second is called the frequency. The unit of frequency is Hertz (Hz), which is equal to 1 cycle per second. In the sine wave curve shown above along the X axis we have phase angle in radians or degrees, whereas Y axis represent the amplitude at a particular time. At $\pi/2$ or 90° we have the maximum positive amplitude of the wave form, while at $3\pi/2$ or 270° we have maximum negative amplitude of the wave form. The angle subtended by any point of the curve to its initial position is called as the phase angle. At any time t the instantaneous voltage $V(t)$ is given by

$$V(t) = V_0 \sin \omega t = V_0 \sin(2\pi f t), \quad (2.7)$$

where

$V(t)$ = instantaneous voltage

V_0 = initial voltage

ω = angular frequency

t = time

f = frequency

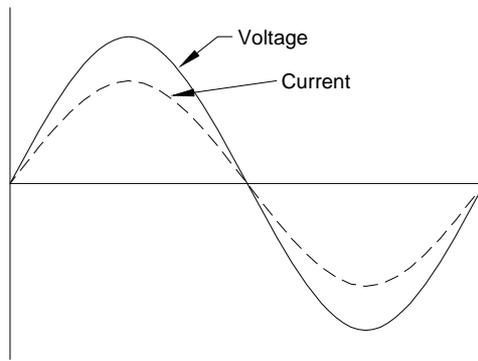


FIG. 2.3. Voltage and current in phase.

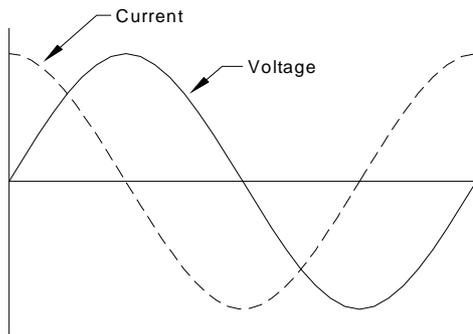


FIG. 2.4.a. Current leading voltage by 90° .

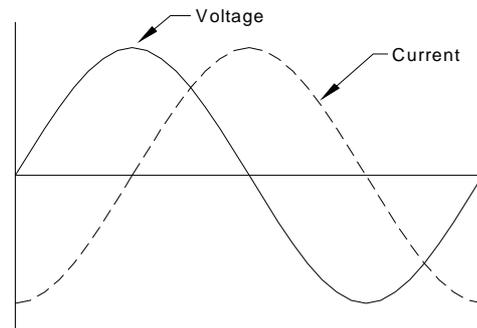


FIG. 2.4.b. Current lagging voltage by 90° .

Phase angles

Although the sine wave shown in FIG. 2.2 can be used to represent either the current or the voltage, if both current and voltage are to be shown then two sine waves are required. When the sine waves of the current and the voltage both pass through zero in the same direction and at the same time, then the voltage and current are said to be in phase with each other, as shown in FIG. 2.3. However, as will be discussed later, the current and voltage may not be in phase with one another. The current may lead or lag the voltage. The amount by which the current leads or lags can be expressed in degrees or time as shown in FIG. 2.4.

Effect of pure resistance

When an alternating current is passed through a pure resistance the current can be calculated by dividing the voltage by the resistance. As the resistance remains constant, the current is proportional to the voltage. As the voltage is continually changing, in both strength and direction, the current will change in a similar manner. Therefore, the voltage and current curves will rise and fall together as shown in FIG. 2.5 and are said to be **'in phase'** at the same frequency. However, as the value of the resistance affects the current flow, the amplitudes of the voltage and current may be different in accordance with Ohms Law. The value of resistance is not affected by a change in frequency.

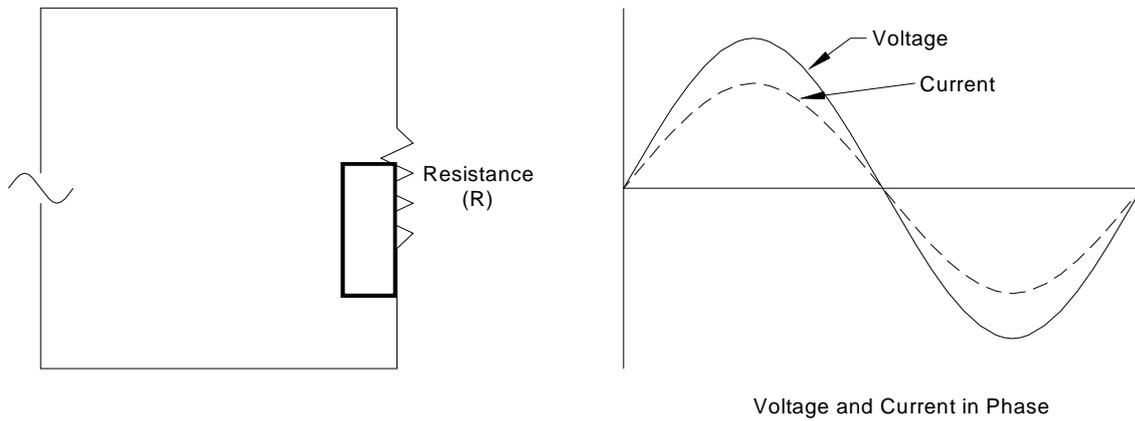


FIG. 2.5. Circuit having pure resistance.

Effect of pure inductance

Inductance, like resistance, imposes a limit on the current which a given ac voltage will cause to flow in a circuit. The magnitude of opposition to current flow by an inductance is called inductive reactance (X_L), which, unlike resistance, varies with frequency. If the frequency is zero (dc), there is no inductance and a coil will act as an ordinary conductor, but as frequency increases (ac), the rate of change of the coil magnetic field increases and the coil will become more and more inductive, thereby increasing the opposition to current flow. Therefore the higher the frequency, the higher the inductive reactance. As inductance is a magnetic property dependent on the rate of change of the current, in a purely inductive circuit (where it is assumed there is no resistance), the current will lag the voltage by 90° as shown in FIG. 2.6. This is further explained by appreciating that the magnetic field is changing in each cycle at its maximum rate of change when the voltage is zero. As the voltage passes through zero on each cycle, the induced (opposite) EMF is a maximum. Inductive reactance, like resistance, is measured in Ohms.

$$X_L = 2\pi fL \quad (2.8)$$

Where X_L = inductive reactance
 f = frequency
 L = inductance

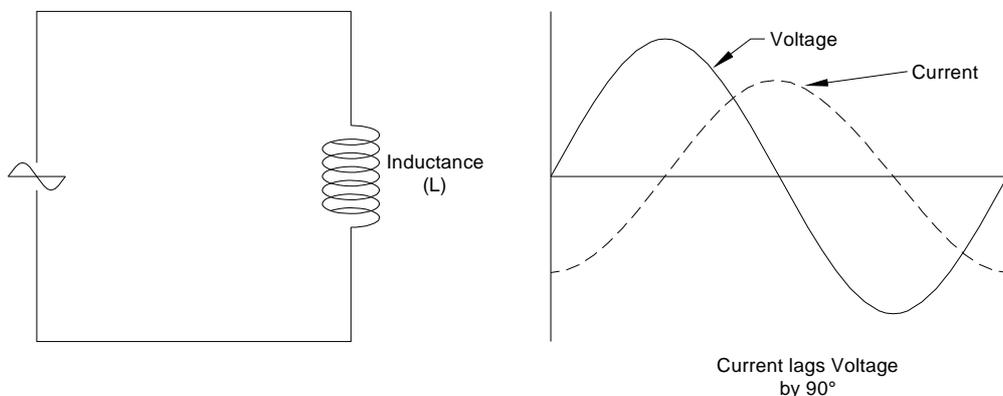


FIG 2.6. Circuit having pure inductance.

Effect of pure capacitance

In a dc circuit, a fully charged capacitor acts as a complete break and no current will flow. However, in an ac circuit the capacitor is continually being charged and discharged as the voltage alternates. As can be seen in FIG. 2.7, when the voltage is at its maximum value the capacitor is fully charged and no current will flow. When the voltage falls the capacitor discharges and the current will be at its maximum value when the voltage is zero. As the voltage increases again, the current will decrease and so on. Therefore, in a purely capacitive circuit (where it is assumed there is no resistance), the current will lead the voltage by 90°. One can consider the analogy of a hydraulic accumulator being charged and discharged. As the pump starts and the accumulator is empty the flow is maximum with minimum pressure. Capacitance, like resistance and inductance, imposes a limit on the current which a given ac voltage will cause to flow in a circuit. The magnitude of opposition to current flow by a capacitance is called capacitive reactance (X_C) and is measured in Ohms. Capacitive reactance also varies with frequency but unlike inductive reactance, the higher the frequency, the lower the capacitive reactance.

$$X_C = \frac{1}{2\pi fC} \tag{2.9}$$

$2\pi fC$

where

X_C = capacitive reactance

f = frequency

C = capacitance

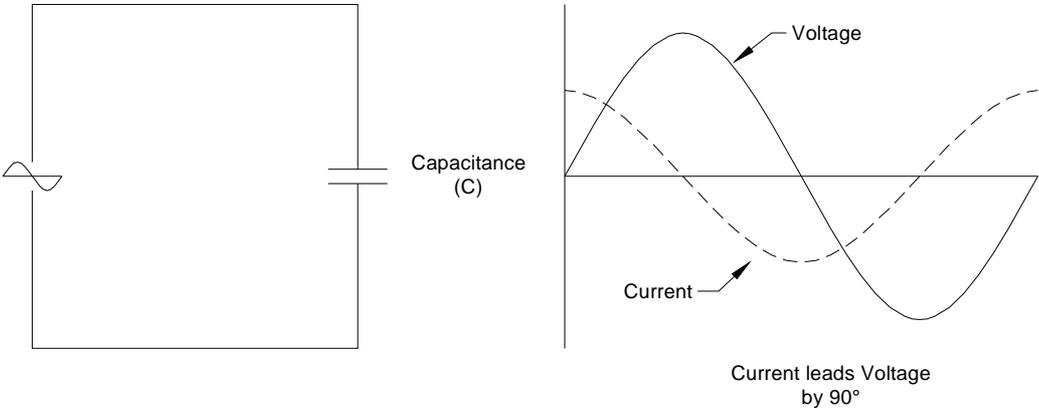


FIG. 2.7. Circuit having pure capacitance.

Resonant frequency

If a circuit contains an inductor and a capacitor and the value of inductive reactance and capacitive reactance are equal the circuit is said to be in resonance ($X_L = X_C$). Because the value of both X_L and X_C are both frequency dependent, it can be seen that resonance will always occur at a fixed frequency dependent on the values of impedance and capacitance.

Impedance

In the circuit shown in FIG. 2.8, the opposition to current flow is due not only to resistance but also to inductive and capacitive reactance. This total opposition is called impedance (Z). If the resistance, inductive reactance and capacitive reactance are drawn vectorially with magnitude and direction and with a horizontal line representing zero phase angle, then the resistance will be drawn as a horizontal line whose length is proportional to its magnitude. As an inductance causes a phase lag of 90° , the inductive reactance can be drawn as a vertical line upwards whose length is proportional to its magnitude. Similarly, as a capacitance causes a phase lead of 90° , capacitive reactance can be drawn as a vertical line downwards as shown in FIG 2.9.

A simplified representation of the 3 component parts of an alternating circuit is shown in FIG. 2.10. below. The inductive reactance and the capacitive reactance are in opposition to each other. The total Reactance in Ohms being $X_C - X_L$. When the effect of Resistance is combined with the reactance the total opposition has a vector value (Amplitude and Phase angle) and becomes Impedance (Z).

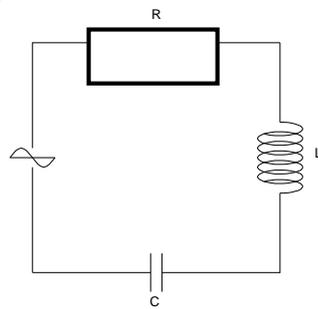


FIG. 2.8. Resistance, inductance, capacitance circuit.

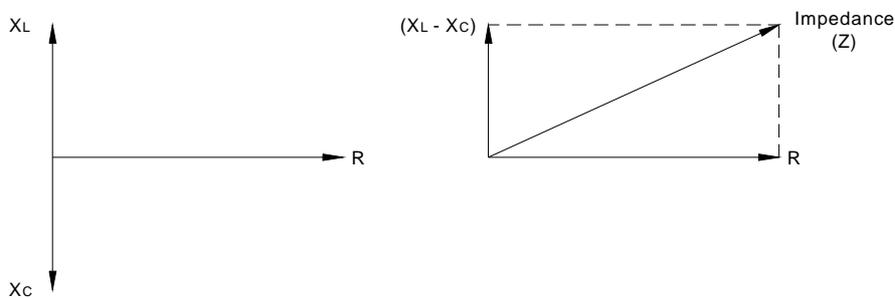


FIG. 2.9. Impedance triangle.

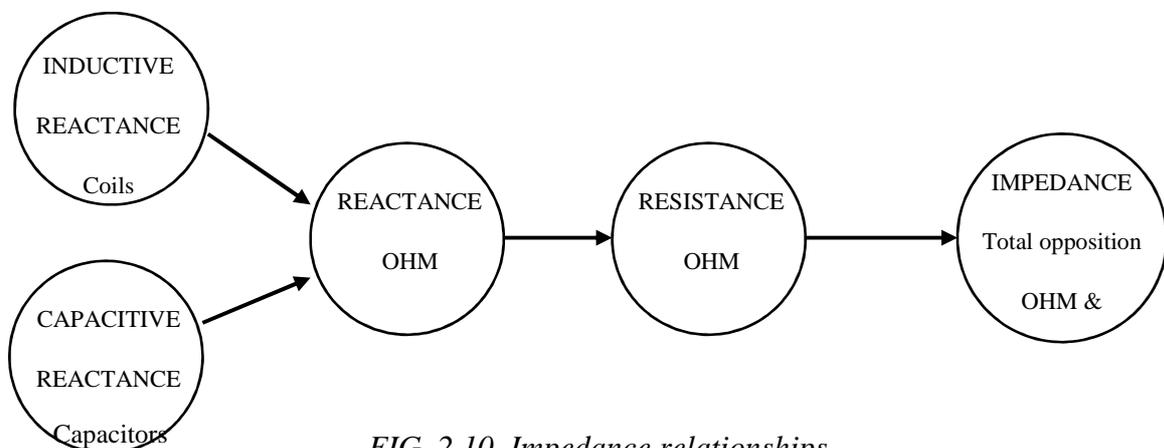


FIG. 2.10. Impedance relationships.

The impedance and the phase angle of the current caused by the voltage applied to the impedance can be calculated using right angle triangle calculations (Pythagoras). The impedance amplitude can be determined using the formula:

$$Z = \sqrt{R^2 + (X_C - X_L)^2} \quad (2.10)$$

where

| | |
|----------------|------------------------|
| Z | = impedance |
| R | = resistance |
| X _c | = capacitive reactance |
| X _L | = inductive reactance |

Similarly, the phase angle can be determined using trigonometry with the formula:

$$\theta^\circ = \tan^{-1} \frac{(X_C - X_L)}{R} \quad (2.11)$$

where

| | |
|----------------|------------------------|
| θ° | = phase angle |
| X _c | = capacitive reactance |
| X _L | = inductive reactance |
| R | = resistance |

As both the inductive reactance and capacitive reactance vary with frequency, any variation in frequency will change the impedance and phase angle.

- If X_L is greater than X_C then the impedance Z has a lagging phase angle and the circuit is inductive.
- If X_C is greater than X_L then the impedance Z has a leading phase angle and the circuit is capacitive.
- If X_L = X_C then the phase angle is zero. Then Z = R therefore the circuit is resistive only.

2.2. Magnetism

Magnetism is a property possessed by certain material by which this material can exert a mechanical force of attraction and repulsion on other like materials. The most well known example of the effects of magnetism is the attraction that the magnet has for an iron nail.

Magnetic materials

If an object is placed in a magnetic field a force is exerted on it and it becomes magnetized. The intensity of magnetization depends upon the susceptibility of the metal to become magnetized. Some metals are attracted to a magnet, these are para-magnetic metals of which ferro-magnetic materials are a sub group. Others are repelled by magnets; these are dia-magnetic metals. An illustration of these relationships is shown in FIG. 2.11.

Para-magnetic materials

Para-magnetic metals have a positive susceptibility to magnetization that means they are attracted to magnets. Some are only weakly attracted; magnesium, molybdenum, lithium and tantalum are examples.

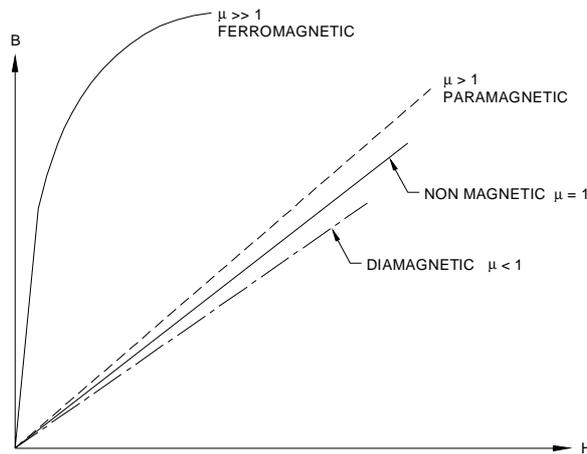


FIG. 2.11. Ferro-, para-, dia- and non-magnetic permeability relationships.

Ferromagnetic metals

These are para-magnetic materials that have a large and positive susceptibility to magnetization. They have a strong attraction and are able to retain their magnetization after the magnetizing field has been removed. Iron, cobalt and nickel are examples of ferromagnetic metals.

Ferromagnetic materials are the only metals commonly inspected with the magnetic particle testing method. This includes welded steel structures and nickel based jet turbine blades.

Dia-magnetic materials

Diamagnetic metals have a small and negative susceptibility to magnetization or are slightly repelled by magnets. Copper, silver and gold are examples of diamagnetic materials.

2.2.1 Magnetic theory

A body that attracts small pieces of iron and points towards north-south direction when suspended freely, is called a magnet. The end of a magnet pointing towards north is called the N-Pole while the other is called the S-Pole. Like poles of two magnets repel, while unlike poles attract, each other. The magnetism of the magnet is concentrated in the poles of the magnet. The two poles of a magnet cannot be separated from each other. If a magnet is broken into two pieces, two new magnets are obtained. Each new magnet has both the poles N-pole and a S-pole. This process may be repeated many times as desired but each time a magnet with both poles is obtained.

Induction and magnetic field

A magnetic field, like an electric field, can be represented by lines called lines of induction, whose direction at every point is that of the magnetic induction vector. The number of induction lines per unit area normal to the direction of the magnetic field is called the magnetic induction and is denoted by the letter B. The unit of induction in MKS system is Weber per square meter (Wb/m^2) where one Weber is equal to one line of induction. Similarly, in the CGS system, the unit of induction is Maxwell per square centimetre where one Maxwell is equal to one line of induction. Weber/m^2 is called a Tesla (T) and Maxwell/cm^2 is called a Gauss.

In a uniform magnetic field, where the magnetic induction vector has a constant magnitude, the lines are straight and equally spaced. If the pole pieces of an electromagnet are large and close together, there is a region between the poles where the magnetic field is approximately uniform. The total number of lines of induction threading through a surface is called the magnetic flux through the surface and is denoted by ϕ . In a special case where B is uniform and normal to a finite area A ,

$$\phi = B \bullet A \quad (2.12)$$

where

- ϕ = magnetic flux at surface
- B = flux density
- A = area

Since B is in Wb/m^2 and A is in m^2 , the flux is in Webers. Since the induction B at a point equals the flux per unit area, it is often referred to as the flux density.

The largest values of magnetic induction that can be produced in the laboratory are of the order 10Wb/m^2 or 10^5 Gauss ($1 \text{ Weber/m}^2 = 10^4$ Gauss), while in the magnetic field of the earth the induction is only few hundredth thousandths of Weber per square meter or a few tenths of a Gauss.

Magnetic field is described as the area surrounding a magnet and can be shown by drawing imaginary lines of force to indicate the path that an isolated N pole would take if it were free to move. How close together the lines are drawn depends on the field strength. Lines of field around a bar magnet are as shown in FIG. 2.12.

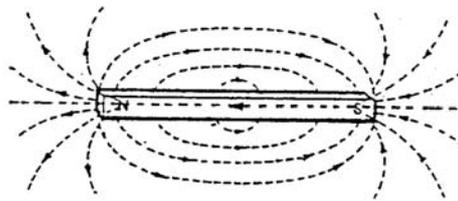


FIG. 2.12. Magnetic fields of bar magnet.

Magnetic Permeability

Magnetic permeability is an intrinsic property of a material. It is the ability of a material to concentrate magnetic lines. It is denoted by the Greek letter μ . Any material that is easily magnetized, such as soft iron, concentrate the magnetic flux. This is the main feature separating magnetic materials from nonmagnetic materials. The magnetic permeability is equal to the induced magnetic flux density B divided by external magnetic field intensity (magnetizing force) H . i.e.

$$\mu = \frac{B}{H}, \quad (2.13)$$

where

- μ = magnetic permeability
- B = flux density (tesla)
- H = magnetizing force (amperes/metre)

For air, vacuum, and non-magnetic materials the μ is constant. For air and vacuum the value of μ is given as, $\mu_0 = 4\pi \times 10^{-7}$ Webers/ ampere-metre. The numerical values of μ for different materials are assigned in comparison with air or vacuum. This is called the relative permeability and is defined as

$$\mu_r = \frac{\mu}{\mu_0} \quad (2.14)$$

where

- μ_r = relative permeability
- μ = permeability
- μ_0 = permeability in vacuum

The μ_r is a dimensionless quantity because it is a ratio comparing two flux densities. Since air, vacuum and any other non-magnetic material cannot affect a magnetic field by induction, they all have the μ_r equal to 1. For magnetic materials μ_r can be very large. Typical values for iron are 100 to 5,000.

Another permeability of concern in eddy current testing is the incremental or recoil permeability, $\Delta\mu$. It is defined as

$$\Delta\mu = \frac{\Delta B}{\Delta H}, \quad (2.15)$$

where

- $\Delta\mu$ = incremental (recoil) permeability
- ΔB = change in flux density
- ΔH = change in magnetizing force

Iron magnetization

Materials such as mild steel which are easily magnetizable, lose part or whole of the magnetism on removal of the applied field. The magnetic domains which align themselves with the applied field are thus easily disturbed on the removal of the external field leaving the material, partially magnetized. Flux can exist in the materials even in the absence of external magnetization force such as in permanent magnets. Magnetic specimen in the form of ring with a toroidal winding can be magnetized from its original un-magnetized state. The plot of respective values of flux density B and intensity of magnetization H is known as magnetization curve. Examples of these curves are given in Figs 2.13. (a) and (b). The horizontal base line, or X axis is marked off in units of magnetization force H, in Oersteds. The vertical, or Y axis indicates flux density B in Gauss. Its shape varies from one type of material to another due to their magnetic permeability.

As the magnetizing force H is applied to iron, the domain walls move so as to favour the growth of domains that happen to have their direction of magnetization more or less along the external field direction. As the field is further increased, forces are great enough to cause the gradual rotation of magnetization direction into exact alignment with the field. Finally, when all dipoles are aligned, B has reached a constant value, or is saturated.

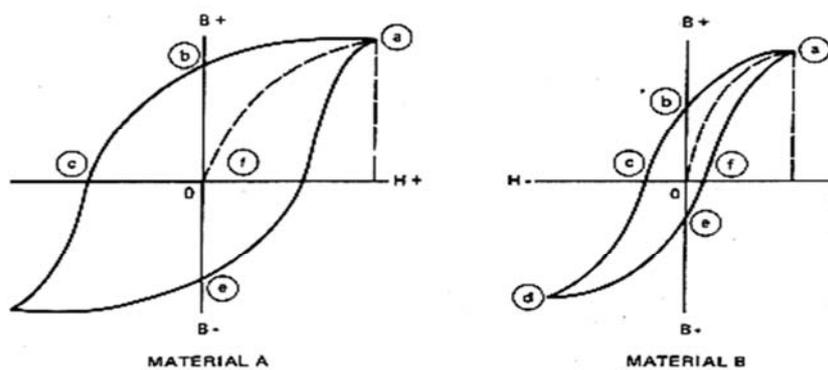


FIG. 2.13. Hysteresis curve for hard (a) and soft materials (b).

If the field is removed after the specimen is magnetized, the material tends to return to its unmagnetized state. But the motion of domain walls is partially inhibited by crystal boundaries and their crystal imperfections. This produces a kind of friction which causes the walls to lag behind the position they would take if they moved easily within the specimen. This means that the magnetic dipoles are not perfectly elastic and they do not return to their original position when the external force is removed.

From the curves shown in FIG. 2.13. for soft and hard iron it is evident that the permeability is not constant and is given by the ratio of B to H, which can be found at any point by noting the respective values.

2.2.2 Induced magnetic flux

Definition

The total number of lines of induction threading through a surface is called magnetic flux. It is denoted by ϕ . The magnetic flux can be induced in a conductor by placing it in the field of a permanent magnet or an electromagnet.

Lines of force and force fields

The space around a magnet where the influence of the magnet is felt by another magnet or a magnetic substance is called magnetic field. The magnetic field is represented by magnetic field lines (or magnetic lines of force). The path along which an isolated north pole of a magnet moves in the magnetic field is called the field line. The field lines are directed from N-pole of the magnet towards the S-pole. The field lines do not intersect one another.

The magnetic field in a test sample can be created either by passing currents directly into the sample or by indirect way, whereby the field is created into the ferromagnetic sample by induction. The sample gets magnetized in this way by placing it axially in the pre-wound coil, solenoid or by placing it around the conductor carrying current. The lines of force as a result of the applied field would be circular or longitudinal.

Flux conservation and residual magnetism

As the ferromagnetic material is subjected to external magnetization force, for an unmagnetized material, the behaviour or response to magnetic intensity and resultant flux is as shown in the magnetization curve of FIG. 2.13. If the magnetizing field is strong enough, the gradual process of alignment of domains goes on until all the domains are aligned and the

specimen is saturated. The behaviour of the ferromagnetic material under the complete cycle of magnetization is complex and we notice that flux density B is not zero as the value of H becomes zero and there is still residual magnetism, also called the remanance, equal to the value of 'ob' of curve in FIG. 2.13.

If the direction of the magnetizing current is reversed and gradually increased in value, the magnetic field will be further reduced until it reaches zero flux density of point (c). Point (c) gives the coercive force, the reverse field necessary to demagnetize the sample. Further increase in the reverse magnetizing current causes the magnetic field to ultimately reach saturation in the opposite direction at point (d).

If the magnetizing force is now decreased to zero, the residual field of point (e) is in the opposite direction to what it was before. Further increase in the magnetizing current (not in the original direction) reduces the magnetic field to zero at point (f) and then builds the magnetic field in the original direction until it reaches point (e).

If the magnetizing force is now decreased to zero, the residual field point (e) is in the opposite direction to what it was before. Further increase in the magnetizing current (now in the original direction) reduces the magnetic field to zero at point (f) and then builds the magnetic field in the original direction until saturation is reached at point (a). The total curve is called the hysteresis loop.

2.2.3 Magnetic Ohm's law

The Ohm's law in magnetism is analogous to that of the Ohm's law in electricity. It states that 'The Magnetomotive Force (MMF) is directly proportional to the magnetic flux (ϕ) produced by this force.'

Mathematically, it can be written as

$$MMF \propto \phi$$

or

$$MMF = \phi R$$

or

$$\phi = MMF / R, \tag{2.16}$$

where

| | |
|--------|-----------------------|
| ϕ | = magnetic flux |
| MMF | = magnetomotive force |
| R | = resistance |

Magnetomotive force

The force that produces the magnetic field is called the Magnetomotive force (MMF). In an electrical circuit an EMF drives a current through conductor. In magnetism the magnetomotive force (MMF) produces the flux which flows through the lines of flux. More the electric current, stronger the electric field, and in case of a coil, more the number of turns, more concentrate is the field. Therefore the MMF is given as

$$MMF = NI \quad (2.17)$$

where

| | |
|-----|---------------------------|
| MMF | = magnetomotive force |
| N | = number of turns in coil |
| I | = current |

where N is the number of turns of the coil and I is the current in Amperes.

The unit of MMF in SI units is Ampere-turn. In CGS system the unit of MMF is Gilbert, abbreviated as Gb. 1 Ampere-turn = $4\pi/10$ Gilbert (= 1.26 Gilbert).

Reluctance

Reluctance in the magnetic circuit is comparable to resistance in the electrical circuit. It is defined as the opposition to the establishment of magnetic flux in the material under the influence of the magnetizing field.

The material with high permeability has low reluctance and vice versa. Reluctance of the material determines the magnitude of the flux produced by the MMF as given by the magnetic Ohm's law.

Magnetic circuits

The magnetic flux lines form closed loops. If all the magnetic flux (or substantially all of it) associated with a particular distribution of currents is confined to a rather well-defined path, then we may speak of a magnetic circuit. A toroid is an example of a magnetic circuit since the magnetic flux is confined to the region inside the toroidal winding.

The magnetic circuit is analogous to current circuit and because of this analogy, the series and parallel reluctance combinations may be combined in the same manner as series and parallel resistance combinations.

The reluctance R is inversely proportional to the permeability μ . Since the permeability of ferromagnetic material may be 100 times μ_0 , 103 μ_0 , or even 105 μ_0 in certain circumstances, it is apparent that ferromagnetic material forms a low-reluctance path for the magnetic flux. If the magnetic flux encounters two parallel paths, one high reluctance R_h and the other low reluctance R_l , then most of the flux will pass through the low reluctance path, and the equivalent reluctance of the combination is given by

$$R = \frac{R_h R_l}{(R_h + R_l)} \quad (2.18)$$

| | |
|---------|-------------------|
| Where R | = reluctance |
| R_h | = reluctance high |
| R_l | = reluctance low |

2.3. Magnetic field produced by a current

The first recorded observations of magnetic fields set up by currents were those of Oersted, who discovered that a pivoted compass needle, beneath a wire in which there was a current, set itself with its long axis perpendicular to the wire. Later experiments by Biot and Savart, and by Ampere, led to a relation by means of which we can compute the flux density at any point of space around a circuit in which there is a current.

2.3.1 Biot and Savart law

Definition

The magnetic field surrounds the current carrying conductor. For a long straight conductor carrying a unidirectional current, the lines of magnetic flux are closed circular paths concentric with the axis of the conductor. Biot and Savart deduced, from the experimental study of the field around a long straight conductor, that the magnetic flux density B associated with the infinitely long current carrying conductor at a point P which is at a radial distance r , as illustrated in FIG. 2.14, is

$$B = \frac{\mu_0 I}{2\pi r}, \quad (2.19)$$

Where B = magnetic flux density
 μ_0 = permeability of free space
 I = current
 r = radial distance

Unlike the electric field around a charged wire, which is radial, the lines of magnetic induction are circles concentric with the wire and lying in planes perpendicular to it. The direction of this concentric closed loop of magnetic lines is given by right hand rule.

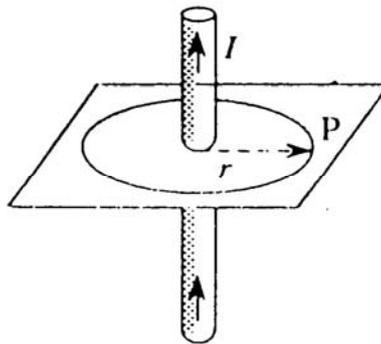


FIG. 2.14. Magnetic field around a long straight current conductor carrying.

Practical rules

Consider a conductor through which current I is flowing vertically upward, as shown in FIG. 2.14. Suppose we want to find the magnetic flux density due to this current carrying conductor at a point P whose perpendicular distance from the conductor is r . It was found experimentally by Biot and Savart that at any point:

- (a) the magnetic flux density is directly proportional to the current. i.e. $B \propto I$.
- (b) the magnetic flux density is directly proportional to the effective length of the conductor, i.e. $B \propto l$.
- (c) iii) the magnetic flux density is inversely proportional to square of the distance r of point P from the conductor, i.e. $B \propto 1/r^2$.

Combining the above three statements the magnetic flux density comes out to be as given by the equation (2.19).

Right hand rule

The lines of magnetic induction are circles concentric with the wire and lying in planes perpendicular to it. The direction of this concentric closed loop of magnetic lines is given by right hand rule, which states, ‘If the conductor is grasped in the right hand with the thumb pointing in the direction of the current, the curled fingers of the hand will point in the direction of the magnetic field’ as shown in FIG. 2.15.

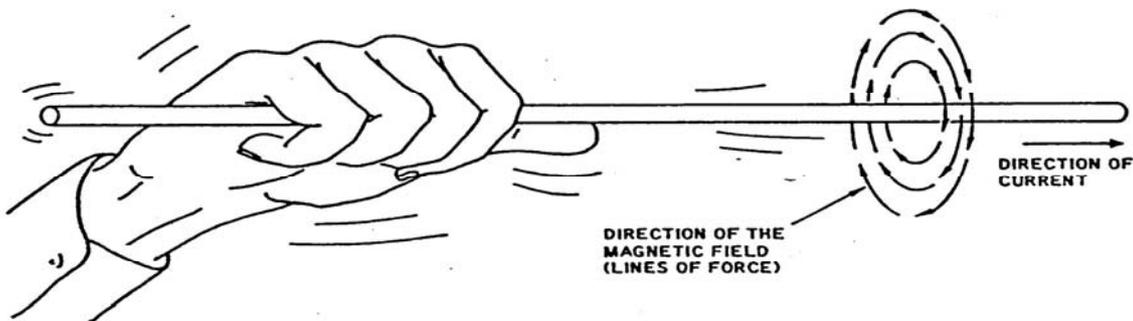


FIG. 2.15. Fleming's right hand rule.

2.3.2 Ampere's law

Definition

The Ampere's law states that “the magnetic flux density over a closed surface is directly proportional to the current enclosed by the surface.”

The equation 2.19 can be written as $2\pi rB = \mu_0 I$. This shows that the product of $2\pi r$ and B equals $\mu_0 I$. But $2\pi r$ is the length of the path around the conductor and on it the value of B is the same at every point. Ampere generalized this result into a law. Mathematically, it can be written as

$$B \cdot l = \mu_0 I \tag{2.20}$$

where

- l = length
- B = magnetic flux density
- μ_0 = permeability of free space
- I = current

This law is applicable to closed paths other than circular ones.

Thus Ampere's law can also be defined as "The dot product of B and l around any closed path equals $\mu_0 I$, where I is the total steady current threaded by the path."

The path is divided into several small length elements as shown in FIG. 2.16. Consider a length element dl of the closed path. According to Ampere's law it can be written as

$$\int Bdl = \mu_0 I \quad (2.21)$$

where

dl = length

B = magnetic flux density

μ_0 = permeability of free space

I = current

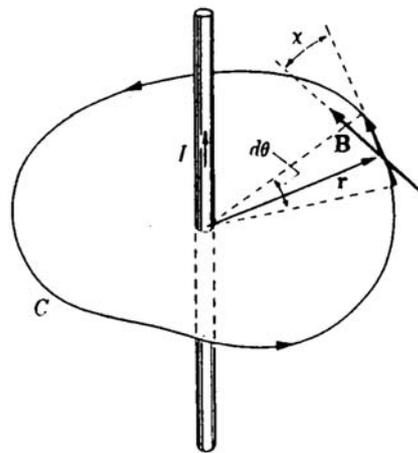


FIG. 2.16. Verification of Ampere's law for long straight conductor geometry.

Applications

(a) Field due to current in a toroid

A toroid is a solenoid that has been bent into a circle. Consider a toroid of radius r , having N turns and current I flowing through it. When current passes through each turn, circular magnetic lines of force pass through the turns of the toroid.

Applying Ampere's law along the axis of the toroid, we can write

$$\int B \cdot dl = \mu_0 \times (\text{current enclosed}) = \mu_0 NI$$

As the angle between B and dl is zero and $\int dl = 2\pi r$, therefore the magnetic field due to current in a toroid according to Ampere's law is given by

$$B = \frac{\mu_0 NI}{2\pi r} \quad (2.22)$$

where

- B = magnetic flux density
- μ_0 = permeability of free space
- N = number of turns
- I = current
- r = radial distance

The magnetic field is not uniform over a cross-section of core, because the path length l is larger at the outside of the section than at the inner side. However, if the radial thickness of the core is small compared to the toroid radius r , the field varies only slightly across a section. In this case, considering that $2\pi r$ is the circumference length of the toroid and that $n = N/2\pi r$ is the number of turns per unit length, the field may be written as

$$B = \mu_0 n I \quad (2.23)$$

where

- B = magnetic flux density
- μ_0 = permeability of free space
- n = number of turns/unit length
- I = current

The equations derived above for the field in a closely wound solenoid or toroid are strictly correct only for a winding in vacuum. For most practical purposes, however, they can be used for a winding in air, or on core of non-ferromagnetic material.

(b) Field due to current in a coil

A coil is constructed by winding wire in a helix around a cylindrical surface. The turns of the winding are ordinarily closely spaced and may consist of one or more layers. When it is connected to a battery an electric current flows through each turn and produce magnetic field. This magnetic field is fairly uniform and stronger inside the turns but it is weaker and negligible outside the coil.

To find the magnetic field due the coil we apply the Ampere's law. The field outside the coil is zero and the field inside the coil is uniform and stronger and is along the axis of the coil. Therefore by Ampere's law

$$\int B \cdot dl = \mu_0 I$$

The value of B will be same as in the case of a toroid, i.e.

$$B = \mu_0 n I$$

The direction of B is along the axis of the coil.

2.4. Electromagnetic induction law

Induced voltage is the result of a magnetic flux cutting across a conductor, produced by physical motion of either the magnetic field or the conductor. When the current in a conductor varies in amplitude, however, the variations of current and its associated magnetic field are equivalent to motion of the flux. As the current increases in value, the magnetic field expands outward from the conductor. When the current decreases, the field collapses into the conductor. As the field expands and collapses with changes of current, the flux is effectively in motion. Therefore, a varying current can produce induced voltage without the need for motion of the conductor.

The result of an expanding and collapsing flux field is the same as that of a field in motion. This moving flux cuts across the conductor that is providing the current, producing induced voltage in the wire itself. Furthermore, any other conductor in the field, whether carrying current or not, also is cut by the varying flux and has induced voltage.

2.4.1 Lenz's law

Definition

Lenz's law states, "The direction of an induced current is such as to oppose the cause producing it."

The 'cause' of the current may be the motion of a conductor in a magnetic field, or it may be the change of flux through a stationary circuit. In the first case, the direction of the induced current in the moving conductor is such that the direction of the side thrust exerted on the conductor by the magnetic field is opposite in direction to its motion. The motion of the conductor is therefore 'opposed'.

In the second case, the current sets up a magnetic field of its own, which within the area bounded by the circuit is opposite to the original field if this is increasing, but is in the same direction as the original field if the later is decreasing. Thus it is the change in flux through the circuit (not the flux itself), which is 'opposed' by the induced current.

Auto-induction factor

The ability of a conductor to induce voltage in itself when the current changes, is called the auto-inductance or self-inductance or simply the inductance. The symbol for inductance is L and its unit is the Henry. One Henry is the amount of inductance that allows one Volt to be induced when the current changes at the rate of one Ampere per second. The auto-induction factor is given by

$$L = -\frac{E_{ind}}{(\Delta I / T)} \quad (2.24)$$

where

- L = inductance
- E_{ind} = induced voltage
- ΔI = change in current
- T = time

The negative sign for E indicates that the polarity of induced voltage is in opposition to the current change, but the polarity can be disregarded in calculating the value of L.

The inductance of a coil increases with the number of turns, diameter of the coil, and the permeability of the core. For a straight air-core coil, the inductance increases as the square of the turns and diameter. Doubling the turns provides four times the inductance, and doubling the diameter provides four times the inductance. If both the number of turns and the diameter are doubled, the inductance is increased by a factor of 16. The inductance also increases directly with the length, i.e. doubling the length provides twice the inductance.

Mutual inductance factor

When the current in an inductor changes, the varying flux can cut across any other inductor nearby, producing induced voltage in both inductors. Consider two coils L_1 and L_2 placed close to each other. The coil L_1 is connected to an AC generator. The winding L_2 is not connected to L_1 , but the turns are linked by the magnetic field. Varying the current in L_1 induces voltage across L_1 and across L_2 . If all of the flux of current in L_1 links all the turns of the coil L_2 , each turn in L_2 will have the same amount of induced voltage as each turn in L_1 . Additionally, when the induced voltage produces current in L_2 , its varying magnetic field induces voltage in L_1 . The two coils have mutual inductance because current in one coil can induce voltage in the other. The mutual inductance of the two coils (M) can be written as

$$M = (L_1 L_2)^{1/2} \quad (2.25)$$

where

M = mutual inductance

L_1 = inductance coil 1

L_2 = inductance coil 2

Coupling factor

The fraction of total flux from one coil linking another coil is the coefficient of coupling. It is denoted by the letter k . The coefficient increases by placing the sensing coil close to the conductor. When probe coils are used, the spacing between the coil and conductor is called lift-off. When encircling or internal coils are used, the coupling is called fill-factor. The coefficient of coupling is increased by placing the coil close to the conductor. A higher value of k , called 'tight' coupling, allows better mutual induction. 'Loose' coupling, with a low value of k , has the opposite effect.

2.4.2 Induced currents

Induced current in a short-circuit coil

Faraday's law states that whenever a magnetic field cuts a conductor an electrical current will flow in the conductor if a closed path is provided over which current can circulate. The alternating current flowing through the test coil will produce a changing magnetic field in the coil. If any other coil is placed in the magnetic field of the coil, a current in the second coil will be induced. If the coil is placed very close to the excitation coil then the amount of current induced in the other coil may be the same as that flowing through the excitation coil.

Induced current in a metallic mass

The alternating current flowing through the test coil produces an alternating magnetic field in the coil. When the test coil is brought near to, or placed on the metallic conductor, the magnetic field passes into (cuts) the material and circular (eddy) currents are induced in the material as shown in FIG. 2.17.

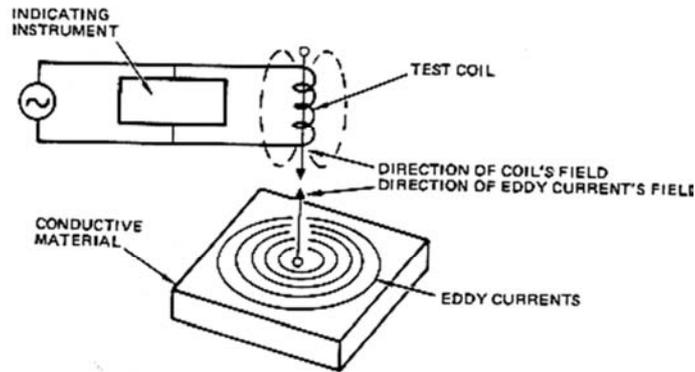


FIG. 2.17. Basic eddy current testing equipment.

The current in the conductor (eddy current) will generate a secondary magnetic field, which induces a current in the sensor coil. This mutual inductance causes a change in the impedance of the coil. The impedance signals sensed by the search coil are the measurements of the test specimen. Hence, the eddy current technique uses the effect of electromagnetic fields and induction to characterize physical properties of metallic materials.

Skin effect

Eddy currents induced by a changing magnetic field concentrate near the surface adjacent to the excitation coil. The eddy currents flowing in the test object at any depth produce magnetic fields which oppose the primary field thus reducing net magnetic flux and causing a decrease in current flow as depth increases.

Alternatively, eddy currents near the surface can be viewed as shielding the coil's magnetic field thereby weakening the magnetic field at greater depths and reducing induced currents. This phenomenon is known as the skin effect.

Field created by eddy current

In a test coil flux is set up by passing the alternating current through it. When this coil is brought close to the conductive sample, eddy currents are induced in the sample. The induced currents have their own magnetic flux associated with them. The direction of the magnetic flux ϕ_s associated with the induced currents is such as to oppose the coil's magnetic flux ϕ_p (Lenz's law) thereby decreasing net magnetic flux. This results in change of coil impedance and voltage drop. FIG. 2.18. illustrates direction of primary and secondary fluxes.

It is the opposition between the primary and secondary (eddy currents) field that provides the basis for extracting information during eddy current testing. It should be noted if sample is ferromagnetic the magnetic flux is strengthened despite opposing eddy current effects. The high permeability of ferromagnetic materials distinguishes them from non-ferromagnetic materials and strongly influences eddy current test parameters.

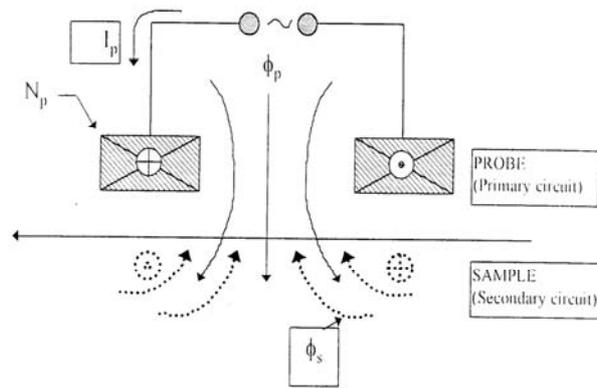


FIG. 2.18. Field generated by the eddy currents.

Reactance

The net magnetic flux of the coil decreases as its field intercepts a non-magnetic conductive material. This reduces both exciting coil's inductance and its inductive reactance. The magnitude of this reduction depends on the following:

- (a) test materials conductivity
- (b) test frequency
- (c) proximity of the magnetizing coil to the test material.

The test coil reactance in the vicinity of the ferromagnetic material, on the other hand, increases as the highly permeable material is placed in the exciting coil's field. This happens so as these flux lines which enter the ferromagnetic test part find portion of their path in the material which has far less reluctance than air. The exciting field then includes increased flux densities which are encircled by coil's windings.

2.5. Factors effecting eddy currents

2.5.1 Introduction

The factors which affect eddy currents are:

- (a) Conductivity σ (Sigma)
- (b) Permeability μ (mu)
- (c) Frequency f
- (d) Proximity (Lift off/fill factor)
- (e) Geometry
- (f) Probe Handling
- (g) Discontinuities (Defects)

Due to the large number of variables in eddy current inspection, in order to correctly interpret the cause on an indication, all of the above seven (7) factors must be considered.

2.5.2 Practical considerations

Conductivity

While the inherent conductivity of a material is always the same, there are internal factors that can cause what appears to be a change in the inherent conductivity

(a) Alloys.

Alloys are combinations of other metals and/or chemical elements with a base metal. Each metal or chemical element has an individual effect on the conductivity of the base metal. The conductivity of the base metal is changed to a value related to the composition of the alloy. Thus it is possible to identify basic metals and their alloys by measuring their conductivities.

(b) Hardness.

When a metal or alloy is subjected to heat treatment (or to excessive heat during normal operation) the metal will become harder or softer depending on the material. This change in hardness is brought about by an internal change in the material which also affects the conductivity of the material. This change in conductivity can also be detected by eddy current test methods. An improper heat treatment can be detected in this manner.

(c) Temperature and Residual Stresses.

The ambient temperature and internal residual stresses of a material under test also have an effect on the conductivity of the material. These changes can also be detected by eddy current testing. An increase in the temperature of the material normally results in a decrease in the conductivity of the material. Residual stresses cause an unpredictable, but detectable, change in conductivity.

(d) Conductive Coatings.

The presence of a conductive coating on a conductive material changes the inherent conductivity of the base metal just as an alloy would. However, if the thickness of the cladding varies, the conductivity will vary. This change in thickness can be detected by eddy current testing methods.

Permeability

When an energized test coil is placed upon non-magnetised ferromagnetic material, the field is greatly intensified by the magnetic properties of the material so that a large change in the impedance of the test coil occurs.

If the magnetic field strength at various locations varies even slightly, these small variations have a large effect on the impedance of the coil. These changes in the impedance of the coil are often so large (in comparison to the changes caused by changes in conductivity or dimension) that they mask all other changes. When specimen geometry permits, this effect may be overcome by magnetizing the material to saturation using a separate coil powered by direct current. Magnetic saturation effectively eliminates any variations in the residual magnetic field due to magnetic variables, and thus allows other variations to be measured. After testing is completed, the article must be demagnetized.

Frequency

Frequency is one of the few operator controlled variables in eddy current testing. The main use of frequency is controlling depth of penetration, density and phase of induced eddy currents. In general terms, higher frequencies are used to detect surface breaking discontinuities, and lower frequencies for sub surface testing.

Proximity

Lift off and fill factor are the terms used to describe any space that occurs between the article under test and the inspection coil. Each has an identical effect on the eddy currents. Lift off and fill factor are essentially the same thing; one is applied to surface coils and the other to encircling and internal coils.

(a) Lift Off.

When a surface coil is energized and held in air above a conductor the impedance of the coil has a certain value. As the coil is moved closer to the conductor the initial value will change when the field of the coil begins to intercept the conductor. Because the field of the coil is strongest close to the coil, the impedance value will continue to change until the coil is directly on the conductor. Conversely, once the coil is on the conductor any small variation in the separation of coil and conductor will change the impedance of the coil. The lift off effect is so pronounced that small variations in spacing can mask many indications.

(b) Fill Factor.

In an encircling coil, or an internal coil, fill factor is a measure of how well the conductor (test specimen) fits the coil. It is necessary to maintain a constant relationship between the diameter of the coil and the diameter of the conductor. Again, small changes in the diameter of the conductor can cause changes in the impedance of the coil. This can be useful in detecting changes in the diameter of the conductor but it can also mask other indications.

Geometry

The two main factors in component geometry affecting eddy currents are thickness and edge/end effect.

(a) Thickness.

Changes in material thickness may be caused by manufactured geometry or in service corrosion/erosion. If the material thickness is less than the effective depth of penetration, any change in the material thickness will affect the eddy currents, this can be used to good effect to measure material thickness.

(b) Edge/end effect.

Eddy currents are distorted when the end, or an edge, of a part is approached with the test coil since the currents have no place to flow. The distortion results in a false indication that is known as 'edge effect'. However, when scanning into tight radii the opposite effect occurs. Edge effect is also apparent at the junction of different materials.

Since, to the test coil, the edge of the part looks like a very large crack or hole, there is a very strong reaction that will mask any changes due to other factors. The limit as to how close to the edge a coil can be placed is determined by the size of the coil and any shielding applied.

Probe handling

Under ideal conditions the probe coil should be presented to the test surface at a constant angle to the surface with constant lift off and pressure. Changes in probe angle, contact pressure, or the way the probe is held (hand capacitance) will cause changes to the signal from the probe.

In nondestructive testing where the majority of inspections utilize the hand held surface contact coil method, the influence of a bad probe handling technique cannot be over emphasized. The effects of probe handling can be reduced with the use of special spring loaded probes which maintain the probe at a constant angle and pressure to the surface. These are usually used where scanning is to be carried out on flat surfaces, or where conductivity or paint thickness measurements are being taken. When scanning close to changes of section (geometry effect) the use of simple probe guides will assist in good probe handling resulting in a more effective inspection.

Discontinuities

Cracks cause a distortion of the eddy current field due to the fact that the eddy currents have to flow around them. This results in an increased resistance path and a corresponding reduction in eddy current strength. Similarly corrosion causes an increased resistance within the material with a corresponding reduction in eddy current strength. In each case a meter or spot display change will result.

To ensure that inspections are carried out to a repetitive standard, reference blocks with artificial defects are used. These blocks should be of similar material specification (alloying, heat treatment, conductivity) to the component under test. By setting up the flaw detector (standardization) to give a known response from the artificial defect, an inspection can be carried out repeatedly to the same standard.

The flaw detector sensitivity settings (standardization) must be checked, at regular intervals, and as a minimum.

- (a) Prior to each inspection.
- (b) After each inspection.
- (c) When obtaining a suspect fault indication/prior to confirming a fault indication.

Note: If it is discovered that the flaw detector setting are incorrect, all components tested since previous correct standardization was confirmed, must be re-tested.

3. INSTRUMENTATION

3.1. Principles and basic characteristics of eddy current probes

Eddy current probes are based on relatively simple principles and usually consist of an assembly containing one or more coils in a suitable configuration. The shape of the coil, its cross-section, size, and configuration are parameters that need to be considered to produce a particular probe suitable for a specific application or range of applications. This coil is energized by an alternating current of known frequency and amplitude which gives rise to the magnetic field which is also of varying type. When this coil is brought closer to a conductive test material, there is an induced voltage generated in the sample.

3.1.1 Induction and Reception Function

There are two methods of sensing changes in the eddy current characteristics:

- (a) The impedance method
- (b) The send receive method

Impedance method

In the impedance method, the driving coil is monitored. As the changes in coil voltage or a coil current are due to impedance changes in the coil, it is possible to use the method for sensing any material parameters that result in impedance changes.

The resultant impedance is a sum of the coil impedance (in air) plus the impedance generated by the eddy currents in the test material.

The impedance method of eddy current testing consists of monitoring the voltage drop across a test coil. The impedance has resistive and inductive components. The impedance magnitude is calculated from the equation:

$$|Z| = [R^2 + (X_L)^2]^{1/2} \quad (3.1)$$

where

- Z = impedance
- R = resistance
- X_L = inductive reactance

and the impedance phase is calculated as:

$$\theta = \text{Arctan} (X_L/R) \quad (3.2)$$

where

- θ = phase angle
- R = resistance
- X_L = inductive reactance

The voltage across the test coil is $V = IZ$, where I is the current through coil and Z is the impedance.

A test sample's resistance to the flow of eddy currents is reflected as a resistive load and is equivalent to a resistance in parallel to the coil inductive reactance. This load results in a resistive and inductive impedance change in the test coil. Coil impedance can be displayed on normalized impedance diagrams. With this display we can analyse the effect of sample and test parameters on coil impedance. The equivalent circuit derivation of coil impedance is useful for a quantitative understanding of the effect of various test parameters.

Send receive method

The send-receive method consists of separate driving coil (or coils) and pick-up coil (or coils). In this case, the induced voltage across the pick-up coil is measured. The send-receive method in eddy current testing is used to eliminate the temperature drift. The flow of eddy currents is monitored by observing the effect of their associated electromagnetic fields on the voltage induced in an independent receiver coil(s). This is shown in FIG. 3.1.

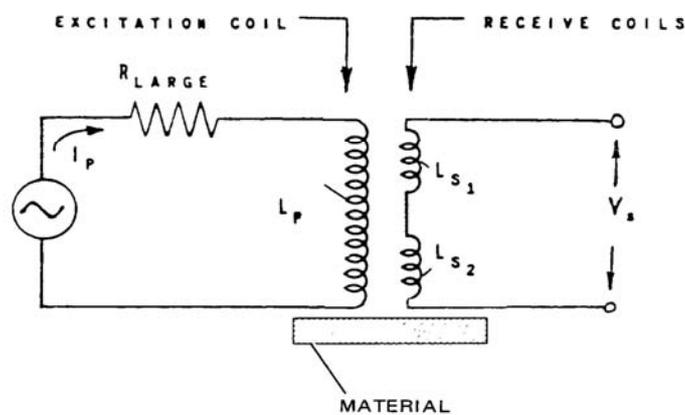


FIG. 3.1. Send - receive circuit.

The excitation or primary coil is driven with a sinusoidal current with constant peak to peak amplitude to obtain a constant magnetomotive force. As a result the flux of the excitation coil is independent of coil resistance.

The wire resistance of both the excitation and receiver coils can change, because of temperature, without affecting the output signals. The effect of temperature drift is thus eliminated. Temperature independence makes this method useful for measuring conductivity, wall thickness and spacing between metal layers.

3.1.2 Absolute and differential measure

The most basic distinction between probes can be made based on their mode of operation. This includes:

- (a) Absolute eddy current probes.
- (b) Differential eddy current probes.

Absolute Eddy Current Measure Absolute eddy current probes consist of a single coil or its equivalent. A winding separated into two or more sections, would still be considered absolute if it performs as such. In this type of probe, the impedance or the induced voltage in the coil is measured directly (their absolute values rather than changes in impedance or induced voltage). FIG. 3.2 and FIG. 3.3 show absolute eddy current probes.

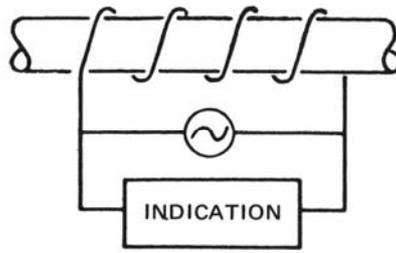


FIG. 3.2. Single-coil absolute arrangement.

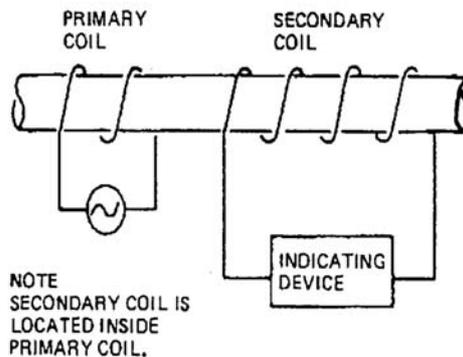


FIG. 3.3. Double-coil absolute arrangement.

In the single coil absolute arrangement, it will test only the area under coil and does not compare itself with a reference standard (external reference). As was observed in Fig. 3.3 for double coils, the secondary coil has the indicating device connected across the coil and is not connected to an AC source. Normally the secondary coil is located inside the primary coil and the two coils are referred to as a double coil.

When double coils are used the primary coil generates or induces eddy currents into the article. The eddy currents in turn, generate a magnetic field that reacts against the field of the primary coil and also induces a current into the secondary coil. Changes in eddy current flow are reflected as changes in the current induced in the secondary coil. Thus the indicating device presents the change in eddy current flow. The double coil absolute arrangement is also known by names such as, driver pickup probe, driver driven probe, pitch catch probe and, more commonly, a reflection probe.

Differential eddy current measure

Differential eddy current probes consist of a pair of coils connected in opposition so that a net measured impedance or induced voltage is cancelled out when both coils experience identical conditions. The coils can sense only changes in the material under test, therefore differential eddy current probes are used to react to changes in test materials while cancelling out noise and any unwanted signals that affect both coils. FIG. 3.4 shows a typical single coil self comparison differential arrangement and FIG. 3.5 shows a typical single coil external reference differential arrangement. FIG. 3.6 shows a typical double coil self comparison differential arrangement and FIG. 3.7 shows a typical double coil external reference differential arrangement.

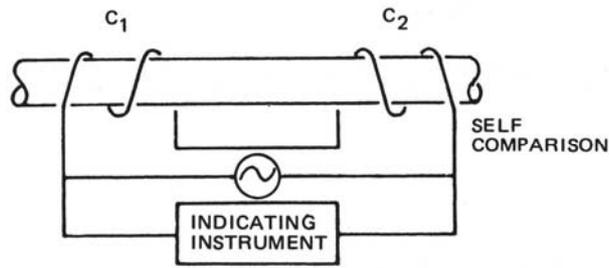


FIG. 3.4. Single coil self comparison differential arrangement.

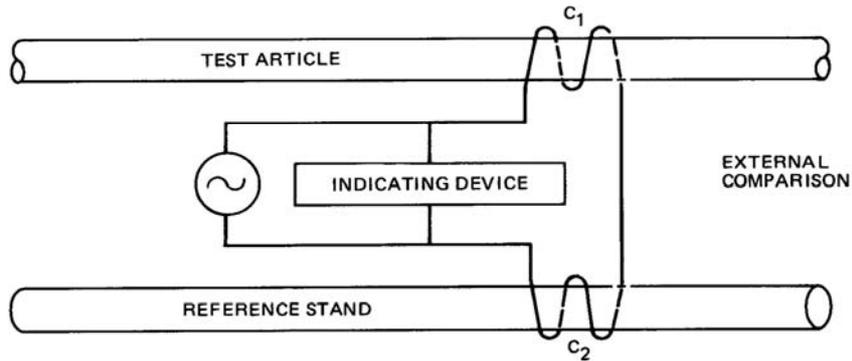


FIG. 3.5. Single coil external comparison differential arrangement.

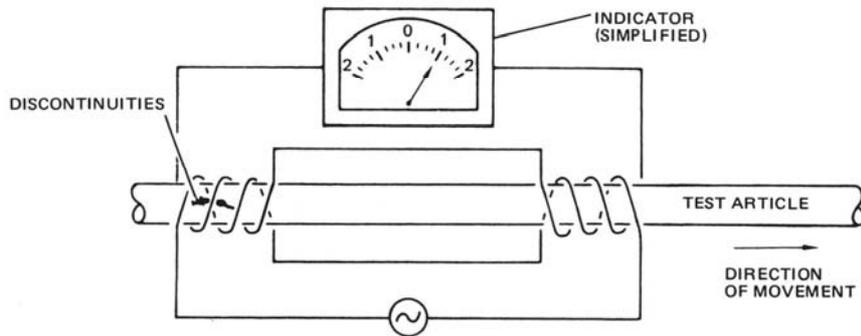


FIG. 3.6. Double coil self comparison differential arrangement.

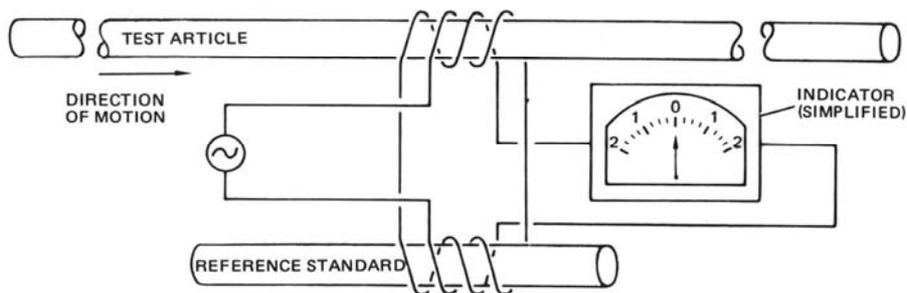


FIG. 3.7. Double coil external comparison differential arrangement.

Comparison between absolute and differential probes

| Absolute probes | Differential probes |
|---|---|
| 1. Sensitive to both sudden and gradual changes in properties and dimensions. | 1. Not sensitive to gradual changes in properties of dimensions (may not sense long gradual flaws). |
| 2. Combined signals are usually easy to interpret. | 2. Signals could be difficult to interpret. |
| 3. Show total length of flaws. | 3. Detect only ends of long flaws. |
| 4. Sensitive to drift from temperature changes. | 4. Not Sensitive to drift from temperature changes |
| 5. Sensitive to probe wobble. | 5. Less Sensitive to probe wobble |

3.1.3 Types of probe

The eddy current probes can have a variety of forms. The choice of the type depends upon the test situation. Following are the three major types of probe mainly used in eddy current testing:

- (a) Internal (bobbin type) probe.
- (b) Encircling probe.
- (c) Surface probe.

Internal probe

Internal probes consist of circular coils used to test the interior of tubes or circular holes. FIG. 3.8 illustrates a type of coil which can be inserted into a tube to inspect discontinuities on the inner circumference of the tube. As with the encircling coil, the internal coil induces currents that encircle the entire circumference of the tube so that the entire section surrounding the coil is inspected.

As the currents induced in the material are strongest near the coil, the internal coil is more sensitive to defects lying on or near the inner surface of the tube.

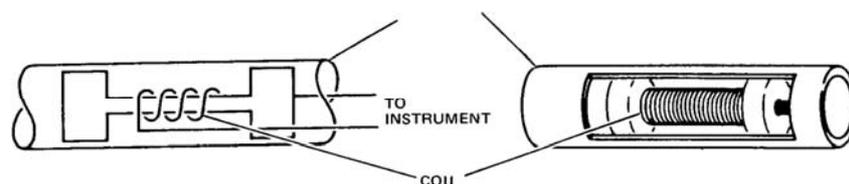


FIG. 3.8. Internal coil.

Encircling probes

Encircling probes are similar in structure to internal probes except for the fact that the test material is passed inside the coils. They are primarily used to inspect the outside surface of round materials such as tubes and rods. FIG 3.9. shows an encircling coil. The magnetic field

induces eddy currents in the bar that encircle the entire circumference of the tube or rod so that the entire section under the coil is inspected at any one instance.

The width of the coil is a function of the application. Wide coils cover large areas, so they respond mostly to bulk effects, e.g. conductivity, whereas narrow coils sense small areas and so are more responsive to small changes such as those produced by discontinuities. The magnetic field of the coil extends slightly beyond the ends of the coil.

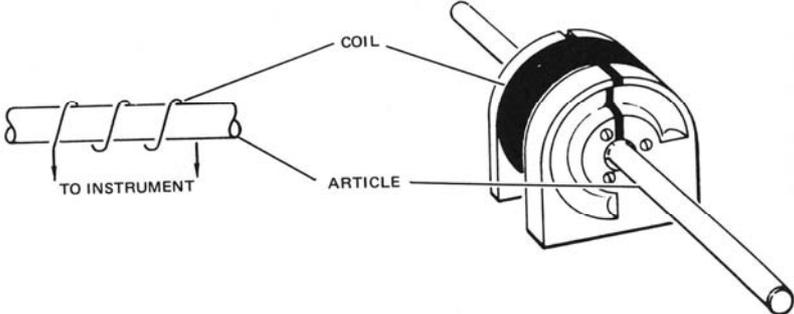


FIG. 3.9. Encircling coil.

Surface probes

Surface probes are one of the most widely used eddy current probes for inspecting surfaces, flat or contoured for defects or material properties. Defects can either be surface or sub-surface. These are also called probe coils. FIG. 3.10 shows a typical surface probe. The surface probe may be hand held or mounted in automated scanning equipment. The coil mounted in the end of the probe is provided with a protective coating of epoxy to serve as a wear surface. The magnetic field produced by a coil is approximately of the size of the coil. Other variations of surface probe designs are pancake probe, flat probe, horse shoe or gap probe, spring loaded probe spinning probe and pencil probe.

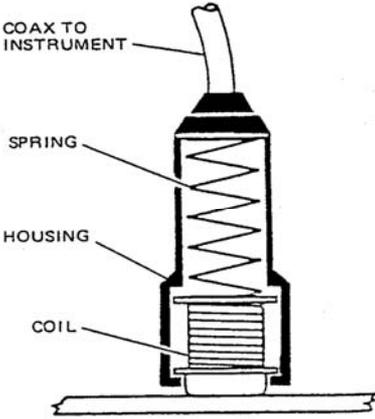


FIG. 3.10. A typical surface probe.

3.2. Eddy current distribution relative to coil position

3.2.1 Field Generated by Non-load Inductor Coil

In the case of a long straight conductor carrying current, the lines of magnetic force (or flux) exist which are closed circular paths concentric with the axis of the conductor.

The relative permeability of air and non-magnetic materials for all practical purposes is considered to be 1. In case of ferromagnetic materials the relative permeability is not constant but is a function of flux density. However, for eddy current probe energized by low levels of magnetization, the permeability can be considered reasonably constant. Now when the straight wire is wound into a coil (many loops of wire), the lines of the force encircling the wire form a magnetic field inside and outside the loop as illustrated in FIG. 3.11.

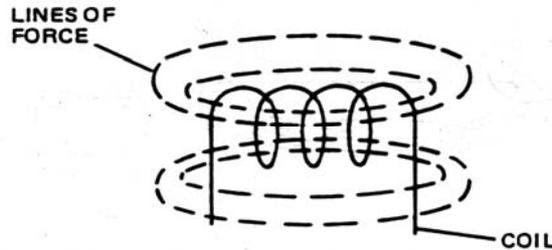


FIG.3.11. Magnetic field of a coil.

The field thus created is similar to the field of a bar magnet. The strength of this field is dependent upon two factors: the number of turns in the coil and the magnitude of the current. The field strength H_z along the axis of a current carrying coil of radius r meters at a point z meters from the center, and having N turns, is given by:

$$H_z = \frac{NI r^2}{2\sqrt{(r^2 + z^2)^3}} \quad (3.3)$$

where

- H_z = field strength
- r = coil radii
- N = number of turns
- I = current
- z = distance from centre

3.2.1 Eddy current path in a part according to its position relative to inductor coil

Eddy currents are closed loops of induced currents circulating in a plane perpendicular to the direction of the magnetic flux. Their normal direction of travel is parallel to coil's winding and parallel to the surface. Eddy current flow is limited to the area of the inducing magnetic field. For detection of flaws it is essential that the eddy current flow be perpendicular to the crack to obtain maximum response. If the eddy currents flow is parallel to the defect there will be no disruption of current and hence no change in coil's impedance. FIG. 3.12.a illustrates the sensitivity of a surface probe to discontinuities relative to their position in the test piece.

A surface probe such as pancake type will have poor sensitivity to laminations, bonding of coatings and those discontinuities lying parallel to the surface of the test sample.

For defects lying parallel to coil's winding a horseshoe (U- shaped) probe with wide gap may have reasonable sensitivity. A gap probe uses ferromagnetic material to shape the magnetic field. The field is confined by the core causing eddy currents to flow in circular loops perpendicular to the flux lines.

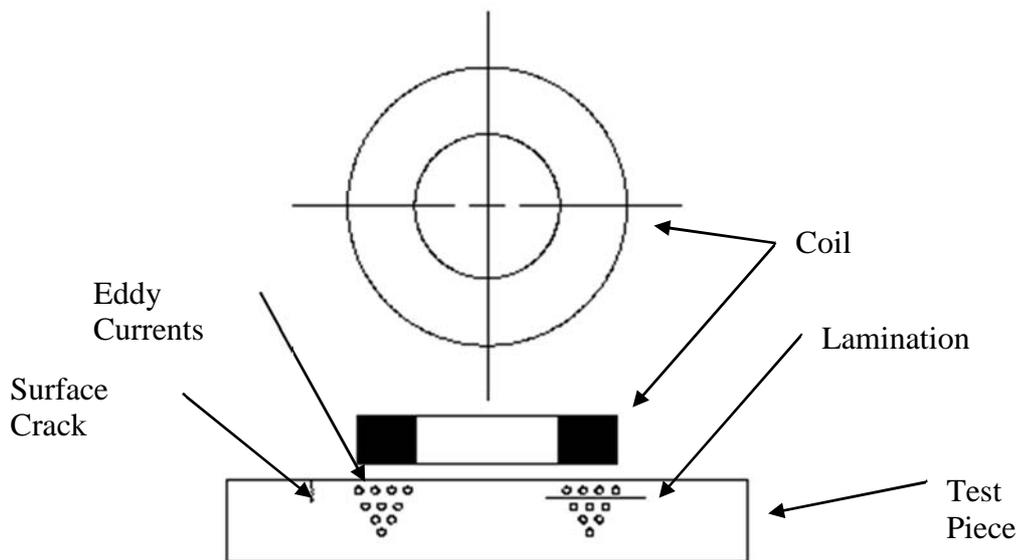


FIG. 3.12.a Directional properties of a surface probe.

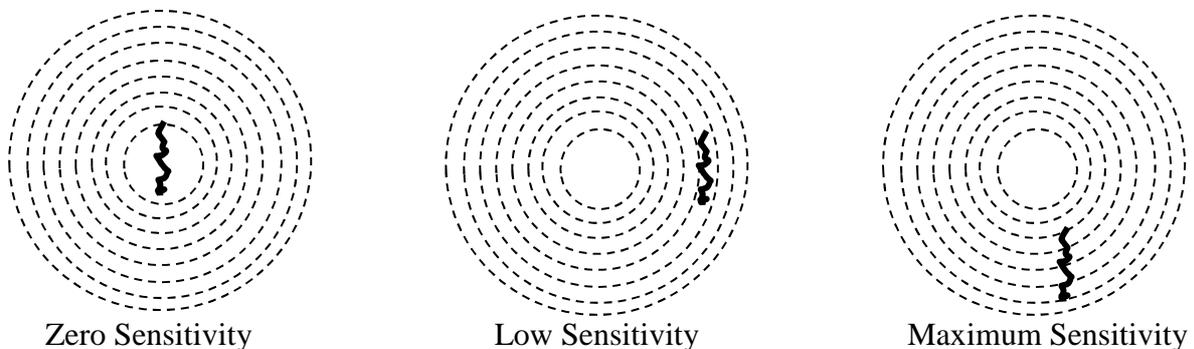


FIG. 3.12.b Directional properties of a surface probe for a given crack size.

3.2.2 Distance influence on coupling in various shapes

Many practical eddy current test systems are arranged with some spacing between the coil and the test material so that test objects can be handled and moved within the coil fields. The effects of such spacing on reactance and the induced eddy currents are however significant and should be taken into account when designing the probes. For surface coils or feed through coils the effect of spacing affects in a way on the coupling between the coil's field and material under test.

When an eddy current coil is lifted away from the surface of nonmagnetic conducting material by some distance, a portion of the magnetic flux created by the test coil current fails to reach the test material. If the coil is lifted so far above the material surface that none of its magnetic flux lines reaches the test material, the coil exhibits its empty coil inductive reactance. This is the highest value attainable during tests of nonmagnetic materials. If the coil then approaches the surface of the test material, more of its magnetic flux lines intercept the test material inducing eddy currents that oppose a change in the coil's magnetic field. As the eddy current reaction field strength increases, the total magnetic flux linkage with the exciting coil is reduced.

As the eddy current reaction field increases with close proximity of the coil to the test material surface, the coil inductance and inductive reactance are accordingly reduced. The limit of this reduction is attained when the face of the coil assembly is placed in firm contact with the test material surface.

The eddy current test sensitivity to material properties is greatest when the eddy current resistance losses are maximized. Maximum probe sensitivity is attained when the coil is in direct contact with the flat surface of a nonmagnetic test material. Increase in lift-off always reduces the sensitivity of eddy current tests.

3.2.3 *Focusing method*

Shielding of eddy currents is required for focusing purpose i.e. larger part of the available flux may be concentrated below the probe. Use of shielded eddy current probes may also be necessary to prevent the field generated by the probe from interacting with certain objects in the vicinity of the probe. The primary concern is the interaction with conducting and magnetic bodies that are not part of test but lie in close proximity and may produce false indications or mask the signal from discontinuities in the vicinity. Testing for discontinuities near edges (such as testing fastener holes) is an example. Shielding of eddy current probes can be done by three ways:

- (a) Magnetic shielding.
- (b) Active shielding.
- (c) Eddy current shielding.

Magnetic shielding is achieved by creating a low reluctance path for field lines within the area required and away from unwanted region. A very simple shielded probe could be built by covering the coil (with or without a ferrite core) using a sleeve of high permeability, low conductivity material such as ferrite. In active shielding the generation of an active field is employed by means of a coil or system of coils to cancel part of the original field in specific area. Eddy current shielding employs the skin effect to prevent the magnetic field from extending to its normal limit. In this case, shielding is achieved through attenuation rather than changing the magnetic path.

3.3. Reaction of different types of probes according to coil layout

3.3.1 *Reaction to small defects*

The eddy current flow is limited to the area of the inducing magnetic field which is a function of coil geometry and design (the use of shielding and cores has a significant effect on resultant magnitude of the eddy current field). Defect sensitivity is proportional to the magnitude of the field in a surface probe, and to a gap width in a horse shoe probe. As a general rule the field diameter should be equal to or less than the expected defect length. The effect of probe diameter and defect length is shown in FIG. 3.13. and FIG. 3.14. In the curve we can see that when defect length equals probe diameter, the signal amplitude ranges from one-third to two-third amplitude for an infinitely long crack.

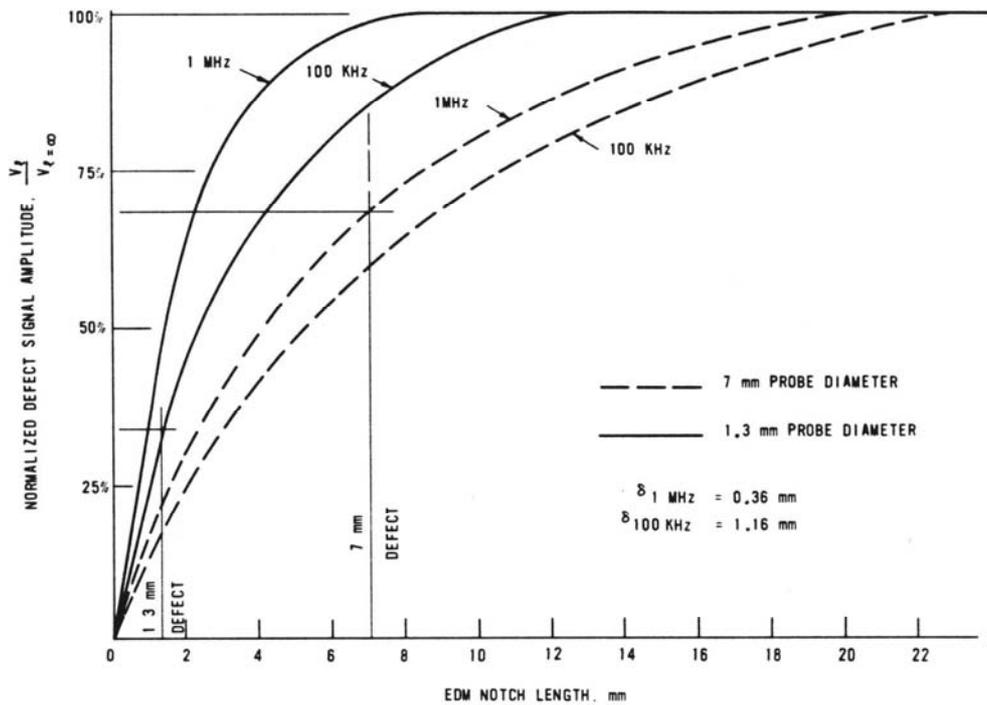


FIG. 3.13. Effect of defect length.



Small Eddy Current Field
Results in High Sensitivity

Larger Eddy Current Field
Results in Lower Sensitivity

FIG. 3.14. Effect of defect length.

3.3.2 Reaction to long defects

The magnitude of the indication caused by a discontinuity is primarily dependent on amount of current disrupted by the discontinuity. Depth, width and length of the discontinuity determine the change in indication. In case of absolute coil arrangements (single coil or double), the system responds to both sudden and gradual changes in properties and dimensions. The total length of the defect is indicated.

In case of differential coil arrangement, so long as there is no difference under the coils there is no indication in the indicating system, but when a discontinuity is located under either one of the coils, an imbalance occurs which is indicated by the instrument.

3.3.3 Reaction to continuous defects

In the case of an absolute coil a continuous defect will produce a continuous indication. In the case of differential coils, there will be no indication of the defect if the defect is continuous from one end to the other end in a test sample.

3.4. Technology and practical characteristics of probes

3.4.1 Design technology

Eddy current probes are based on relatively simple principles and consist of one or more coils in a given configuration. Practical eddy current transducers may range from tiny coils less than 2.5 mm (0.1 in) to over 300 mm (12 in) in diameter, may be long or short, and may have square, round or elliptical shape in cross section, with magnetic or nonmagnetic cores and/or shields. The basic design tools for these variations remain the same and are based on the following principal parameters:

- (a) Coil inductance
- (b) Coil resistance
- (c) Field distribution in space
- (d) Coil response to relevant material property changes
- (e) Lift-off characteristics; and
- (f) Response to a notch, drilled hole or other simulated discontinuity.

In addition, the design may be influenced by other constraints either intrinsic to the testing environment (special shapes or sizes) or required by the testing technique (source strength, impedance matching, etc.) and these complicate the process. Some of the parameters are:

- (a) Source specifications (strength, frequency and the configuration).
- (b) Minimum/maximum required or allowed field.
- (c) Impedance required from the probe.
- (d) Special shapes and dimensions of the coil and field pattern.

Some of these requirements may in fact be contradictory. The design should therefore be flexible and based on some sort of iterative or adjustable process.

3.4.2 Manufacturing technology

Eddy current probes are designed and manufactured accordingly to have highest sensitivity and resolution to the discontinuities.

Dimensional factors and electrical parameters are considered at the time of designing for a consequent manufacturing of a particular probe. The copper insulated wire is wound over the bobbin or former of desired size and shape. Each of the factors recognized as dimensional factors such as spacing between the test coil and the material, the depth of penetration of the eddy current produced by the coil, and the coil's size and shape, affect the eddy currents induced into the material and therefore affect the readings obtained during the test. Lift-off and fill factor are two dimensional aspects to be kept in mind at the time of manufacturing the probes.

There is a need of keeping spacing between the probe and material fixed to obtain consistent results. Furthermore lift-off effect is so pronounced that small variations in spacing can mask

many indications. For ensuring a constant pressure being applied at all times to prevent separation (lift-off) of the coil, the coil may be mounted in a spring loaded housing. A surface probe may be hand held or mounted in automated scanning equipment.

If the eddy current test requires large probe lift-off (as with orbiting coil systems that provide adequate clearance for moving test materials), it may be necessary to use a larger diameter coil winding than would be used during contact tests. The large exciting coil can project a reasonably strong field to the test material and ensure adequate signal levels. However, the area of the test material inspected by large coils, at any instant, is increased in proportion to the coil diameter. This will reduce test sensitivity to small discontinuities such as cracks with lengths only a fraction of the coil diameter. However, to detect discontinuities or property variations in the test material, it is essential to provide adequate field strengths to induce eddy currents with detectable reaction effects. This may be done by increasing the driving power to the coil. This can be achieved by increasing either current or number of turns of the coil.

3.4.3 Electrical parameters

The main purpose of eddy current probe is to induce eddy currents into the test object and receive back the change in their value due to variations in the material's properties (presence of discontinuities, conductivity variations and dimensional variations, etc.). The probe receives an alternating current excitation of known frequency and constant amplitude from the equipment and this helps in generating a magnetic field of desired strength for subsequent induction of eddy currents into the material. The parameters such as value of inductance of coil, selection of frequency, mode of operation (absolute or differential) and type of probe (single coil or double coil) all are important considerations related to probes. Similarly, there has to be a consideration regarding the spread of field as it is related in a way to the sensitivity of the inspection.

3.4.4 Maintenance

The probe is an essential and vital component of any eddy current testing system and as such should be properly cared and handled to avoid any possible damage to it during the use. Knowledge of design parameters such as wearing material used, temperature desired, working atmosphere situation and stability (mechanical stress etc.) should be well borne in mind for a better use and maintenance of the probe in an order. Wear can normally be reduced by selection of wear resistant plastic compounds such as Teflon tape. Where severe wear is expected probe holders are designed to provide constant lift off.

Temperature stability may be accomplished by using coil holder material with poor heat transfer characteristics instead of metal. Most commercially available copper wire may be used for temperatures up to 150 °C to 200 °C. For higher temperatures silicon insulation may have to be used for coils wound of silver or aluminium. Materials must be chemically compatible with the test object. Mechanical and electrical stability of the test coil may be enhanced by an application of epoxy resin between each layer of coil winding.

3.5. Main function and adjustment of the equipment

Generally an eddy current instrument consists of an oscillator, an amplifier, a balance, a filter, a phase rotation, a DC meter or an X-Y monitor. A typical eddy current instrument is shown in FIG. 3.15. Adjustments are made in various components of the equipment to get good inspection results.

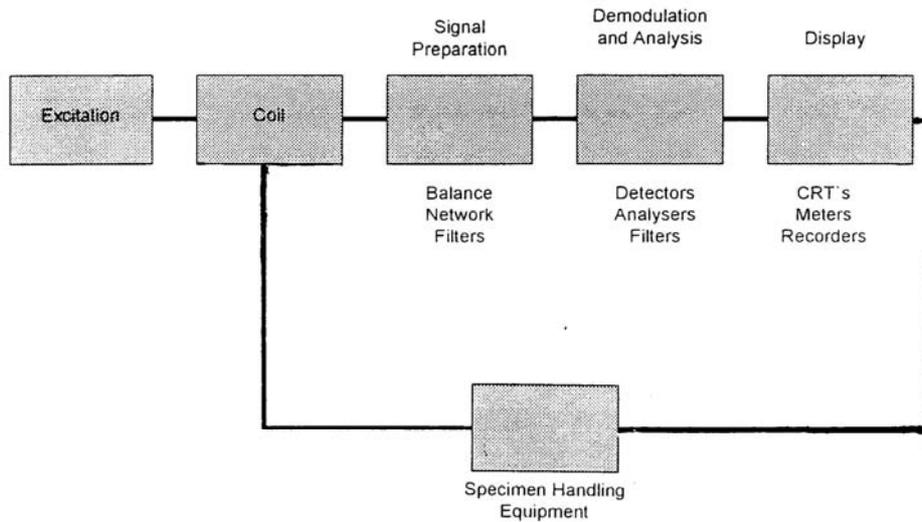


FIG.3. 15. Block diagram of eddy current instrument.

3.5.1 Oscillator

An oscillator or generator generates sinusoidal current at a specified frequency that passes through the test coils. It can be a single frequency sinusoidal wave generator and a power amplifier, a multiple frequency sinusoidal wave generator and power amplifiers or a pulse generator delivering the form of desired pulse wave. It may also be a self excited oscillator whose behaviour is governed by the impedance of the coil. The oscillator must be capable of generating a time varying sinusoidal current at frequencies ranging typically from <1 KHz to 6 MHz.

3.5.2 Energizing Device

Probe coil used as energizing device is an insulated copper wire wound onto a suitable former. It establishes essential coupling between the eddy current equipment and the material under test. The excitation current into the coil is fed by the generator or the oscillator of the unit, which in turn becomes the basis of induction of eddy currents into the specimen. Different types of probes are used in various arrangements for achieving the specific purpose. Most eddy current instruments use AC bridge to sense slight impedance changes between the coils or between a single coil and reference impedance. Most instruments can operate with probe impedances between 10 and 200 Ohms.

3.5.3 Measuring System

Probe impedance (or voltage) changes only slightly as the probe passes a defect, typically less than 1%. This small change is difficult to detect by measuring absolute impedance or voltage. Special instruments have been developed incorporating various methods of detecting and amplifying small impedance changes.

The AC Bridge, once balanced, the presence of a defect in the vicinity of one coil creates a small unbalanced signal which is then amplified. Since the sinusoidal unbalance voltage signal is too difficult and inefficient to analyze, it is converted to a direct current (DC) signal retaining the amplitude and phase characteristics of the AC signal. This is normally achieved by resolving the AC signal into quadrature components and then rectifying them while retaining the appropriate polarity. In general purpose instruments, these signals are normally

displayed on X-Y monitors. Some crack detectors, have a meter to display only the change in voltage amplitude.

3.5.4 Balance

Coil impedance is normally balanced using an AC bridge circuit. A common bridge circuit is shown in general form of FIG. 3.16. The arms of the bridge are being indicated as impedance of unspecified sorts. The detector is represented by a voltmeter. Balance is secured by adjustments of one or more of the bridge arms. Balance is indicated by zero response of the detector which means that points B and C are at the same potential (have the same instantaneous voltage). Current will flow through the detector (voltmeter) if points B and C on the bridge arms are at different voltage levels. Current may flow in either direction depending on whether B or C is at higher potential.

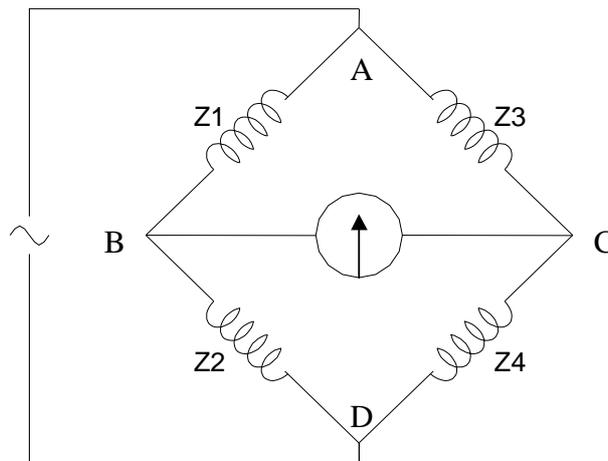


FIG. 3.16. Common bridge circuit.

If the bridge is made of four impedance arms, having inductive and resistive components, the voltage from A-B-D must equal the voltage from A-C-D in both amplitude and phase for the bridge to be balanced. At balance:

$$I_1 Z_1 = I_2 Z_2 \text{ and } I_1 Z_3 = I_2 Z_4$$

From above equations we have:

$$\frac{Z_1}{Z_2} = \frac{Z_3}{Z_4} \tag{3.4}$$

The equation (3.4) states that ratio of impedance of pair of adjacent arms must equal the ratio of impedance of the other pair of adjacent arms for bridge balance.

In a typical bridge circuit in eddy current instruments as shown in FIG. 3.17., the probe coils are placed in parallel to the variable resistors. The balancing is achieved by varying these resistors until null or balance condition is achieved.

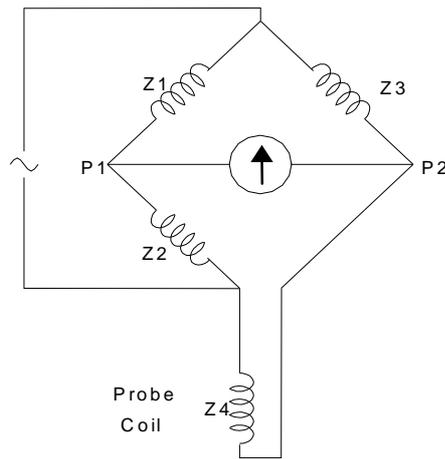


FIG. 3.17. Common Testing Arrangement

3.5.5 Amplifier and Filter

Electronic signal amplifiers in eddy current test equipment vary greatly in their design requirements, depending on where they are in the signal chain. They must accommodate frequencies which range from carrier frequencies as high as the MegaHertz range to anomaly modulation signals that can go down to DC. The dynamic range of signals to be amplified may vary from microVolts at the probe to tens of Volts for display.

Amplification of the signal developed across the bridge therefore requires the use of a differential amplifier. Such an amplifier produces an output proportional to the difference between the signals at its input terminals. It is also possible to use an isolation element such as a transformer to convert the differential signal to a single ground-referenced signal and then an ordinary single-ended amplifier can be used. The output of the first differential amplifier can be taken as single ended and subsequent amplifying stages are usually single ended.

In a general purpose instrument, the bridge output signal amplitude is controlled by the GAIN control. In some instruments it is labelled as SENSITIVITY. It controls amplifier of the bridge output signal. Pre-amplification is a commonly used technique to increase inspection sensitivity by providing increased probe drive voltage.

There are many situations that require the use of a filter network to modify a time-varying voltage or current. Filters are used to eliminate all time variations of a voltage, to select only a narrow band of sinusoidal frequencies from a time-varying voltage, or to select all frequencies above or below some given value. A simple case is that of obtaining a steady voltage from a rectified AC voltage. A filter circuit is used with a rectifier to smooth out the time variations of voltage to whatever extent is required in the application.

3.5.6 Demodulation

After the transducer signal is amplified to a suitable level it must be processed to extract the modulation impressed on it by the discontinuities of the test part. This requires demodulation by a detector circuit. The simplest type is an amplitude or envelope detector consisting of a diode and low pass filter or sometimes a peak detector. Such a detector gives an output proportional to the signal amplitude but independent of its phase angle.

A phase sensitive detector is used to recover the information contained in the electrical phase angle of the signal. Detector design and the selection of amplification before and after detection is influenced by several design considerations. Among them are the requirements for linearity, transient or overdrive response, noise level, and output signal drive.

3.5.7 Display

When an eddy current test indication is small, displays more than a simple meter may be required. An X-Y screen presentation permits a detailed examination of a test response so that an operation can detect subtle signal indications. Various formats of screen signals are possible with selection depending on the nature and purpose of the test.

Ellipse Display Method (Historical)

In the ellipse display, the amplified AC voltage output from the test coil is applied directly to the display without a detector. The horizontal signal is not a sawtooth sweep waveform but a sinusoidal signal derived from the carrier.

Various test object properties such as variations in dimensions, electrical conductivity (related to alloy), permeability (related to structure in steels), or surface cracks can be determined from the shapes of the screen patterns displayed by ellipse test instruments.

Linear Time Base Display Method (Historical)

The linear time base method uses a linear horizontal sweep that is approximately one cycle of the eddy current frequency in duration. This results in a display that shows a single cycle of the eddy current frequency. The display does not show a demodulated signal but displays the amplified carrier directly. This kind of display is quite similar to the ellipse display. The only difference is that in an ellipse display a sine wave is used for horizontal deflection instead of the saw-tooth waveform.

Impedance Plane Display (Vector Point Method)

If a display of the phase relationships of the transducer voltages is desired, a x-y display gives the most complete and easily comprehended representation of the voltages in a form known variously as an impedance plane, flying dot, vector point, or phase display. In this type of display, the position of the indications on the display screen is made to represent the complex impedance of the probe bridge resolved into real and imaginary axes. The amplitude of the signal is represented by its distance from a balanced point. The electrical phase angle is represented by the geometric angle with respect to the balance point.

An oscillator feeds the probe bridge and the bridge output voltage is combined with a carrier suppression signal. This permits the test operator to move the field of view on the screen to any point on the impedance plane. One control permits movement in the imaginary direction (reactance direction on the impedance plane). The other control permits movement in the real direction (resistance direction on the impedance plane). The result is analogous to moving the field of view of a microscope by operating the mechanical stage that carries the object under inspection. The carrier suppression controls obtain their drive signals from a phase shift network connected to the carrier oscillator. The carrier amplifier increases the balanced signal voltage from the transducer. Its function is analogous to the magnification adjustment of a microscope.

At very high magnifications, only a very small portion of the impedance plane is shown on the screen. The output signal from the amplifier is applied to a pair of phase detectors and then to the horizontal and vertical amplifiers that drive the screen. The phase detector outputs correspond to components of the eddy current test signal that lie in a specific direction on the impedance plane. The phase detectors receive their reference signal from the phase shifters that are variable in phase with respect to the carrier (in the range of 0 to 360 degrees), but that are always 90 degrees apart from each other. The vertical channel then contains signal components in the direction perpendicular (on the impedance plane) to the direction selected for the horizontal channel.

Impedance Plane Basics

Effect of Frequency

In FIG. 3.18 points A, B, C, D and E on the true impedance plane represent increasing coil impedance (X_L) due to increasing frequency (air points). From each of these points the arrow represents the eddy current impedance value, each one increasing in amplitude with frequency. The curve of the loci of these values represents the balance points changing with increasing frequency. As $X_L = 2\pi f l$, the inductive reactance of the coil and the inductive reactance of the eddy currents both increase with frequency. However the increase in frequency raises the inductance of the coil in air (L_o) by a greater amount. By dividing the coils inductive reactance in air by L_o the air point remains at unity and the corresponding increase in the eddy current impedance due to the frequency change causes the point on the diagram to move down the curve relative to the fixed (normalized) air point as shown in the normalized impedance plane diagram on the right (FIG. 3.18b).

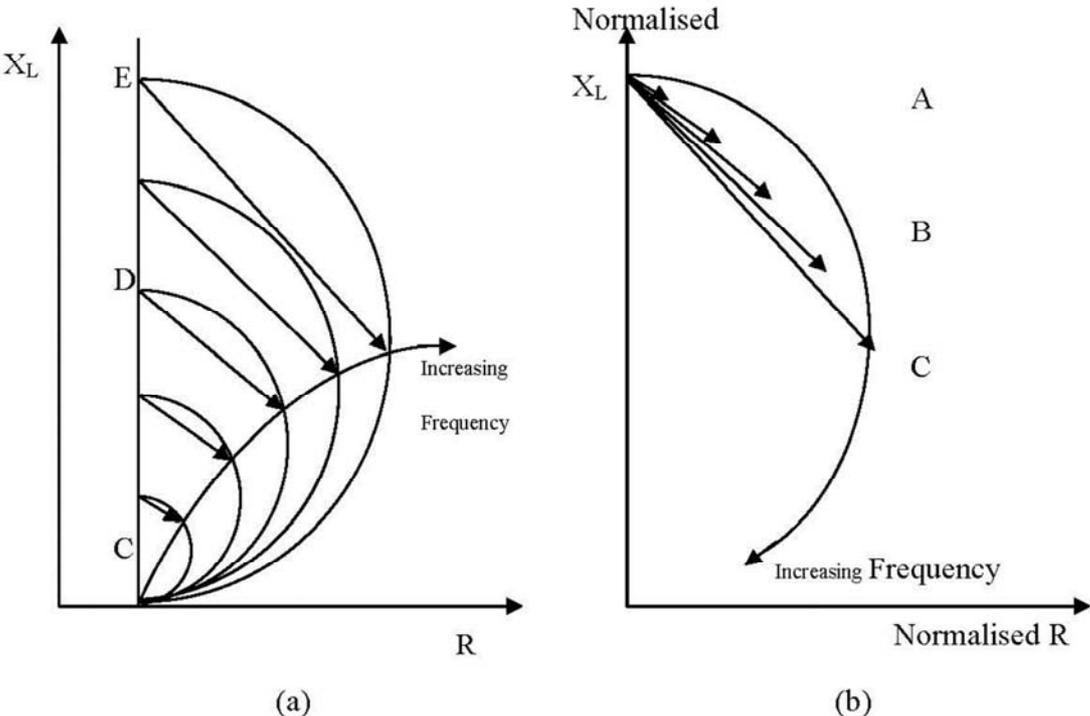


FIG. 3.18. Effect of Frequency on (a) un-normalised curve (b) normalised curve.

Effect of Conductivity

As seen in FIG. 3.18 placing the probe onto a conductive material caused the spot to move due to the effect of the eddy currents on the coil circuit. By placing the probe on a range of materials of differing conductivities a range of different spot positions can be observed. If these points are joined together a curve will be drawn which represents changes in conductivity. The materials having the highest conductivity will have the strongest eddy currents and so the resulting vector will be larger. Thus the material having the higher conductivities will appear at the bottom of the curve (the furthest away from the air point). The resultant impedance curve is shown in FIG. 3.19.

Note 1: All materials appearing on the conductivity curve are non-ferrous and have a relative permeability of 1.

Note 2: The Conductivity curve can be considered to follow the same line as the normalized frequency curve

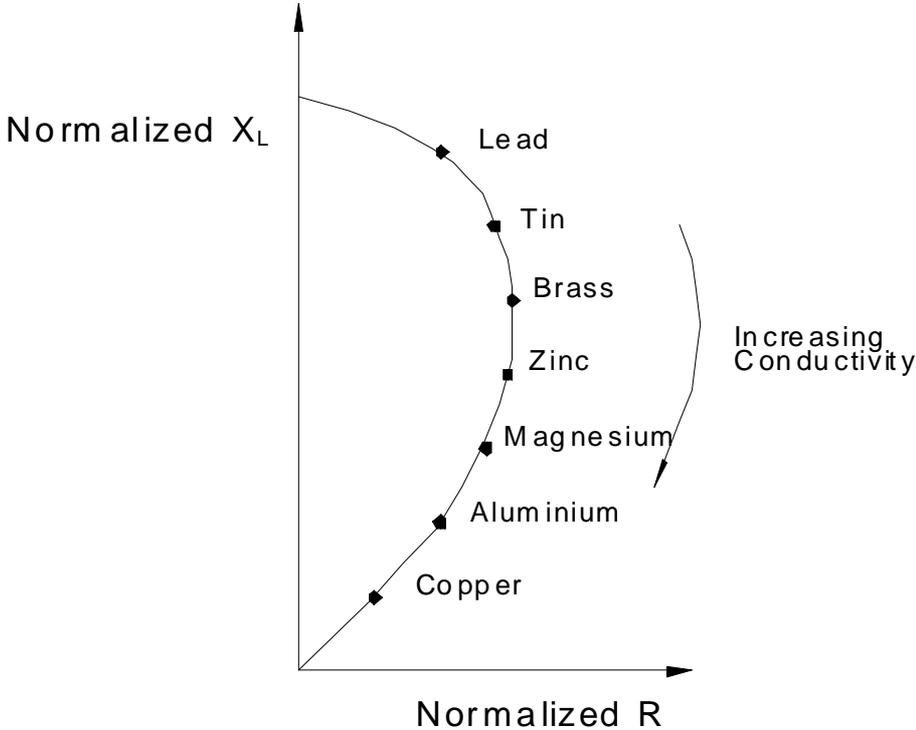


FIG. 3.19. Effect of Conductivity on normalised curve

Effect of Lift Off and probe Handling

With the probe placed on a piece of material (Aluminium) the spot will appear on the conductivity curve at the point for Aluminium (Balance Point). If the probe is then lifted off the material the spot will move along a vector towards the Air Point see FIG. 3.20. This line represents 'Lift Off' and can be used to measure changes in coating thickness.

In a similar way if the probe is angled to the surface the spot will move along the same vector. This effect is known as 'probe Handling'. To ensure the spot is stable whilst scanning it is important to ensure that the probe is held at a constant angle to the material surface whilst scanning. This can sometimes be aided by the use of probe holders and guides.

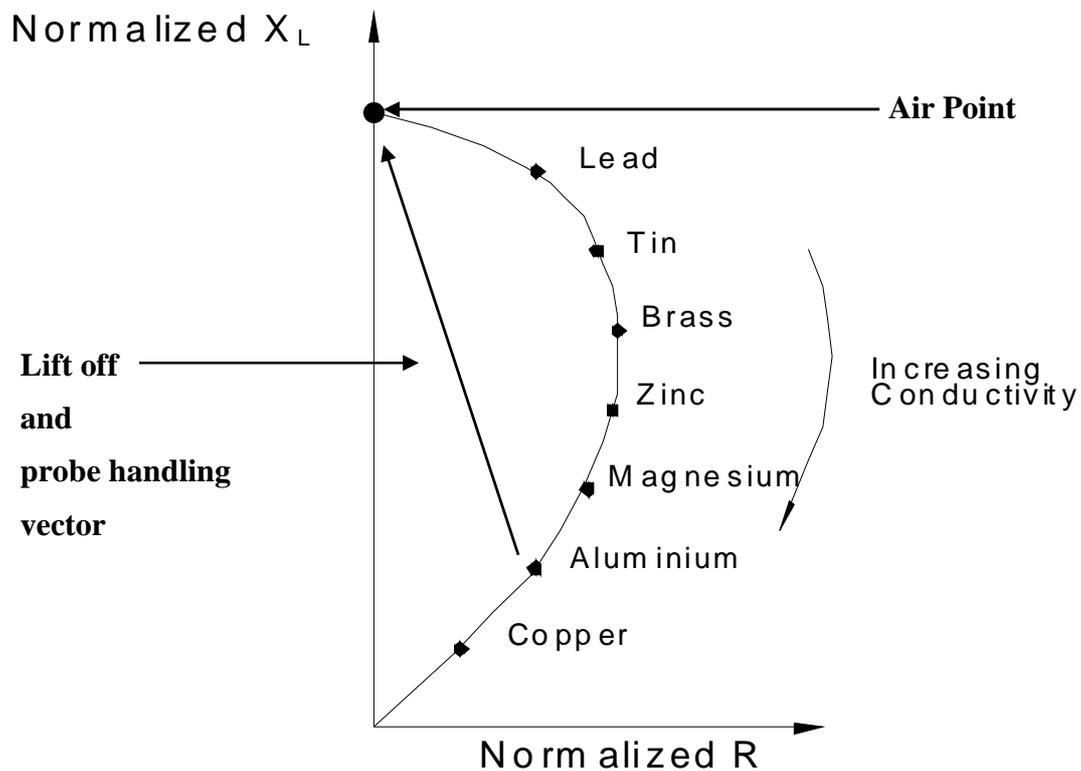


FIG. 3.20. Effect of lift off and probe handling on normalised curve

Effect of Geometry

With the probe on a sample of material and the spot at the balance point the instrument is balanced. If the probe is now scanned towards the edge of the material the spot will move due to the change in geometry of the component. Initially as the probe reaches the edge of the material, the eddy current field is compressed and a smaller and weaker eddy current field is produced. The effect is the same as a reduction in conductivity and the spot moves up the conductivity curve. Additional movement towards the edge causes the probe to move over the edge and an effect similar to lift off causes the spot to curve towards the air point. This compound movement is shown in FIG. 3.21.

Effect of Permeability

An increase in material permeability has a direct influence on the coils magnetic field causing an increase in the coils Inductive Reactance (X_L). The effect of this is that the spot will move vertically up the screen (Increasing Inductive reactance (X_L)). Different positions on the conductivity curve will cause a change in the relationship between the phase angles for Lift Off, Crack and Permeability variations. FIG. 3.22 shows that the angular difference at low frequency is different compared to that at a higher frequency for the same material.

Effect of Discontinuities

The presence of a discontinuity will result in an interruption of the eddy currents, effectively reducing the conductivity locally. Dependant on discontinuity depth and width the indication produced will be a composite signal with a phase angle greater than the lift off vector (FIG. 3.23).

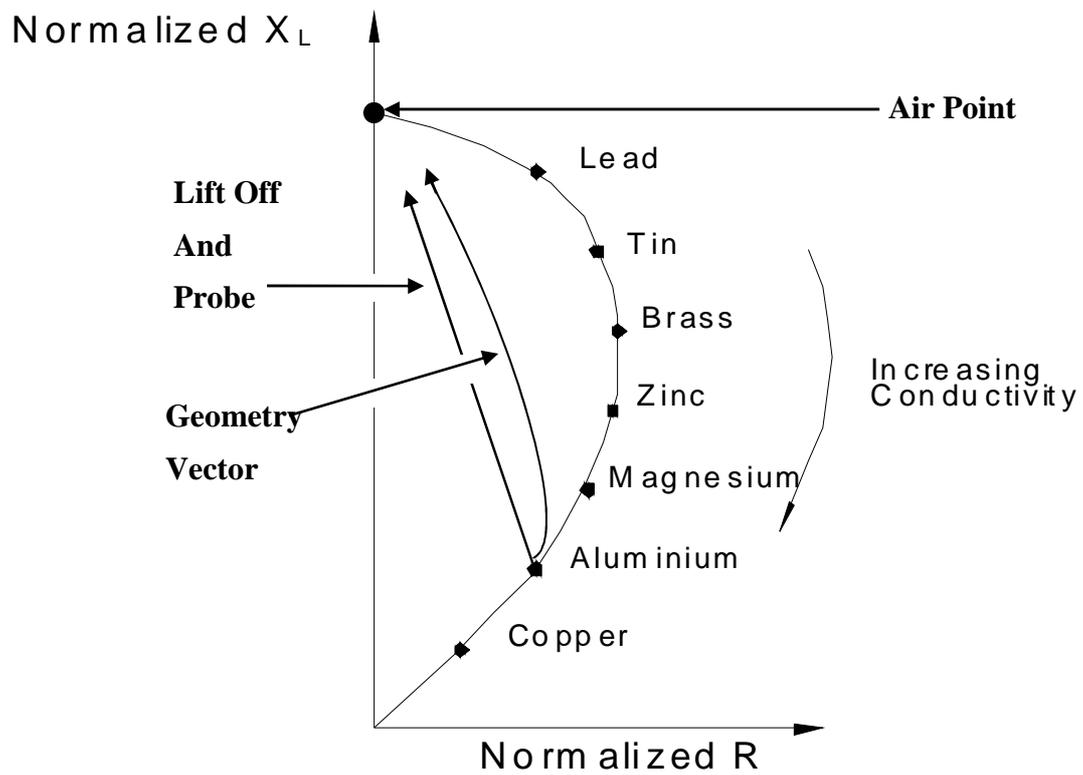


FIG. 3.21. Effect of geometry on normalised curve.

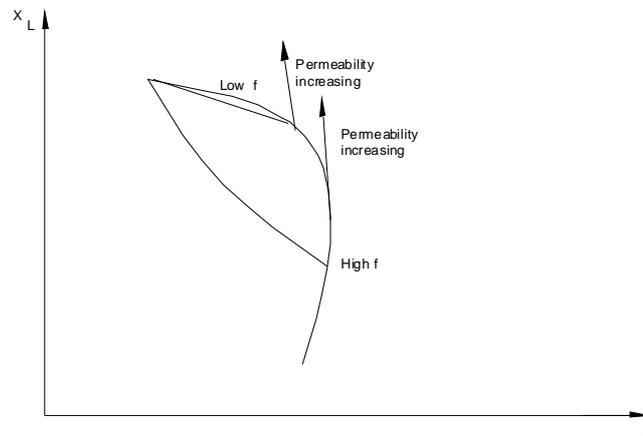


FIG. 3.22. Effect of permeability on normalised curve.

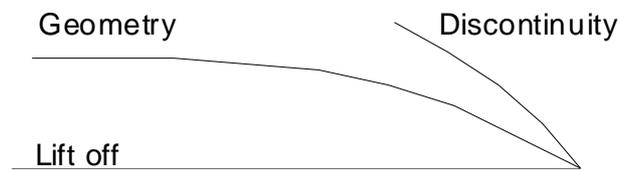


FIG. 3.23. Effect of discontinuity on normalised curve. Note: Lift off signal set to horizontal, as in typical inspection.

3.5.8 Phase Rotation

In an instrument having a phase display, suppression of an undesired signal is most easily done by rotating the display until the dot motion resulting from the undesired condition lies on either the horizontal or vertical axis. This means that the undesired condition will then be present in only one phase channel of the instrument and absent or minimized in the other.

The application of differential gain on the axis allows for amplification of signals of interest and suppression of noise.

It is often convenient to rotate undesired effects into the horizontal direction when making a test. Other angles of display rotation might be selected to separate two or more desired effects into separate quadrants of the display for convenience in signal gating.

3.5.9 Output Filter

In an eddy current test instrument, it is necessary to separate test signals from noise to ensure maximum signal detectability in the output. This separation is done using various types of filters. Typical sources of unwanted noise signals can be classified as follows:

- (a) External, stray magnetic and electric fields.
- (b) Mechanical vibrations of the test material or of the test coils.
- (d) Variations in test material properties that are of no interest during the specific test; and
- (e) Electrical noise generated within the eddy current test instrument.

3.6. Different types of eddy current equipment

3.6.1 Monoparameter, Monochannel and Specialized Equipment

In eddy current testing method, the equipment designed for a particular purpose or application sense in a way a change in the test coil impedance which can be caused by various parameters. Among factors related to material properties are conductivity, dimension and the permeability. Dimensional factors that affect eddy current testing are thickness of the material and presence of discontinuities. Similarly permeability is a factor of concern for ferromagnetic materials under test. Geometrical factors of coils such as the geometric relationship between the coil and the suspected discontinuities, the effect of changes in lift off or fill factor and depth of penetration, also affect eddy current testing.

There is thus a strong need of knowing precisely which factor has caused the change in impedance among various parameters of concern. Eddy current equipment classified as monoparameter utilizes certain circuitry and principles by which they indicate exclusively the measurement of variable of interest. Few of such instruments are described in brief.

Crack Detectors

The crack detectors are used to inspect for surface defects. In a typical crack detector, as shown in FIG. 3.24, an oscillator supplies an AC to an AC bridge, containing an eddy current probe coil as one arm of the bridge. A capacitor is connected in parallel with the coil so that L-C inductance-capacitance) circuit is near resonance.

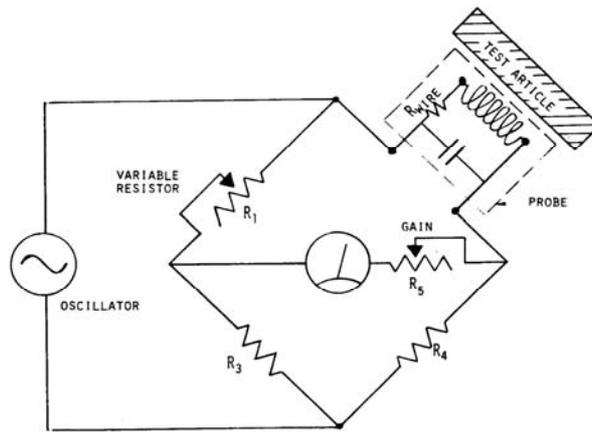


FIG. 3.24. Simplified circuit of a crack detector.

When the coil is placed on the test sample, the bridge is unbalanced and the pointer swings off the scale. The bridge can be balanced by adjusting R_1 . Since the meter works at resonant frequency, the output voltage is maximum for a given change in coil impedance.

Crack detectors have a meter output and three basic controls namely balance, lift-off and sensitivity. Balancing control is performed by adjusting the potentiometer on the adjacent bridge arm, until the bridge output is zero or nearly so. 'GAIN' control (sensitivity) adjustment occurs at the bridge output. The signal is then rectified and displayed on the meter. 'LIFT OFF' control adjusts the test frequency (by less than 25%) to operate slightly off resonance. The test frequency is chosen to compensate for probe wobble (lift off), not to change the skin depth or phase lag. The meter output is a complex function of signal amplitude, and cannot be used to reliably measure depth or to distinguish between real and false indications such as ferromagnetic inclusions.

Conductivity Testers

In this instance a conductivity tester is defined as a simple instrument designed only to check the conductivity of various types of materials and their alloys. The instrument scale may be (and often is) direct reading in% IACS. Most instruments are equipped with calibration knobs so that the high and low meter readings may be adjusted to agree with the high and low conductivity standards supplied with the equipment. These instruments are most often used in the sorting of material but may be used to determine the thickness of conductive coatings. They are of fixed frequency and do not give any indication of the voltage current phase relationship.

In using the conductivity tester the operator must be continuously aware of the factors that affect conductivity (thickness of materials, presence of discontinuity, edge effect, lift off and the effect of heat treatment) before reaching any final conclusions. Material sorting or conductivity instruments have a pre-calibrated meter output and a unique way of compensating for lift off. They incorporate AC bridges and normally have two coils (one as a reference). Lift off compensation is normally preset.

Resistance and Reactance Measuring Testers (Impedance Measurements Circuits)

The equipment designed is capable of measuring any variable when used with the impedance plane diagram. Proper test frequency for the proposed test is selected first. The type of material involved and variable to be measured and suppressed, determine the optimum

frequency. In selecting the frequency to be used for a particular test, it is necessary to obtain reference standards and conduct tests at various frequencies and then select frequency that gives the best results. Once the frequency has been selected, the impedance plane curves are plotted. To plot conductivity locus or curve, samples of different materials are needed. For each material a point on conductivity curve is obtained as follows:

- (a) The probe is placed on a sample and alternately adjustment of the resistance and reactance controls is made until null (minimum) reading is obtained. Use of scale control is made to keep the readings on scale at all times. Repetition of the above procedure at higher sensitivity settings is made until an absolute null point is obtained. The resistance and reactance values are noted on the control and this point on the graph paper is plotted.
- (b) The above procedure is repeated for each material sample. Now if variable lift-off is to be suppressed, lift-off is varied by placing varying thickness of paper between the material and the probe. For each setting we have thus the values of resistance and reactance and their plot gives the lift off curve. For conductivity measurement it is necessary to conduct the operation at a point where the conductivity curve and lift off curve meet at greatest angles.

3.6.2 Multiparameter and Multichannel Equipment

Based on single frequency phase discrimination, it becomes increasingly difficult to detect much smaller size tubing discontinuities, especially in the immediate vicinity of signal interfering artefacts such as tube support and tube sheets. Depending on a given operating frequency and severity of the discontinuity, the signal from such intersection may or may not be identified and certainly could not be characterized reliably. This condition is caused by the vectorial summation of several signals combined simultaneously to form a distorted signal. The equipment employing the multifrequency and multiparameter analysis techniques help in minimizing the effects of undesirable variables for a better and reliable inspection of tubes. Various multifrequency eddy current testing instruments have been built with two to four frequencies for special applications, especially tube inspection.

All such instruments consist of (1) a detection system giving a real component x and an imaginary component y for each frequency; and (2) the analysis system which is their primary feature.

Multifrequency Test Equipment

A multifrequency test instrument is generally a combination of two or more single frequency instruments.

Various components of a two frequency instrument are listed below:

- (a) An oscillator, which generates the sinusoidal voltages required for eddy current generation and demodulation.
- (b) A power amplifier, frequently followed by an impedance matching transformer.
- (c) A bridge containing the transducer.
- (d) A balancing system.
- (e) A variable gain signal amplifier.
- (f) A demodulator, which extracts the signal resistive and reactive components.
- (g) A 0-360 degree phase rotation system which outputs the signals used for analysis (X_1 and Y_1 for channel frequency f_1 and X_2 and Y_2 for channel frequency f_2)

The special feature of this system is that the two channels use only one transducer to induce eddy currents and to receive data from the test object.

There are two basic types of multifrequency systems. They are separated here according to whether multifrequency power is supplied to the probe simultaneously or sequentially for each instrument, the way in which power is supplied to the probe, the way in which the received signals are separated and the type of demodulation, are all important considerations.

3.7. Auxiliary devices

3.7.1 *Auxiliary Devices for Signal Acquisition*

The phase display on a screen shows the maximum information about an eddy current signal. Besides the displays made on the screen, there are other devices instituted to acquire eddy current signal for interpretation and evaluation of indications. Some of such auxiliary devices are discussed in brief as under.

Analogue Meter Displays

In some cases where the test procedure is well established or when it is only necessary to display the magnitude of the response from the condition of interest, it may be sufficient to use a simple and inexpensive output device such as an analogue panel meter. A meter may be used to display a phase detected signal or an amplitude detected signal. The pointer of a typical analogue meter will move from zero to full scale in approximately 0.5 seconds. This rise time is equivalent to a signal bandwidth of approximately 0.6 Hz. An analogue meter is useful only in test where the scan is made at slow rate.

Digital Alphanumeric Displays

When the signal being displayed can be related to a numerical quantity such as conductivity or probe lift-off instead of just a relative reading such as a crack response, it may be desirable to use a digital display that has more potential accuracy and resolution than an analogue meter. A digital meter contains an analogue-to-digital converter (to change the input voltage to a number) and a digital readout to display this number.

Digital displays that are suitable for instrument usage are available in both segment and dot matrixes form. The major display technologies are light emitting diodes (LED), liquid crystal displays (LCD), vacuum fluorescent (low voltage CRT with phosphor-coated display segments), electroluminescent (high voltage electrically excited phosphor), and gas plasma (high voltage, neon gas, glow discharge).

Of particular significance in alphanumeric displays of eddy current test indications is the possibility of displaying words as well as numbers to identify

- (a) The nature of the discontinuity or property variation in the test material
- (b) The severity of the variation from standard reference conditions
- (c) The locations of the discontinuity within the test material.

Displays could also include identification of the condition detected, its location on the test object, or its level of severity. Words such as crack seam, wall thinning and other descriptors could be displayed. Other words such as OD (outside diameter), ID (inside diameter), surface or subsurface, longitudinal or transverse, or numerical identifications of locations on the test

object could also be displayed. Degree of variation or dimensions of discontinuities (such as lengths of cracks or seams) could be displayed numerically or in coded ranges such as numbers from 1 to 10. Combinations of such descriptors could provide the test operator with much more useful information than a simple warning light. Such a display could allow a quantitative interpretation as well as a qualitative evaluation of signals compared to simple digital displays where the operator must evaluate the test object's condition for each significant indication. The interpretive test readout could be transmitted to a remote computer or to a printer, providing an inspection log interpretable by management, inspection supervisors, outside inspectors, or other agencies.

Digital Bar Graph Indicator Displays

Flashing numeric values are hard to interpret when the signals are changing rapidly. If it is desirable to show a signal trend it is possible to use a bar graph display. This can take the form of a special display consisting of a large number of segments activated in sequence to simulate the mechanical motion of an analogue pointer. A standard numeric or alphanumeric display can also be used this way at a lower resolution by activating individual segments or dots in sequence. There are two common modes for this kind of display. The first is the bar graph mode in which all segments up to the value being displayed are turned on. Alternately only the segment representing the display value can be activated. This kind of display is commonly available in liquid crystal display (LCD), light emitting diode (LED) and plasma display form.

3.7.2 Auxiliary Devices For Noise Reduction

Driving Mechanism

Driving mechanisms are often employed to increase the speed and reliability of inspection. Common applications are tube inspection, bolt hole inspection and area scanning. Constant scan speeds in conjunction with appropriate filter selection is required to minimize noise and maximize reliability and sensitivity.

Saturating Unit

Eddy current testing of welded tubes made of austenitic steel is always accompanied with the need for magnetization of the part during eddy current probe scanning. Small localized permeabilities in the absence of auxiliary magnetization lead to a noise level which prevents high sensitivity during testing. Fluctuations can result from the heating and cooling process caused during welding, or they may be present in the sheet material used to make the tubes.

The construction of a device based on a coil carriage with a permanent magnet before and after the test coil, helps to induce sufficient magnetization to reduce the noise level. Similarly, pole shoes for concentrating and guiding the field into the tube surface are used at times for highly magnetic materials.

Demagnetizers

Eddy current tests respond specifically only to the electrical conductivity, magnetic permeability, geometric properties of test objects and to the spatial relationship of the test probes to the surfaces of test objects. Many other material properties can be related to these primary eddy current test measurements, but proof of such correlation must be obtained for each case. In particular, many different metallurgical factors (such as alloy structure, heat

treatment, hot or cold working and other processing steps) may influence the material conductivity or permeability. Residual magnetism within steels and ferromagnetic materials can affect the eddy current test indications. Sometimes it is extremely difficult to separate the desired from undesired facts (spurious indications).

Use of Demagnetizers is thus at or some times necessary to get rid of existing magnetism within the test piece for carrying out a successful eddy current inspection.

3.7.3 Equipment for Signal Storage

Strip Chart Recorders

The eddy current signal is recorded on the X-Y or two-channel recorder. The important characteristic of these recording instruments is frequency response or speed response, which limits inspection speeds. Strip chart recorders, record X and Y signal components against time, which is used in locating defects and determining their length.

Magnetic Tape Recorders

Magnetic tape recorders allow storage of eddy current signals on magnetic tape for subsequent retrieval. They have a frequency response proportional to recording speed.

Digital Memories

Digital numeric displays are suitable if the voltage has meaning as a numeric value. This kind of display is ideal when used in the measurement of electrical conductivity or coating thickness.

Digital Trace Acquisition and Storage

Some impedance plane instrumentation allow for the acquisition of impedance plane data for saving, exporting and overlay comparisons of the screen display.

3.7.4 System for automatic processing of signals

An eddy current testing system can range from a simple to a more sophisticated depending upon its scope of application. The basic chain of circuitry in most of the automatic electromagnetic test systems performs six internal functions. These functions are:

- (a) Excitation.
- (b) Modulation.
- (c) Signal preparation.
- (d) Signal demodulation and analysis.
- (e) Signal display.
- (f) Test object handling.

The integration of such chain of functions and similar additional advanced instruments all keep in one way or the other to process the signals automatically.

Excitation

The oscillator provides test coil assembly excitation signals. It can be a single frequency sinusoidal generator and power amplifier, a multiple sinusoidal waveform generator and

power amplifiers, or a pulse generator delivering the desired pulse waveform. It may also be a self excited oscillator whose behaviour is governed by the impedance of the test coil.

Variations in the coil impedance caused by variations of test object conditions produce changes in the performance of the oscillator. These may be changes in frequency or amplitude of oscillation or both. Their effects are demodulated and fed to the display or readout circuits. Some degree of discrimination against an unwanted test variable can be obtained by adjusting the oscillator circuits.

Modulation

The signal modulation occurs in the electromagnetic field of the test coil or coils. The test coils are labelled 'test coil assemblies' because of the variety of configurations in which this part of the equipment can appear. The test coil assembly equipment is often closely related mechanically to the test object handling equipment to be discussed later.

Signal Preparation

The signal preparation portion of the test equipment consists of circuits which prepare the signal output of the test coil assemblies for the following demodulation and analysis functions. These circuits consist of AC compensating or balance networks which subtract a steady AC component from the input signal. Filters are often included to improve signal to noise ratio or to separate different carrier signals in the case of multi frequency tests. Signal shaping circuits are sometimes included. An important part of this portion of the equipment is the amplifiers which amplify the signal to the desired level for the demodulation and analysis process.

Demodulation and Analysis

The demodulation and analysis section of the equipment comprises of detectors and analyzers. The detectors range from simple amplitude detectors to amplitude phase detectors or more highly specialized circuits. For the coherent detectors, a reference signal is provided from the generator section. Sampling circuits and discriminators may be included in the analysis section. Various types of summing and comparison circuits may also be used here. Filters may also be included for filtering the demodulated signal to accentuate or discriminate against certain characteristics of the signal.

Signal Display

The signal display or indication portion of the equipment is the real link between the test equipment and its intended purpose. The signal may be displayed by the use of meters, recorders, screens, visual or audible alarm signals, relay outputs, and automatic signalling or reject equipment.

Test Object Handling

Depending upon the nature of the tests, test object handling equipment needs may be minimal or may require very complicated mechanical design. In some tests the test coil assemblies are designed so that they are positioned and held manually. In this case the demands for test object handling equipment are minimum, and all that is required is a place to set or hold the test object while it is being inspected. In many tests mechanical feeders feed the test object or objects past the test coil assemblies so that tests can be made rapidly under uniform

conditions. Such equipment requires coordination in the design of the test coil and the feed equipment. Such tests are amenable to complete automatic operation.

The above discussion has been made for a signal chain linked in various interconnecting circuitry incorporated for automatic processing and acquisition of signal in most of the instruments.

4. TESTING PROCEDURES

4.1. Influence of defect position and orientation

Eddy currents induced by a changing magnetic field concentrate near the surface adjacent to the excitation coil. The depth of penetration decreases with test frequency and is a function of electrical conductivity and magnetic permeability of the specimen. This phenomenon is known as the skin effect and is analogous to the situation in terrestrial heat conduction where daily surface temperature fluctuations are not appreciable below the earth's surface. Skin effect arises as follows: the eddy currents flowing in the test object at any depth produce magnetic fields which oppose the primary field, thus reducing net magnetic flux and causing a decrease in current flow as depth increases. Alternatively, eddy currents near the surface can be viewed as shielding the coil's magnetic field thereby weakening the magnetic field at greater depths and reducing induced currents.

4.1.1 Eddy current path

Eddy currents are closed loops in induced current circulating in planes perpendicular to the magnetic flux. They normally travel parallel to the coil's winding and parallel to the surface. Eddy current flow is limited to the area of the inducing magnetic field. Test frequency determines depth of penetration into the specimen; as frequency is increased, penetration decreases and eddy current distribution becomes denser near the specimen's surface. Test frequency also affects the sensitivity to changes in material properties and defects. FIG. 4.1 shows the relationship of eddy current distribution with depth into the specimen and increasing phase lag with depth. Both the eddy currents and magnetic flux get weaker with depth because of 'skin effect'. In addition to this attenuation, eddy currents lag in phase with depth. Eddy currents' phase lag is the key parameter that makes eddy current testing a useful testing method.

4.1.2 Penetration depth & phase lag

Eddy current density decreases exponentially with depth. The depth at which eddy current density has decreased to 1/e or 36.8% of the surface density is called the standard depth of penetration. The word 'standard' denotes plane wave electromagnetic field excitation within the test sample. The standard depth of penetration is given by:

$$\delta = 50\sqrt{\rho / f\mu_r} , \text{ mm} \quad (4.1a)$$

or

$$\delta = 660 / (\sigma \mu f)^{0.5} \text{ mm} \quad (4.1b)$$

where

f = frequency

σ = IACS

μ_r = relative permeability

ρ = resistivity $\mu\Omega\text{-cm}$

The skin depth equation is strictly true only for infinitely thick material and planar magnetic fields. Using the standard depth δ , calculated from the above equation makes it a material/test parameter rather than a true measure of penetration.

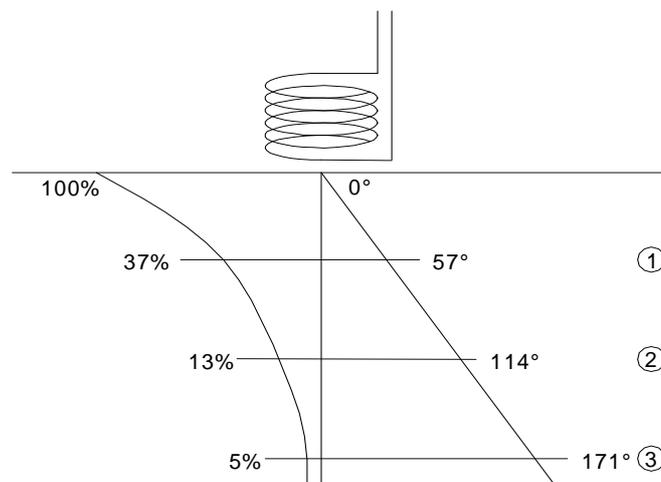


FIG. 4.1. Eddy current distribution with depth in a thick plate and resultant phase lag.

Sensitivity to defects depends on eddy current density at defect location. Although eddy currents penetrate deeper than one standard depth of penetration they decrease rapidly with depth. At two standard depths of penetration (2δ), eddy current density has decreased to $(1/e)^2$ or 13.5% of the surface density. At three depths (3δ), the eddy current density is down to only 5% of the surface density. However, one should keep in mind these values only apply to thick sample (thickness, $t > 5\rho$) and planar magnetic excitation fields. Planar field conditions require large diameter probes (diameter $> 10t$) in plate testing or long coils (length $> 5t$) in tube testing. Real test coils will rarely meet these requirements since they would possess low defect sensitivity. For thin plate or tube samples, current density drops off less than calculated from Eq. (4.1). For solid cylinders the overriding factor is a decrease to zero at the centre resulting from geometry effects.

One should also note that the magnetic flux is attenuated across the sample, but not completely. Although the currents are restricted to flow within specimen boundaries, the magnetic field extends into the air space beyond. This allows the inspection of multi-layer components separated by an air space.

The sensitivity to a subsurface defect depends on the eddy current density at that depth, it is therefore important to know the effective depth of penetration. The effective depth of penetration is arbitrarily defined as the depth at which eddy current density decreases to 5% of the surface density. For large probes and thick samples, this depth is about three standard depths of penetration. Unfortunately, for most components and practical probe sizes, this depth will be less than 3δ , the eddy currents being attenuated more than predicted by the skin depth equation.

$$\beta = \frac{x}{\delta} \text{ radians} \quad (4.2)$$

where

β = phase lag

X = distance below surface

δ = standard depth of penetration

4.1.3 Zone of probe action

Eddy currents are closed loops of induced current circulating in a plane perpendicular to the direction of magnetic flux. Their normal direction of travel is parallel to the coil winding and parallel to the surface. See FIG. 4.2a and FIG. 4.2b Pancake type surface probes are therefore insensitive to poor bonding of coating and flaws parallel to the surface of sample.

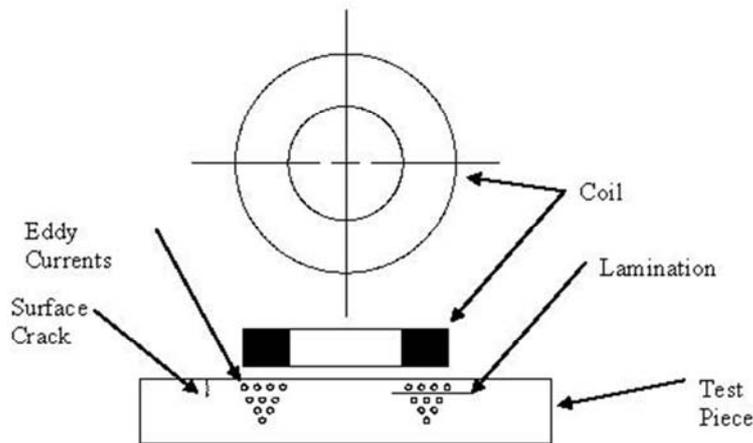


FIG. 4.2.a Directional properties of a surface probe.

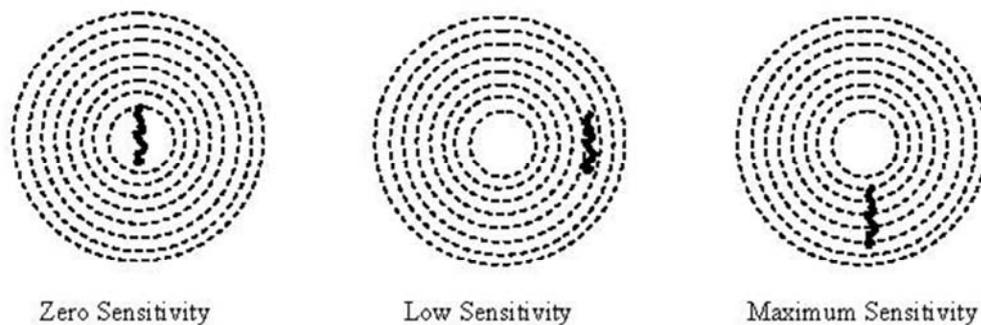


FIG. 4.2.b Directional properties of a surface probe for a given crack size.

When testing for flaws such as cracks, it is essential that the eddy current flow be at a large angle (preferably perpendicular) to the crack to obtain maximum response. If eddy current flow is parallel to the defect there will be little or no disruption of currents and hence no coil impedance change.

When testing for flaws parallel to the surface, such as laminations, a horseshoe shaped probe (a gap probe with a very large gap) may have reasonable sensitivity.

4.2. Influence of material temperature

Temperature is an important test variable, particularly when eddy currents are used to establish a basic conductivity range for an alloy. Consideration must be given to (1) the temperature of the test material, (2) the difference in temperature between the test sample and the reference sample, and (3) type of eddy current instrument being used.

4.2.1 Heating

Higher temperature increases the thermal activity of the atoms in a metal lattice. The thermal activity causes the atoms to vibrate around their normal positions. The thermal vibration of the atoms increases the resistance to electron flow, thereby lowering the conductivity of the metal. Lower temperature reduces thermal oscillation of the atoms resulting in increased electrical conductivity.

The influence of temperature on the resistivity of a metal can be determined from the following equation.

$$R_t = R_0(1 + \alpha T) \quad (4.3)$$

where

R_t = resistivity of the metal at the test temperature,

R_0 = resistivity of the metal at standard temperature

α = resistivity temperature coefficient

T = difference between the standard and test temperature (°C).

From Eq. (4.3) it can be seen that if the temperature is increased, resistivity increases and conductivity decreases from their ambient temperature levels. Conversely, if temperature is decreased the resistivity decreases and conductivity increases.

To convert resistivity values, such as those obtained from Eq. (4.3) to conductivity in terms of % IACS, the conversion formula is,

$$\% IACS = 172.41 / \rho \quad (4.4)$$

where

IACS = international annealed copper standard

ρ = resistivity

4.2.2 Deviations

The conductivity of standards is usually determined at a specific temperature; 20°C is most commonly used. Typical conductivity values are allowable conductivity ranges also established at approximately this temperature. If all instrument calibration and conductivity measurement could be performed at this temperature, errors in conductivity measurement related to temperature variation would not occur and/or temperature compensation would not be required. In field applications, testing temperatures can conceivably be anywhere in the range of -20 to 50°C. Unless precautions are taken in selection of standards, calibration of the instrument and testing, error can be obtained in the measured conductivity values. Two ways in which erroneous readings occur are (1) difference in temperature between standards and test part; and/or (2) difference in temperature at which conductivity of the standard was originally established, and the temperature at which instrument calibration and conductivity measurements are performed.

To prevent errors from differences in temperature between standard and test part, the instrument and standards should be allowed to stabilize at the test part temperature before calibration and conductivity measurements are performed. In no instance should measurements be taken if the part and standard temperatures differ by more than 5 °C. Even though standards and test part are at the same temperature, error in determining conductivity value occurs when the measuring temperature differs from the temperature at which the conductivity of the standards was originally established. The magnitude of the error becomes larger as this difference in temperature increases.

Two other factors also contribute to errors caused by temperature differences: (1) increased difference in conductivity between the upper and lower reference standards; and (2) differences in the temperature coefficient of electrical resistivity between references and the test part. These two sources of error can be reduced by decreasing the range between the conductivity standards and using standards of the same or approximately the same temperature coefficient of electrical resistivity as the test part. Because all aluminum alloys have approximately the same rate of change of electrical resistivity with temperature change, aluminium conductivity standards are preferred for aluminium alloys.

Conductivity measurements should not be performed under conditions where the relative humidity exceeds 85%.

4.2.3 Compensation

The eddy current conductivity should be corrected by using Equations (4.3) and (4.4). In aluminium alloy, for example, a change of approximately 12% IACS for a 55°C change in temperature, using handbook resistivity values of 2.828 micro-ohm centimeters and a temperature coefficient of 0.0039 at 20°C. If the conductivity of commercially pure aluminium is 62% IACS at 20°C, then one would expect a conductivity of 55% IACS at 48°C and a conductivity of 69% IACS at -10 °C.

4.3. Influence of structure and geometry of tested parts (noise)

The most accurate results will be obtained using a high signal to noise ratio. A high signal to noise ratio will allow easy identification of a relevant discontinuity with low electronic background noise.

Background noise can be produced from variables that have no interest to the examiner. This would include material configuration, surface roughness, lift-off, permeability, and conductivity.

Abrupt changes in surface curvature result in changes to eddy current signals as probes traverse them. It causes changes in coupling creating a large lift-off signal and the curvature also changes eddy current flow distribution creating an effective resistance change, yielding a signal at an angle to the lift-off direction. The appearance of this type of signal will not change significantly when rescanned at higher and lower test frequency.

Such signals can be difficult to analyze because they depend on how well the probe follows complicated surface curvatures. Basically the direction of the impedance change obeys the following rules when using surface probes:

- (a) decreasing radius of curvature on an external surface, e.g., ridge, produce change in the direction of increasing resistivity,
- (b) decreasing radius of curvature of an internal surface, e.g., groove, produces a change in the direction of decreasing resistivity.

The most troublesome parameter in eddy current testing is lift-off (probe-to-specimen spacing). A small change in lift-off creates a large output signal.

A particular condition such as ‘wobble’ can be suppressed by making the amplitude of its response at the first frequency equal and its phase 180 ° away from the response at the second frequency and then adding the two signals together. The resulting sum will result in cancellation of the responses and thus a zero signal for that particular condition.

4.3.1 Choice of test frequency

Test frequency is often the only variable over which the inspector has appreciable control. Material properties and geometry are normally fixed and probe choice is often dictated by test material geometry and probe availability. Choice of a suitable test frequency depends on the type of inspection. Testing for diameter variations normally requires maximum response to fill-factor which occurs at high frequencies. Testing for defects requires penetration to possible defect locations; surface defects can be detected at higher frequencies than subsurface defects. Maximum penetration requires a low frequency which still permits clear discrimination between signals from harmless variations in material properties and serious defects. The above factors show choice of test frequency is usually a compromise.

4.3.2 Phase discrimination

In the majority of cases, no detailed knowledge of the discontinuity types, shapes, depths and orientations exists before the start of the eddy current examinations. Consequently, the majority of the data analysis depends on the phase angle analysis to determine discontinuity parameters.

It is important, however, to detect and to identify discontinuity signals and to separate them from non-relevant background signals before any crack depth analysis can be performed. The phase angle discrimination technique is ideally suited for this separation.

The phase angle discrimination technique depends on the proper choice of test frequencies for providing optimum phase angle separation among different variables. For a given test material, phase angle orientations among the variables shift because of changing test frequencies. This capacity to obtain different information at different frequencies is used.

The most common practice involving the phase angle discrimination is to rotate the lift-off/fill-factor variations to horizontal and monitor the remaining variables. Based on this concept of maintaining the lift-off/fill-factor as horizontal, a detailed comparison of phase angle separations among variables can be determined.

It should be emphasized that the selected frequency might not necessarily be the ideal frequency for estimating discontinuity depths. The concept of detection first, followed by discontinuity analysis has been an accepted evaluation method.

4.3.3 Filtering

To accentuate desired frequencies and to eliminate undesired frequencies, electronic filtering is employed. Three types of filters can be used; the high pass, the low pass and the band pass. High pass filtering utilizes a resistance-capacitance circuit, which removes the low frequency components of the eddy current signal from the bridge. This type of filtering can eliminate the effect of gradual variations in conductivity or dimensions on the eddy current inspection response. Low pass filtering employs signal averaging circuits to remove rapid (high frequency) response from electronic noise and from harmonic frequencies related to variations in magnetic permeability. Band pass filters use combinations of both types of circuitry to promote response over a specific range of frequencies and suppress frequencies above and below this range. The effects of each type of filter on the recorded appearance of eddy current signals is illustrated in FIG. 4.3.

Selection of frequencies

For a known discontinuity type, eg: fine cracks, appropriate filters can be calculated by selecting filters either side of the Response Frequency (F_r) refer formula 4.7.

For components with various discontinuities eg: tube inspection, selection of filter frequencies can be optimized by using an appropriate reference sample.

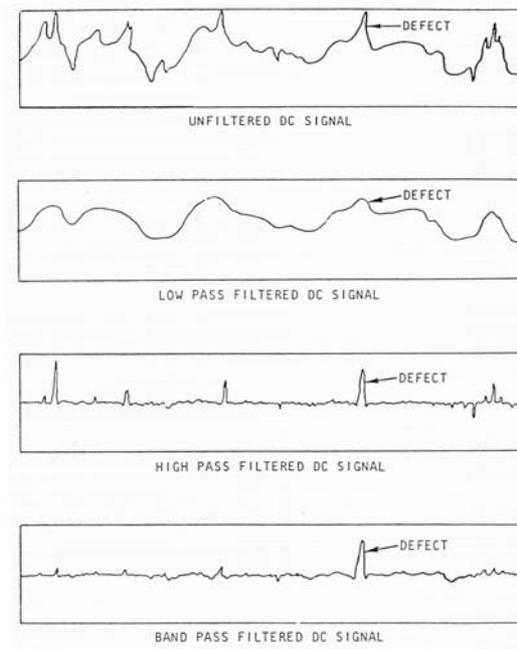


FIG. 4.3. Effects of Filtering.

4.3.4 Magnetic saturation

Eddy current inspection of magnetic materials for defects is difficult or impossible because of random permeability variation. In addition there are skin depth limitations. Without saturation, the initial permeability of steel products can range from 50 to over 500. Since depth of penetration is inversely proportional to the square root of permeability and test frequency, to obtain equal penetration requires a reduction in frequency by the same factor of 50 to over 500. Unfortunately, lowering frequency will move the operating point to where there is poor signal separation between lift-off, permeability and resistivity as well as reduced sensitivity to defects. Therefore magnetic saturation is required to suppress effects of usually harmless permeability variations, which could be mistaken for or obscure, defect signals.

Coupling influence

4.4.1 Vibrations

Vibrations during probe motion can make undesirable signals, or so called 'probe wobble'. The multi-frequency technique can suppress this effect can by making the amplitude of its response at the first frequency equal and its phase 180 degrees away from the response at the second frequency and then adding the two signals together. The resulting sum will result in cancellation of the responses and thus a zero signal for that particular condition.

4.4.2 Lift off

When a surface coil is energized and held in air above a conductor the impedance of the coil has a certain value. As the coil is moved closer to the conductor the initial value will change when the field of the coil begins to intercept the conductor. Because the field of the coil is strongest close to the coil, the impedance value will continue to change until the coil is directly on the conductor. Conversely, once the coil is on the conductor any small variation in the separation of coil and conductor will change the impedance of the coil. The lift off effect is so pronounced that small variations in spacing can mask many indications.

The lift off effect is regularly used to measure the thickness of non conductive coatings.

The angle of orientation (tilt) of the probe will also have a significant impact of coupling efficiency. The use of mechanical guide/holders and spring loaded probes can assist in reducing the effect of lift off.

4.4.3 Centring, fill factor

In an encircling coil, or an internal coil, fill factor is a measure of how well the conductor (test specimen) fits the coil. It is necessary to maintain a constant relationship between the diameter of the coil and the diameter of the conductor. Again, small changes in the diameter of the conductor can cause changes in the impedance of the coil. This can be useful in detecting changes in the diameter of the conductor but it can also mask other indications.

For an external coil:

$$\text{Fill Factor } \eta = (D_1/D_2)^2 \quad (4.5)$$

For an internal coil:

$$\text{Fill Factor } \eta = (D_2/D_1)^2 \quad (4.6)$$

where

η = fill factor

D_1 = part diameter

D_2 = coil diameter

Thus the fill factor must be less than 1 since if $\eta = 1$ the coil is exactly the same size as the material. However, the closer the fill factor is to 1 the more precise the test.

The fill factor can also be expressed as a%. For maximum sensitivity, the fill factor should be as high as possible compatible with easy movement of the probe in the tube. Note that the fill factor can never exceed 1 (100%).

4.4.4 Sensitivity

The distribution of eddy currents on a round bar using an encircling coil is such that the field is maximum at the surface and is zero at the centre of the bar.

The distribution of eddy currents on a flat plate using a surface probe is such that the field is maximum at the surface directly below the coil windings and is zero at the centre of the coil.

4.4.5 Compensation

To optimize probe coupling numerous techniques can be employed, these include;

- (a) The use of mechanical guide/holders and spring loaded probes can assist in reducing the effect of lift off.
- (b) Appropriate probe diameter to maximize fill factor.

4.5. Influence of relative part/probe speed

4.5.1 Instrument frequencies according to speed

Eddy current instruments and recording instrumentation have limited frequency response. This means they require finite time to respond to an input signal. Frequency response, sometimes called speed of response, is defined as the frequency at which the output signal falls to 0.707 (-3 dB) of the maximum input signal.

A test coil with an effective sensing width W , passing over a localized defect of width w at a speed s , will sense the point defect for a duration of w/s seconds. This signal is approximately equal to one wavelength with a frequency.

The Response Frequency (F_r) is the inverse value of the time taken for the probe to cross the fault and can be shown by the formula:

$$F_r = \frac{S}{W + w} \quad (4.7)$$

where

S = speed of probe movement (mm Sec⁻¹)

W = probe width (mm)

w = crack width (mm)

NOTE: For practical purposes crack width can be considered as Zero.

For example, at a probe speed of 0.5 m/s and probe sensing width of 2 mm, $F_r = 250$ hertz. If the instrumentation has a frequency response of 250 hertz, the output signal is reduced to 0.707 the input signal and the X-Y signal is distorted. If the instrumentation frequency response is 500 hertz, the output signal decreases only slightly. For this example, the eddy current instrument should have a frequency response equal to or greater than 500 hertz to obtain undistorted signals. Or inversely, if the instrument frequency response is only 350 hertz, the maximum inspection speed should be reduced to 0.25 m/s.

4.5.2 Frequency response of apparatus according to testing speed

Some standards specify maximum permissible scanning speed. For example, according to the Article I-40 of ASME Article 8 Appendix 1, the maximum scanning speed of eddy current probe can be 0.356 m/s for 100 Hz frequency response system. If an eddy current system with a frequency response of 450 Hz is used, it allows a scanning speed of 1.6 m/s.

4.6. Reference standards used in eddy current testing

Analysis of eddy current signals is for the most part, a comparative technique. Reference standards are necessary for comparing signal amplitude and phase (shape) of unknown defects to known reference defects. Reference signals are also used for standardizing instrument settings, i.e. sensitivity and phase rotation.

4.6.1 Function of reference samples

Existing national specifications and standards only supply broad guidelines in choice of test parameters. They cannot be used to establish reliable eddy current test procedures for most inspection. The effect of the following can be established:

- (a) Varying electrical resistivity
- (b) Varying thickness
- (c) Surface geometry (curvature)
- (d) Defect length for constant depth
- (e) Defect depth for constant length
- (f) Increasing subsurface defect size for constant defect depth
- (g) Increasing distance of subsurface defects from the surface with constant defect size
- (h) Varying thickness of a non-conducting layer (lift-off)
- (i) Varying thickness of conduction layer
- (j) Ferromagnetic inclusions

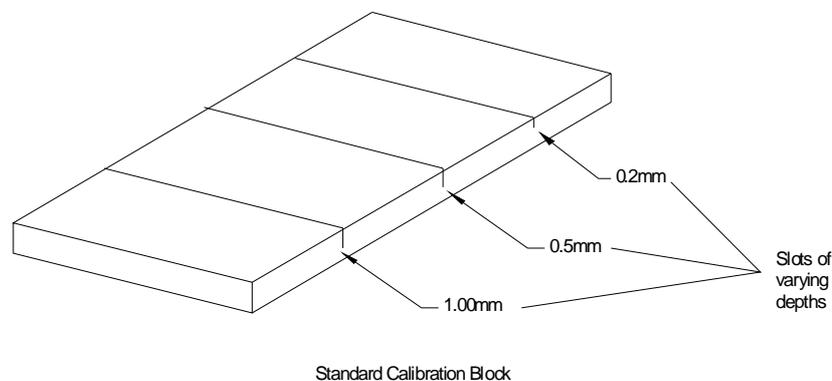


FIG. 4.4. High frequency reference block.

More than one reference plate would be required to cover a complete range of materials.

FIG. 4.5a illustrates eddy current signals obtained with an absolute surface probe from some of the reference sample defects. FIG. 4.5b illustrates signals from the same defects using differential surface probe.

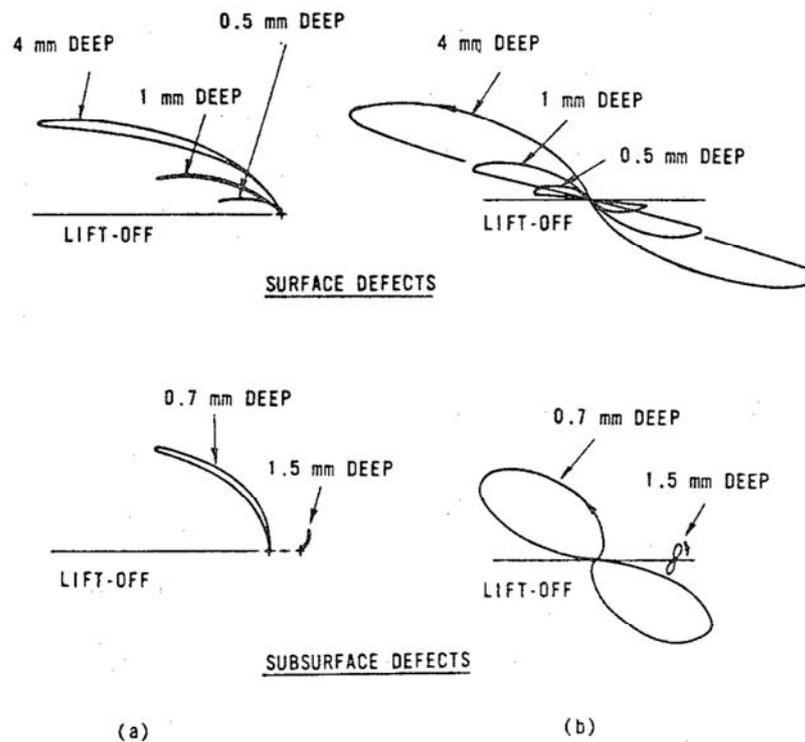


FIG. 4.5. Eddy current signals with (a) absolute and (b) differential surface probes.

4.6.2 Choice of reference sample

The reference sample shall be a part of and shall be processed in the same manner as the product being examined. It shall be of the similar nominal dimensions and the same nominal composition as the product being examined.

The reference sample shall be long enough to simulate the handling of the product being examined through the inspection equipment. The separation between reference discontinuities placed in the same reference sample shall not be less than the length of the sensing unit of the inspection equipment.

4.6.3 Fabrication and reproducibility of various types of reference samples

Most reference standards consist of drilled holes of various diameters and/or various depth from the external surface. Some reference samples have EDM (electric discharge machining) notches in the circumferential and axial directions and on both internal and external surfaces.

4.6. Inspection method

4.7.1 Range of Inspection

Eddy current inspection encompasses a large range of specific inspection techniques, these include but are not limited to:

- a) Surface crack detection in plate like and complex geometry components utilizing surface/pancake coils, generally using high frequency, small diameter probes.
- b) Surface crack detection in fastener holes utilizing manual as well as rotating probes. Using high frequency, small diameter probes.
- c) Subsurface and second layer crack detection in plate like components utilizing surface/pancake coils, generally using low frequency, larger diameter probes.
- d) Conductivity measurement.
- e) Coating thickness measurement.
- f) Material thickness measurement.
- g) Tube and bar inspection utilising encircling, internal or multi coil probe arrangements.

4.7.2 Recording of indications

The recording of indications is dependant on equipment and procedures used. Techniques previously discussed in Section 3.7.3 can be used to record the results of the inspection.

Depending on the inspection procedures used and the qualification level of the inspector, the degree of data analysis and interpretation will differ. For most crack detection inspections a secondary NDT method is commonly employed to confirm results.

4.7.3 Data analysis and interpretation of results

As in any other NDT method, the eddy current method relies on evaluating received eddy current signals containing information about the material characteristics. It is necessary to use applicable reference samples to properly inspect and analyze signals of interest. The reference samples used, therefore, must be made of similar materials with similar electrical and mechanical properties as those materials to be examined. This interpretation of eddy current signals to ascertain the integrity of the test parts, thus, depends largely on the selection and choice of suitable reference samples.

4.8. Preparation of written instructions for level 1

ISO9712 (2005) defines the responsibilities of inspection personnel as follows:

Level 1

An individual certified to level 1 shall have demonstrated competence to carry out NDT according to NDT instructions and under the supervision of level 2 or level 3 personnel.

Within the scope of the competence defined on the certificate, level 1 personnel may be authorized by the employer to perform the following in accordance with NDT instructions:

- (a) set up NDT equipment;
- (b) perform the tests;
- (c) record and classify the results of the tests;
- (d) report the results.

Level 1 certified personnel shall not be responsible for the choice of test method or technique to be used, nor for the assessment of test results.

Level 2

An individual certified to level 2 shall have demonstrated competence to perform non-destructive testing according to established procedures. Within the scope of the competence defined on the certificate, level 2 personnel may be authorized by the employer to

- (a) select the NDT technique for the test method to be used,
- (b) define the limitations of application of the testing method,
- (c) translate NDT codes, standards, specifications and procedures into NDT instructions adapted to the actual working conditions,
- (d) set up and verify equipment settings,
- (e) perform and supervise tests,
- (f) interpret and evaluate results according to applicable codes, standards, specifications or procedures,
- (g) prepare NDT instructions,
- (h) carry out and supervise all tasks at or below level 2,
- (i) provide guidance for personnel at or below level 2, and
- (j) report the results of non-destructive tests.

Therefore all level 1 personnel are required to work according to written instructions prepared by a minimum of a level 2 and authorised by a level 3.

Typical details of written inspection requirements are given in Section 6.3.

5. APPLICATIONS

5.1. Surface testing

5.1.1 Introduction

Eddy current surface testing refers to the testing of surfaces of components of various shapes for surface or subsurface flaws, or material properties.

5.1.2 Probes and their sensitivity

The following outlines the types of probes commonly used in surface testing, their sensitivity to various conditions, and examples of where each type of probe is used. More information on the types of probes used for particular applications, and probes for special applications, is given in the notes on these applications.

The sensitivity of standard surface testing probes

Standard surface testing probes consist of a coil wound on a core of plastic, ferrite, or other material, and are used with the axis of the coil normal to the test surface. FIG 5.1 shows a typical absolute probe and the eddy current field it induces. Differential probes, with two coils, one on each of two adjacent arms of the bridge circuit, and reflection probes, which contain one coil or set of coils which generates the eddy current field (the driver coil(s)), and a second coil or set of coils which detect the response of the test material (the pickup coil(s)), are also sometimes used. The pickup coils in reflection probes can be either absolute or

differential. Reflection probes show a wider frequency range and higher signal to noise ratio than other types of probe.

All of these coils have the magnetic flux essentially normal to the test surface, and so produce eddy currents in circular paths essentially parallel to the coil windings and the test surface.

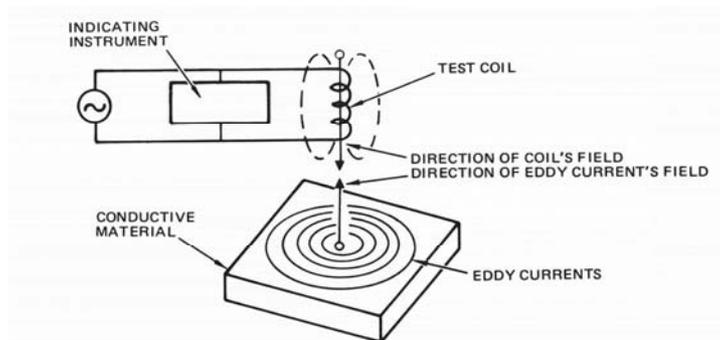


FIG. 5.1. Schematic diagram showing a standard eddy current test coil and the eddy current field induced in the test part. The core is not shown.

The eddy current intensity is maximum immediately below the coil windings, and decreases linearly to zero at the centre of the coil. In addition, except for shielded probes (discussed below), the eddy current field extends laterally for some distance away from the coil, the distance increasing as the coil diameter increases and as the depth of penetration increases. Therefore, large diameter, low frequency coils, which show the greatest depth of penetration, also show the greatest lateral eddy current field.

Flaws can be detected only if they distort the flow of eddy currents. This means that cracks and similar flaws normal to the test surface in any direction can be detected, but flaws parallel to the test surface, like laminations, cannot be detected.

However, if a flaw is shorter than the coil diameter, there is a possibility that it will not be detected because, depending on its location and orientation with respect to the coil, it may not significantly distort the eddy currents (FIG. 5.2). That is flaws can be reliably detected only if their length is approximately equal to or greater than the coil diameter. Because of this, probes for the detection of small surface flaws usually have small diameter coils (approximately 1mm to 2 mm diameter), although if only longer flaws are sought, larger diameter coils can be used.

Although flaws which are the same length as the probe diameter or longer can be reliably detected, provided the scanning index (the distance between successive scans) is small enough, the crack signal amplitude increase with increasing crack length up to a maximum obtained when the crack is long enough to distort the entire surface eddy current field.

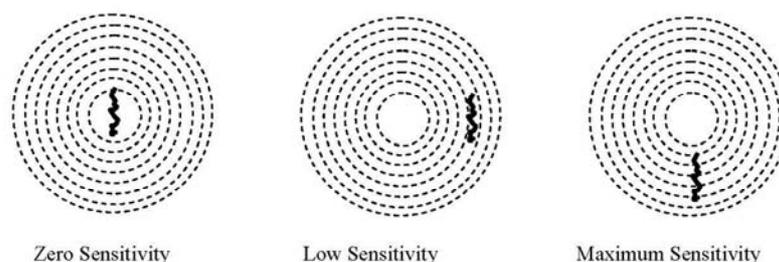


FIG. 5.2 Directional properties of a surface probe for a given crack size

The depth of surface flaws (the distance the flaw extends below the surface) also affects the signal amplitude - the greater the depth the greater the signal amplitude. The depth of surface flaws also affects the signal phase. As the depth of the flaw increases, it distorts eddy currents deeper below the surface. As the depth of the eddy currents below the surface increases, they show a steadily increasing phase lag with respect to the surface eddy currents, the flaw signal shows a corresponding phase rotation clockwise (see FIG. 5.3). This is true even if the flaw extends beyond the effective depth of penetration. In this case, since the eddy currents cannot flow in their normal paths, they are caused to flow below the flaw and show an increasing phase lag. This may not be true for short deep flaws because the eddy currents may be diverted around the ends of the flaw rather than below the flaw.

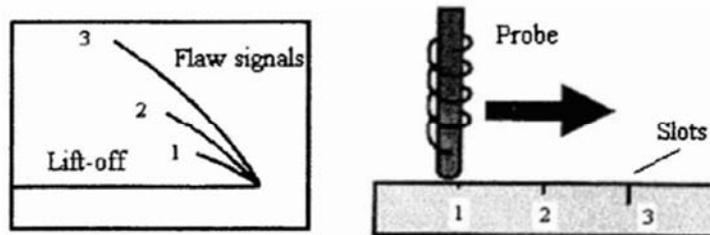


FIG. 5.3. Shows the signals obtained from surface discontinuities of varying depths. As the depth of the discontinuity increases, the signal amplitude increases and the signal phase rotates clockwise.

Increasing lift-off always reduces signal amplitude, although it has no effect on the depth of penetration or the phase of the eddy currents. For this reason, probes should be held so that the coil axis is normal to the test surface. However, despite the reduced sensitivity, it is common practice to apply a small piece of Teflon adhesive tape to the tips of small diameter probes to prevent probe wear.

Types of standard surface testing probes

(a) Pencil probes

Pencil probes are simply small diameter probes with small diameter coils and are the standard probe for the detection of surface flaws because of their sensitivity to small cracks (see FIG. 5.4). Pencil probes are usually high frequency probes for the detection of surface flaws, but low frequency pencil probes are also available, and are used for the detection of subsurface flaws.

Lang type pencil probes are standard pencil probes where the coil is located a few millimeter up from the probe tip, but an elongated ferrite core channels the magnetic field from the coil to the test surface, so reducing lift-off effects (see FIG. 5.5a). This construction means that probe wear will not affect the coil.

(b) Spot probes

Spot probes are probes with a relatively large flat face for testing flat surfaces for flaws or material properties (conductivity or thickness) (see FIG. 5.5b). The coil diameter may be small or large - the size of the probe does not necessarily give a good indication of the coil size.

Spot probes can also have V notches or curved faces for positioning on curved surfaces to get stable signals.

(c) Spring loaded probes

Spot probes are often spring loaded, as shown in FIG. 5.6, to ensure that lift-off is minimized. They are often used for measurement of conductivity or the thickness of non conducting coatings. Pencil probes are rarely spring loaded, but spring loaded probe holders are available for pencil probes from some manufacturers.

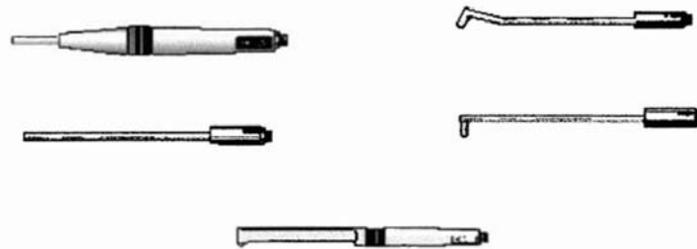


FIG. 5.4. Various types of pencil probe and a knife probe (lowest). The knife probe is equivalent to a pencil probe with a right angle bend (lower right).

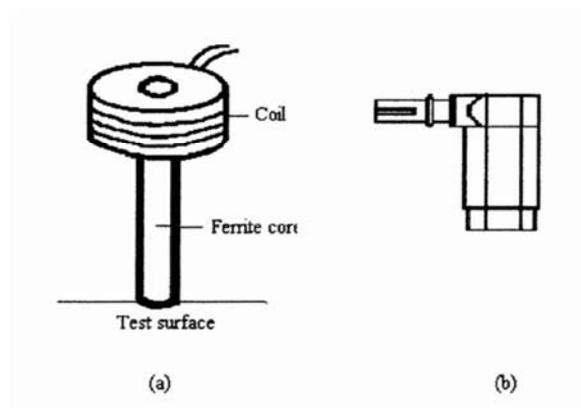


FIG. 5.5. (a) The core and coil of a Lang type pencil probe. (b) A spot probe.

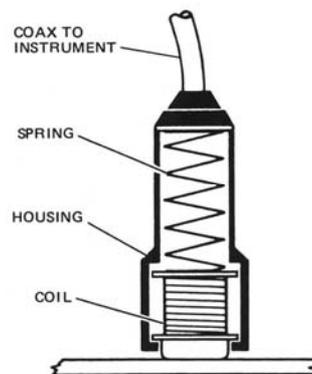


FIG. 5.6. A spring loaded probe.

(d) Shielded probes and ferrite cores

Shielding is often applied to pencil probes, and sometimes to spot probes. The eddy current field of standard unshielded probes extends some distance laterally from the coil. The lateral extent of the field can be found experimentally by locating a probe on a surface then moving it towards an edge. At some distance from the edge, an indication (an edge signal) will be obtained. Edge signals are located in the first quadrant clockwise from the lift-off signal, usually at a greater angle from the lift-off signal than for signals from surface cracks. If the probe is scanned near an edge or a hole, the lateral eddy current field will give an edge signal. Although it is usually evident by its angle that it is an edge signal, a crack signal which may be present simultaneously may not be detected. This is particularly a problem when scanning between two holes or a hole and an edge. Small variations in the distance of the probe from the edge produce a large change in the edge signal, producing a noisy signal, and the possibility of a flaw signal not being observed. Whenever possible the use of a non metallic probe guide should be used to reduce the edge signals while not affecting the crack signal.

Scanning near a hole with a fastener, or near a sharp change in configuration, can give similar problems.

Shielded probes, which usually contain a coil wound on a ferrite core and surrounded by a sleeve ferrite, stainless steel, mu metal or copper (see FIG. 5.7), overcome these problems by restricting the lateral extension of the eddy current field. The use of shielded probes allows scanning close to any of these features without interfering signals. Shielded probes can also be used to measure the length of a surface crack. The probe should be scanned along the crack, monitoring the signal and checking that the probe stays above the crack by moving it slightly laterally to keep the signal at a maximum. As the end of the crack is approached, the signal will decrease in amplitude, and eventually return to the balance position. When the probe is returned to the location where the crack signal just appears, the end of the crack corresponds to the location of the shielding. The other end of the crack can be found similarly.

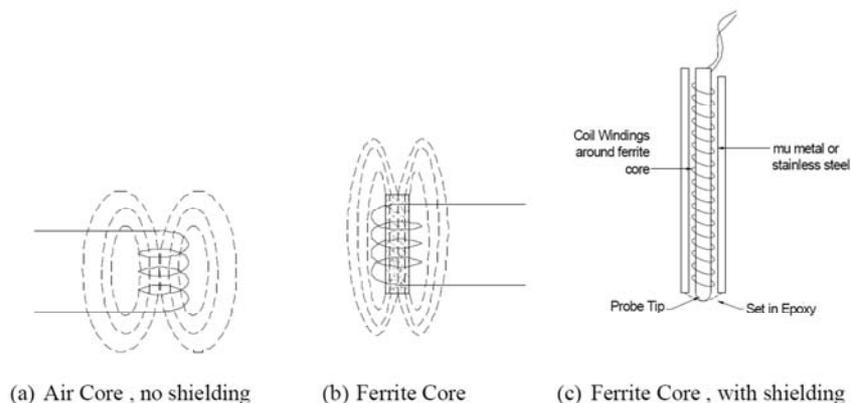


FIG. 5.7. Effects of cores and shields on field extension.

Other types of surface probe

(a) Tangential probes

In a tangential probe, the axis of the test coil is parallel to the test surface, with one side of the coil close to the test surface (see FIG. 5.8). Immediately below the coil, where the eddy currents in the test part are strongest, the magnetic field is essentially parallel to the test surface and in the direction of the axis of the coil, and the eddy currents flow parallel to the

surface at right angles to the field, in the direction of the coil windings. The return paths of the eddy currents are further to the side of the coil and below the surface.

This means that the sensitivity to cracks and similar flaws depends on the direction of the flaw relative to the coil, unlike for standard surface probes. For absolute tangential probes, the maximum sensitivity to surface flaws occurs if the flaw is parallel to the coil axis, and, as the angle between the flaw and the coil axis increases, the sensitivity decreases, reaching zero when the flaw is at 90° to the coil axis (that is, parallel to the windings of the coil).

Tangential probes should therefore only be used when flaws in one direction only are sought. One of their common applications is for the detection of fatigue cracks in the bead seat radius of aircraft wheels, which always occur in a circumferential direction. Tangential probes allow the whole of the bead seat area to be tested in one scan, unlike standard surface probes, which require a number of scans because a small diameter coil needs to be used to reliably detect short cracks. When a tangential probe is used, a short crack in the bead seat radius will always distort the eddy currents, although since the distortion occurs only at one location in the eddy current path, the relative effect on the eddy currents is less than for a standard surface probe, where, if the coil is immediately above the crack, most of the eddy current field is disrupted. This means that the crack signal will not be as strong as that for a small pencil probe, however, the technique shows adequate sensitivity, and is used by a number of major airlines with a consequent saving in either operator costs, or the cost of an automated wheel scan system.

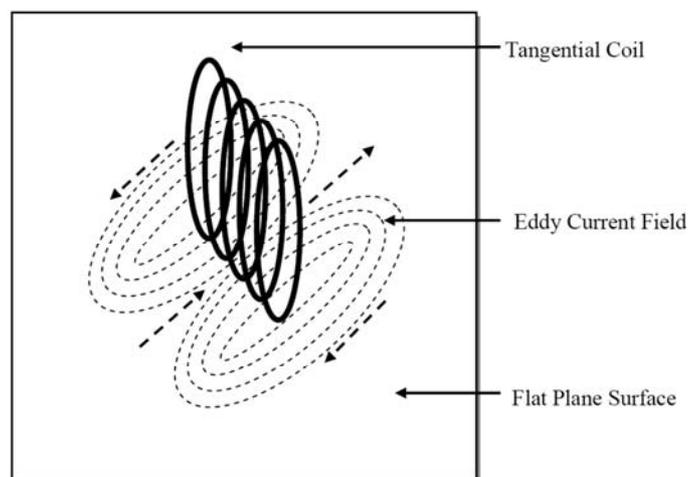


FIG. 5.8. A tangential probe showing the direction of the eddy currents at the test surface.

(b) Gap or horseshoe probes

Gap or horseshoe probes use a U-shaped ferromagnetic core to shape the magnetic field of the coil so that it is essentially parallel to the test surface, as shown in FIG. 5.9. This produces eddy currents loops in planes normal to the test surface. At the surface, the surface eddy currents flow at right angles to the line joining the two ends of the core. Consequently, the maximum sensitivity to surface flaws occurs if the flaw is parallel to this line, and, as the angle between the flaw and the line joining the ends of the core increases, the sensitivity decreases, reaching zero when the flaw is at 90° to this line. This type of probe is used for the detection of laminations in sheet material rather than for cracks or other flaws normal to the test surface.

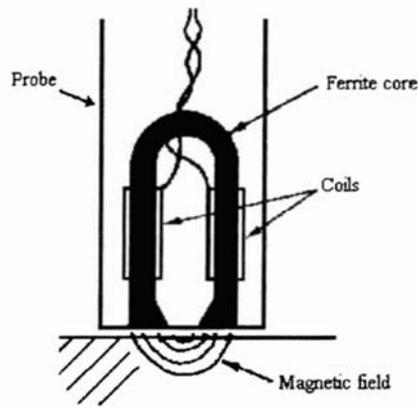


FIG. 5.9. A gap (horseshoe) probe.

5.1.3 Testing for surface-breaking flaws

Introduction

Eddy current testing for surface breaking flaws is one of the major applications of eddy current testing. It is widely used for the detection of fatigue and corrosion-related cracks in aircraft maintenance, and for the in-service testing of welded structures for cracks. Penetrant and magnetic particle testing are also used to detect surface flaws, and have the advantage that the entire surface of complex shaped parts can be examined in one test. Eddy current testing can be used to test the whole of the surface of simple shaped parts, but for more complex shapes, it is appropriate only when testing a small area, usually a location where cracks are known to occur. The advantage of eddy current testing over penetrant testing is that it can detect flaws even if they are blocked with contaminants, and can detect flaws below paint and other coatings. For ferromagnetic materials, the advantage of eddy current testing over magnetic particle testing is that it can detect cracks below thicker paint coatings than is possible for magnetic particle testing, and for this reason, it is preferred for detecting surface cracks in welded steel structures that have been painted. In addition, non-relevant indications, a common problem with magnetic particle testing of welds, are less of a problem with eddy current testing of welds.

The following discusses general test applications. Testing of welds in steel structures is considered separately later.

Selection of probes and frequency

The greater the proportion of the eddy current field that is distorted by a flaw, the greater the eddy current signal and the more likely the flaw is to be detected. Therefore, to detect shallow surface flaws, the eddy current field should be confined to a relatively shallow surface layer, similar to the depth of the flaws required to be detected. To reduce the depth of penetration, a high frequency is required. However, if the frequency is too high, the probe will become excessively sensitive to surface roughness and lift-off, causing a poor signal to noise ratio and a consequent decline in inspection reliability. Typically, for aluminium alloys, frequencies in the range approximately 200 kHz to 500 kHz are appropriate, with approximately 200 kHz being preferred. For low conductivity materials like stainless steel, nickel alloys, and titanium alloys, the penetration would be excessive at these frequencies, and higher frequencies are required. Typically 2 MHz to 6 MHz should be used.

Generally, to detect small flaws, coils with a small diameter, no greater than the length of flaw required to be detected, need to be used. In addition, in-service cracking most often occurs in a change of section, slot, or thread root. Therefore, small diameter pencil probes give good access to such test surfaces and are most commonly used, although spot probes with a small diameter coil can be used on flat surfaces or where the curvature of the test surface is constant and not too great. If only relatively large flaws are sought, larger diameter probes can be used, with a consequent reduction in the number of passes required to scan a given test area.

Absolute probes are almost always used for surface flaw detection, with differential probes being used only for special applications such as testing holes, discussed later. The probe can be shielded or unshielded. Shielded probes should be used for testing around holes.

If the fastener is not removed, cracks will normally be detected only if they extend beyond the fastener. To detect cracks under fasteners, a ring probe or sliding probe should be used. These are discussed later under the heading 'Detection of subsurface flaws'. Shielded probes should also be used for testing near edges, at changes in the section, such as in slots, grooves, and thread roots, and, if testing non-ferromagnetic material, where there is an adjacent ferromagnetic material. Also, because the eddy current field of shielded probes is much more confined than that of an unshielded probe with the same diameter coil, shielded probes are capable of detecting smaller cracks, and so should be used whenever very small cracks are required to be detected. Unshielded probes can be used in other situations, and have the advantage that, because of the greater lateral spread of the eddy currents, fewer passes are required to scan a given test area.

Shielded probes are more sensitive to changes in geometry and probe handling, also the phase separation of the signals is reduced making interpretation more difficult. The use of probe guides may reduce this problem as will the use of special design probes for specific applications.

Following are some examples of specially designed probes:

(a) Threaded components

Probes moulded to a particular thread contour, can be fabricated for detecting cracks at the thread roots. An example is shown in FIG. 5.10. Both external and internal threads can be tested in this way.

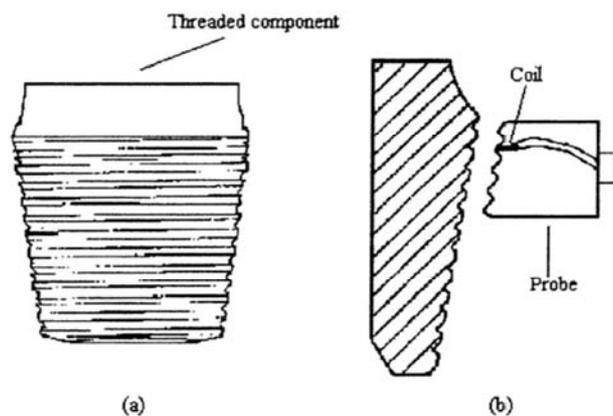


FIG. 5.10. A threaded component (a) and a probe designed to test for cracks in the thread roots (b).

(b) Holes

Testing for cracks along the bores of bolt holes and other holes is carried out using hole probes, also called bolt hole probes, which can be either hand operated or motor driven. A hole probe is still effectively a surface probe, but one which has been fitted into a purpose designed holder. Each probe will be built to fit a specific diameter hole. The probes can be absolute or differential, but differential probes are more commonly used because they eliminate signals from the ends, from interfaces between layers of laminated structures, from circumferential grooves, and from variations in lift-off.

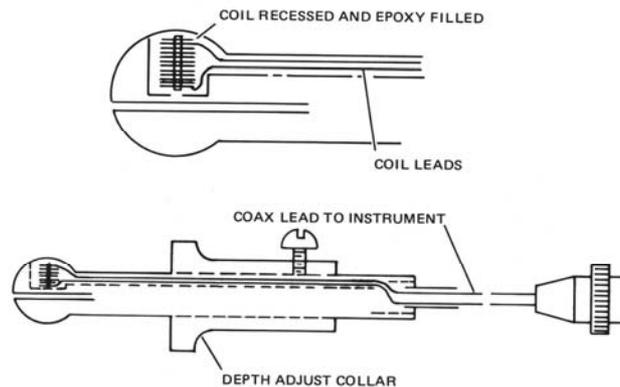


FIG. 5.11. A hand operated hole probe testing for cracks along the hole surface.

Hand operated or manual hole probes, usually consist of a split plastic body, with the core and coil axis at right angles to the probe axis (see FIG. 5.11). The split allows the probe to compress slightly to enter the hole, then expand to press on the walls of the hole so as to minimize lift-off. To test a hole, the probe is inserted until the coil is just inside the far side of the hole, the depth stop is adjusted to be flush with the near surface, and the set screw tightened. The probe is then rotated approximately one and a quarter revolutions, to ensure full coverage at that depth. The set screw is then loosened, the probe withdrawn a given amount, commonly 1 mm to 2 mm, keeping the depth stop flush with the surface, then the screw is retightened. The probe is again rotated as before, and the process repeated until the coil is just inside the near surface.

This process is reliable if carefully performed, but time consuming, and, especially if large numbers of holes are to be tested, motor driven probes are preferred. These are invariably differential because absolute probes would show excessive lift-off noise. In addition differential probes will eliminate signals from the end and interfaces within the hole. Differential probes are essentially cylinders with the two coils near one end, side by side circumferentially with their axis at right angles to the probe axis (similarly to manual probes). The probe diameter is normally slightly smaller than the hole diameter (commonly 0.2 mm) to allow ease of rotation. Alternatively, split, differential, probes similar to manual probes are sometimes used to allow for variations in hole size.

If motor driven probes are to be used, the eddy current instrument must support this facility. The displays are the normal vector point display, and also a time base display which shows the vertical amplitude of the signals against time, the period of time displayed by the screen being automatically adjusted to correspond to a complete rotation of the probe. The position of a flaw signal along the time base display then represents the angular position of the flaw around the hole with respect to a reference mark on the probe motor housing. When setting

up, a signal is obtained on the vector spot display from a discontinuity in a hole in a test block, the material and hole diameter being the same as those being tested. This signal is rotated until it is vertical and the amplitude set, typically 80% full screen height, the signal is then rotated to 30° from vertical, clockwise for ferromagnetic material and anticlockwise for non ferrous materials (FIG. 5.12a). A tight fatigue crack will then appear vertical as in FIG. 5.12b.

The inspection is carried out using the vector point display to enable interpretation of signal cause using phase analysis. To locate the circumferential position of the fault the display is switched to the time base display (FIG. 5.12 c & d).

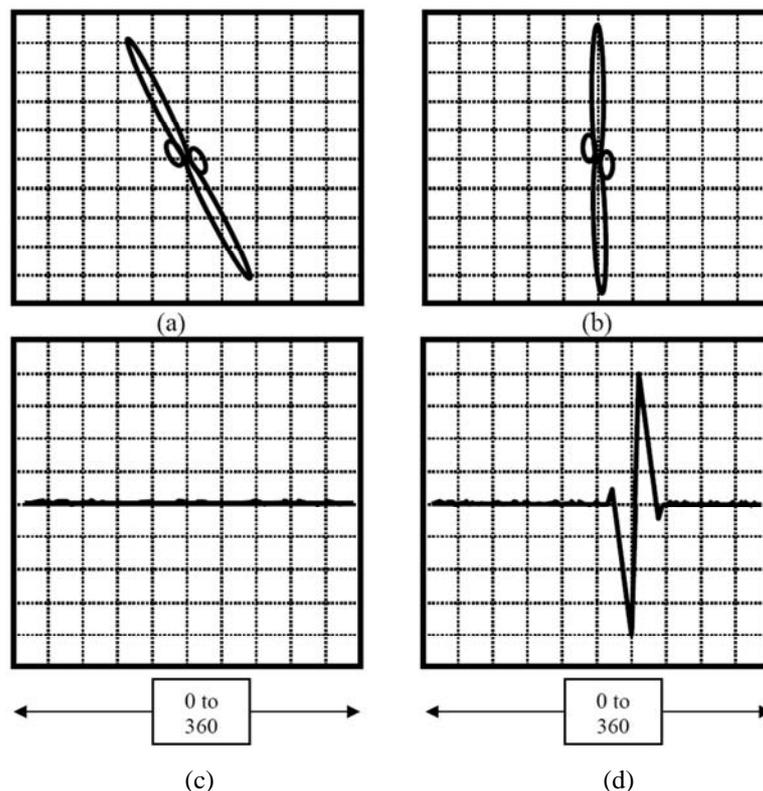


FIG. 5.12. Typical rotating hole probe display showing the vector point display (a) & (b) and a time base display showing a crack signal (c) & (d). The two peaks are produced because a differential probe is used.

(c) Aircraft wheels

Aircraft wheels are prone to fatigue cracks in the tyre bead seat radius with the cracks growing circumferentially along the radius, it is therefore standard practice to test this region, and sometimes other regions, by eddy current testing.

If a standard surface probe is used to test the wheel bead seat radius, it must have a small diameter coil in order to detect small cracks. However, the radius is relatively wide, especially on a large wheel, so a number of scans are required to test the whole area. To ensure the whole area is tested, it is common practice to use a probe guide block, consisting of a plastic block moulded to fit the radius of the wheel being tested, with a number of holes, of a diameter to allow a slender pencil probe (of the type shown in the centre left of FIG. 5.4) to be inserted, drilled through it to meet the radius at small intervals around the radius (see

FIG. 5.13a). For maximum reliability, the probe should fit reasonably tightly into the hole, and the holes should overlap each other by the radius of the hole. Testing is carried out by fitting the probe guide to the radius, inserting the pencil probe into the first hole until it touches the wheel, balancing the instrument, then scanning somewhat more than one revolution (to ensure an area is not left untested) around the bead seat region. The probe is then inserted into the second hole and the process repeated, one hole at a time, until the entire region has been tested. A turntable is very useful as it allows the wheel to be smoothly rotated during scanning, with the operator simply holding the probe in position.

Automated equipment which will perform scans of this type without a probe guide are available. The best of them automatically carry out standardization before and after testing, and provide a printout or computer record of the whole process.

An alternative to using standard surface probes is to use a tangential probe, as shown in FIG. 5.13b. The probe is moulded to fit the bead seat radius being tested, then the coil is fitted into a shallow groove cut into the probe body. The whole bead seat radius is tested in the one scan. The sensitivity is not as great as that of a small pencil probe but is adequate for the purpose of the test.

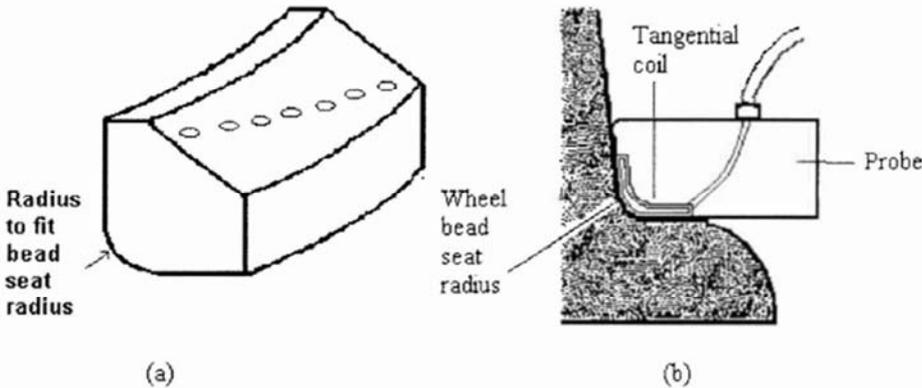


FIG. 5.13. (a) A typical probe guide for testing the bead seat radius of an aircraft wheel. (b) A tangential probe being used to scan a bead seat radius.

Reference blocks

It is essential to use a reference block containing one or more known real or artificial surface flaws to check that the equipment is functioning satisfactorily and to set the gain to an appropriate level. A typical reference block for surface flaws is a block of material of conductivity similar to that being tested, with three spark-eroded slots across one face (see FIG. 5.3). The slots are 0.2 mm, 0.5 mm, and 1.0 mm deep respectively. An aluminium alloy reference block, usually manufactured from aluminium alloy 7075-T6, is suitable for use when testing all aluminium alloys, brass, and other materials of similarly relatively high conductivity, it can also be used for testing magnesium alloys, but because their conductivity is somewhat lower, a magnesium reference standard is preferred. Carbon steel, stainless steel, and titanium alloy reference blocks are also available, and the appropriate block should be used when testing these materials.

Although these blocks can be used for setting up to test parts of any shape, for testing in threads, grooves, or slots, and for testing for cracks in holes, where the eddy current field differs from that for a relatively flat surface, it is strongly recommended that a reference block

of the material and configuration being tested, with one or more known real or artificial surface flaws (usually a spark-eroded slot) at the location at which flaws are expected to be used. This approach is also often used with other test parts, for example the bead seat radius of aircraft wheels, because it gives a higher degree of assurance that the flaws required to be detected can be found,

Test procedure

The general procedure for detection of surface flaws is as follows:

Standardisation

- (a) Connect the probe to be used to the instrument, switch on the test instrument, conduct a battery condition check and allow the instrument to warm up for at least 5 minutes.
- (b) Ensure the test area is clean and free from loose paint, dirt, or other contaminants.
- (c) Select the frequency required and set the gain to the middle of its range.
- (d) Apply the probe to the reference block at a location away from the reference discontinuities with the coil axis at right angles to the surface, and balance the instrument. Adjust the spot if required to approximately the centre of the display. The spot can be located in the lower right hand quadrant if desired to allow more space to view signals to the right (lift-off) and upwards (flaw signals).
- (e) Raise the probe slightly from the surface to obtain a lift-off signal, and adjust the phase so that increasing lift-off gives a signal horizontally to the left, continually raising and lowering the probe to the test surface to monitor the lift-off signal during this adjustment.
- (f) Scan over the appropriate discontinuity in the reference block then adjust the probe position to obtain a maximum signal from the discontinuity. Set the gain so that the maximum signal from the discontinuity has the amplitude required by the test procedure. A common requirement when using a standard reference block is to adjust the gain so that the vertical component of the signal from the 0.5 mm slot is one third of the total screen height (see signal no 2 in FIG. 5.3). For some instruments, changing the gain may affect the balance, so it may be necessary to rebalance and check that the lift-off and discontinuity signals and adjust as required. If the instrument allows changing the X (horizontal) to Y (vertical) gain ratio, the Y gain can be increased above the X gain if desired. This increases the vertical component of flaw signals, making them more easily detected, and reduces the lift-off signal amplitude. Note that if the X and Y gains are different, the phase of the signals is distorted compared with their normal appearance. Excessive difference between the X and Y gain is to be avoided.
- (g) Apply the probe to the test surface with the coil axis at right angles to the surface, and rebalance the instrument. Readjust the phase if necessary so that the lift-off signal is horizontal to the left, but do not adjust the gain.
- (h) Scan the test areas as required. Scanning should not be carried out within 3 metres of AC machinery. Scanning increments should not exceed the width of the test coil of an absolute probe. For shielded coils, the scan index should be determined experimentally

to ensure that the entire area to be tested is covered but a scan index of half the coil diameter is usually satisfactory. Record the results and any other information required.

- (i) During testing for extended periods of time, the sensitivity should be rechecked, and adjustments made if required, at approximately 30 minute intervals and at the completion of the testing (Some standards require more frequent checking). This standardization procedure should include battery condition checks and sensitivity checks. If an instrument is found to be out of standardization, all areas inspected since the previous standardization verification should be rechecked. In addition, the instrument should be re-standardized if any part of the system is replaced or if any control settings that could affect the calibration are changed.

Testing in-service welds in ferromagnetic materials

Welds are normally not tested for weld quality by eddy current testing because of the limited depth of penetration of eddy current. This is especially so for ferromagnetic materials, because the permeability reduces the penetration. However, in-service welds are often tested for fatigue or corrosion-related cracks by eddy current testing in preference to magnetic particle testing because of its ability to detect cracks through much thicker paint coatings, and because it is faster and interpretation of the results is usually generally easier. Fatigue cracks can be reliably detected through thickness of up to 2 mm of paint by eddy current testing, whereas to obtain magnetic particle indications from even large cracks requires the paint to be less than 0.5 mm thick.

Special probes are used for testing welds in ferromagnetic material. Standard surface testing probes give very noisy signals because of variations in conductivity and permeability, particularly the latter, which result from differences in composition and structure, and because the weld configuration causes variations in lift-off. Probes designed for weld testing are differential probes, which reduce this noise to an acceptable level. In fact, a common design for weld testing probes is a differential tangential probe, with both coils tangential, but at 90° to each other (see FIG. 5.14). The two coils are at the same location, so that the windings cross each other, like the equator and a circle through north and south poles on the earth. Although different manufacturers produce probes with a variety of shapes, one of the more common type of probes for testing welds has a semi-cylindrical tip, and is intended to be operated with the axis of the semi-cylinder parallel to the weld. Whatever the shape, weld testing probes should be operated with the plane of one coil parallel to the weld, and the plane of the other transverse to the weld. Since the eddy currents produced at the surface under tangential coils flow along the surface in the direction of the windings, the eddy currents produced by the coil wound parallel to the weld are also parallel to the weld and will therefore detect transverse cracks but not longitudinal cracks. Likewise, the eddy currents produced by the coil wound transverse to the weld are also transverse to the weld and will therefore detect longitudinal cracks but not transverse cracks. Therefore, when these two coils are connected differentially, they will give a signal for either a transverse or a longitudinal crack. If a crack was present at 45° to the weld, which, fortunately, is extremely unlikely, it would not be detected because the eddy currents of both coils would be distorted equally by it. The differing sensitivities of the two coils also explains why crack signals from weld scan probes do not have the typical differential signal shape. Since only one coil detects the crack, the spot simply diverts as the probe approaches the crack, then returns to the balance position after the probe passes it.

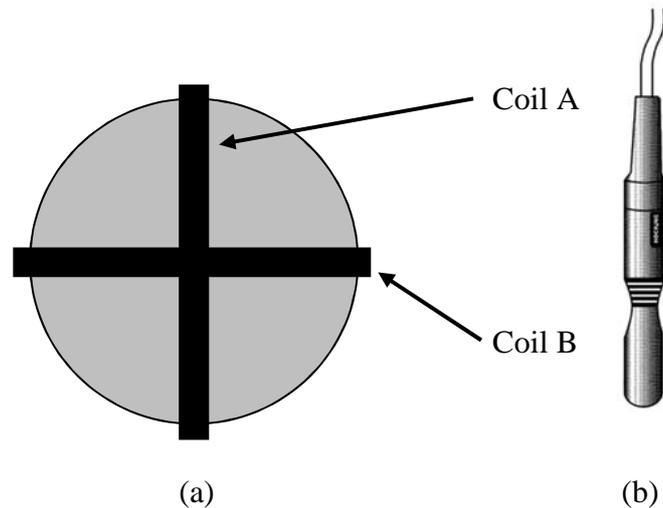


FIG. 5.14 a. Typical weld testing probe coil arrangement (plan view). b. Typical weld testing probe

Test frequencies of approximately 100 kHz have been found satisfactory for testing ferromagnetic structures for surface cracks, although higher frequencies can be used.

The instrument should be standardized using a steel reference block with artificial flaws. Commonly, these are spark eroded slots 0.5 mm, 1 mm, and 2 mm deep. If the welds are painted, the thickness of the paint should be measured first, then standardization performed with plastic shims of the thickness of the paint over the artificial discontinuities. Because the probes are differential, there is no clear lift-off signal to use as a reference signal for adjusting the phase, although the balance points with the probe in air and the probe on a ferromagnetic material usually differ slightly because the different impedance of the coils on the ferromagnetic material changes the impedance of the bridge circuit. After the instrument is balanced on the reference block, the phase is normally adjusted so that flaw signals are vertical. The gain is then adjusted to give the sensitivity required by the procedure being used.

For testing, the instrument should be balanced on the structure to be tested at a location away from the welded area so as to avoid possibly balancing on a crack, then the area required to be tested should be scanned. During scanning, the probe should be kept parallel to the most likely direction of cracking. This will also detect cracking at right angles to this angle, but the spot will be deflected downwards rather than upwards. If the balance point is low on the screen, downward signals may not be distinguishable from noise. Generally, the probe should be maintained at approximately right angles to the test surface, but for maximum sensitivity when scanning along the toe of welds, the probe should be tilted so that weld toe is immediately below the probe tip. Fatigue cracks in welded structures are most likely in the longitudinal direction, and the toe of the weld is the most likely location of fatigue cracking, although cracking can also occur elsewhere in the weld or adjacent parent metal. For scanning the heat affected zone and adjacent parent metal, a zigzag scan at right angles to the weld should be employed. For testing the weld bead, either a zigzag scan across the bead or several scans along the weld may be used, depending on the weld condition. If transverse cracking is considered likely, scanning with the probe transverse to the weld may be required, although such cracks will give downward signals during scanning for longitudinal cracks.

If the display is set up as indicated above, cracks parallel to the probe will produce a vertical deflection of the spot. The signal amplitude is approximately proportional to the depth of the

cracks, so crack depth can be estimated, if required, by comparison of the signal with signals from the slots in the reference blocks, with a plastic shim of thickness equal to that of the paint coating at the crack location on the block.

5.1.3 Detection of subsurface flaws

Introduction

The depth of penetration of the magnetic field produced by eddy current test coils, and therefore of the eddy currents produced by this field is highly dependent of the coil diameter, the larger the coil diameter the greater the depth of penetration. This is the predominant effect in limiting eddy current penetration, and explains why the penetration is often far less than that calculated using the effective depth of penetration formula. Typically, the magnetic field in the axial direction is relatively strong only for a distance of approximately one tenth of the coil diameter, and drops rapidly to only approximately one tenth of the field strength near the coil at a distance of one coil diameter. To penetrate deeply, therefore, large coil diameters are required. However as the coil diameter increases, the sensitivity to small flaws, whether surface or subsurface, decreases. For this reason, eddy current flaw detection is generally limited to depths most commonly of up to approximately 5 mm only, occasionally up to 10 mm.

For materials or components with greater cross-sections, eddy current testing is usually used only for the detection of surface flaws and assessing material properties, and radiography or ultrasonic testing is used to detect flaws which lie below the surface, although eddy current testing can be used to detect flaws near the surface. However, a very common application of eddy current testing is for the detection of flaws in thin material and, for multilayer structures, of flaws in a subsurface layer.

Probe and frequency selection

The essential requirements for the detection of subsurface flaws are, sufficient penetration for sensitivity to the subsurface flaws sought, and sufficient phase separation of the signals for the location or depth of the flaws to be identified. As standard depth of penetration increases, the phase difference between discontinuities of different depth decreases. Therefore, making interpretation of location or depth of the flaws difficult.

Example: If the frequency is set to obtain a standard depth of penetration of 2 mm, the separation between discontinuities at 1 mm and 2 mm would be 57°.

 If the frequency is set to obtain a standard depth of penetration of 4 mm, the separation between discontinuities at 1 mm and 2 mm would be 28.5°.

An acceptable compromise which gives both adequate sensitivity to subsurface flaws and adequate phase separation between near side and far side flaw signals is to use a frequency for which the thickness (t) = 0.8δ . At this frequency, the signal from a shallow far side flaw is close to 90° clockwise from the signal from a shallow near side flaw, so this frequency is termed f_{90} . By substituting $t = 0.8\delta$ into the standard depth of penetration formula, and changing Hz to kHz, the following formula is obtained:

$$f_{90} = 280 / (t^2 \sigma) \quad (5.1)$$

where

f_{90} = the operating frequency (kHz),
 t = the thickness or depth of material to be tested (mm), and
 σ = the conductivity of the test material (% IACS).

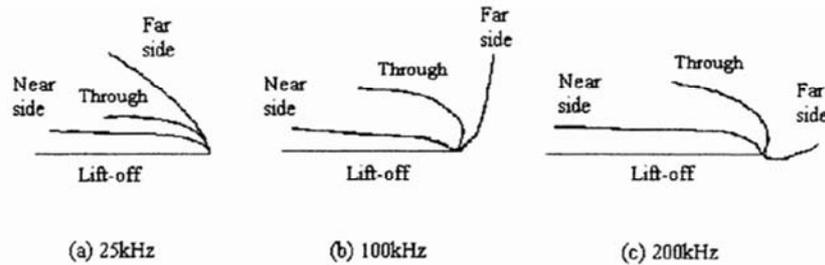


FIG. 5.15. Eddy current signals from a thin plate with a shallow near side flaw, a shallow far side flaw, and a through hole, at three different frequencies. At 25 kHz (a), the sensitivity to far side flaws is high, but the phase difference between near side and far side signals is relatively small. At 200 kHz (c), the phase separation between near side and far side signals is large, but the sensitivity to far side flaws is poor. For this test part, a test frequency of 100 kHz (b) shows both good sensitivity to far side flaws and good phase separation between near side and far side signals.

To obtain adequate depth of penetration, not only must the frequency be lower than for the detection of surface flaws, but also the coil diameter must be larger. On flat surfaces, a spot probe, either absolute or reflection, should be used in order to obtain stable signals (see FIG. 5.16). On curved surfaces, a spot probe with a concave face or a pencil probe should be used. Spring loaded spot probes can be used to minimize lift-off, and shielded spot probes are available for scanning close to edges, fasteners, and sharp changes in configuration.

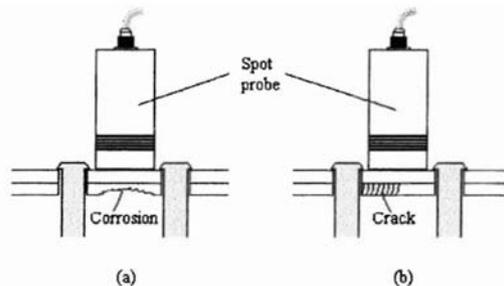


FIG. 5.16. Spot probes testing a layered structure for corrosion (a) and cracks (b) in the second layer of a two-layer laminate.

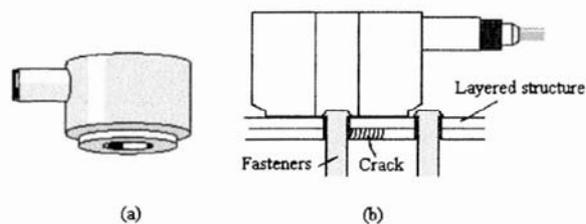


FIG. 5.17. (a) Ring probe. (b) Ring probe positioned over a fastener for flaw detection

Two special-purpose probes should be noted:

Ring probes

Ring probes are doughnut-shaped probes used for the detection of both surface, and subsurface cracks or other flaws at fastener holes when the testing is carried out with the fasteners installed (see FIG. 5.17). These probes are capable of detecting cracks which do not extend far from the hole, for example, those which do not extend beyond the head of the fastener, and therefore may not be detected using a spot probe adjacent to the fastener. Ring probes are commonly absolute reflection probes and may be shielded.

Sliding probes

Sliding probes are also designed to detect both surface, and subsurface cracks or corrosion at fastener holes, but are designed to slide along a row of fasteners (see FIG. 5.18). They are reflection probes, usually with at least two pickup coils. One type has a central driver coil and four small pickup coils equally spaced around it and connected differentially, all housed in a block. Some probes have a recessed slot along the length of the probe for sliding over protruding fastener heads.

Sliding probes give a signal as they pass over a fastener, but if a crack or corrosion is present, a characteristically different and more complex signal is produced. For multilayered structures, characteristically different signals are given for cracks extending along the row of fasteners and for cracks extending normal to the row. In addition, the signals are different for cracks in each layer. Interpretation is therefore done by recognition of the characteristic pattern of the signal from each condition, rather than by analysis of the signal. An appropriate reference sample is essential so the operator can become familiar with the signal patterns. An experienced operator can test a row of fasteners much more rapidly than when using a ring or other type of probe.

Multi-frequency testing can be used to eliminate signals from fasteners, so that the only signals displayed will be flaw signals. The use of multi-frequency inspection for the detection of subsurface cracks and corrosion is becoming more common in use. Two applications of multi-frequency is to, separate the variables due to skin separation and corrosion at similar depths into the material, and to inspect beneath installed fasteners for cracks where the variables caused by the fastener can be eliminated.

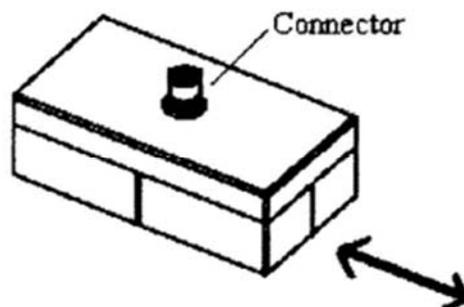


FIG. 5.18. A sliding probe intended for detecting surface and subsurface flaws by sliding it along rows of fasteners in the direction of the arrows

Reference samples

Reference samples should be as far as possible identical to the parts to be tested. They should be of the same material (or material of the same conductivity) and thickness as the parts to be tested, and, if a multilayered part is to be tested, each layer should have the same material (or conductivity), thickness, and separation as the test parts. In addition, they should have real or artificial flaws simulating the type sought and at the locations and orientations at which flaws are required to be detected.

Corrosion may be simulated by drilling shallow holes, using either a standard or flat-bottom drill bit. Alternatively, milled slots may be used. Cracks may be simulated by spark-eroded slots, or by narrow saw cuts.

Test procedure

The test procedures are generally similar to those for detecting surface flaws.

5.1.4 Conductivity testing and material sorting

Introduction

Eddy current testing can be used for material sorting on the basis that different materials, and even the samples of the same material in different heat treatment conditions, have different values of electrical conductivity. The conductivity of a conductor can be measured using a dedicated eddy current conductivity meter. Alternatively, most modern impedance display instruments include a digital conductivity measurement facility when used with a probe designed for this purpose. Neither of these instruments will give a conductivity reading if a ferromagnetic material is tested. For material sorting, a comparison of the phase of the lift-off signals obtained from the unknown samples with signals from known reference materials may suffice: it may not be necessary to determine the actual conductivity value. This approach may be used with both non-ferromagnetic and ferromagnetic materials. Conductivity testing or sorting by conductivity comparison can also be used to determine the density of parts produced by powder metallurgy.

Conductivity and its measurement

The SI unit of conductivity is the Siemens/metre (S/m), but because it is a very small unit, its multiple, the megaSiemens/metre (MS/m) is more commonly used. Eddy current conductivity meters usually give readouts in the practical unit of conductivity, % IACS (% International Annealed Copper Standard), which give the conductivity relative to annealed commercially pure copper. To convert % IACS to MS/m, multiply by 0.58, and to convert MS/m to % IACS, multiply by 1.724.

For instance, the conductivity of Type 304 stainless steel is 2.5% IACS or 1.45MS/m.

Resistivity is the inverse of conductivity, and some publications on eddy current testing refer to resistivity values rather than conductivity values. However, conductivity in % IACS is universally used in the aluminium and aerospace industries.

Factors which affect conductivity

The conductivity of a metal relates to the ease with which the conduction electrons present in the metal can move through the material. Anything which impedes the movement of these

electrons reduces the conductivity. This includes any factor which stresses the crystal lattice. Generally, factors which harden and strengthen metals also reduce the conductivity. This is because most, though not all, hardening mechanisms achieve their hardening by introducing stress into the crystal lattice.

Factors which affect the conductivity include the following:

(a) Temperature.

Increasing the temperature increases the amplitude of vibration of the atoms, which in turn increases the impedance to the electron flow. For accurate readings, the reference standards and the test part should be at the same temperature. For greatest accuracy, measurement should be carried out at approximately 20°C, since this is the temperature the reference standards are certified for, and the effect of temperature on the test part and the reference standards may differ.

(b) Alloying.

Dissolving any element in a solid metal causes stress in the lattice because of the different sizes of the atoms, and so causes both hardening and a reduction of conductivity. Alloys therefore have lower conductivity than the pure metal they are formed from. Some impurities in metals, even in quite small amounts, can significantly reduce the conductivity. For example, 0.1% of phosphorus in copper reduces its conductivity from 100% IACS to 50% IACS. This is important, because phosphorus is sometimes used to deoxidize copper during its refining and, if so, some phosphorus remains in the material. This material is therefore not suitable for high conductivity applications.

(c) Heat treatment.

Many alloys can be hardened by heat treatment, which introduces stress in the lattice and so reduces the conductivity. On the other hand, annealing processes, which generally consist of heating followed by very slow cooling, relieve stresses in the crystal lattice, and so reduce the hardness of the metal to a minimum and increase the conductivity to a maximum.

(d) Cold work

Plastic deformation of metals at ambient temperatures introduces stress into the crystal lattice, and so increases hardness and reduces conductivity. However, the effect on conductivity is generally less than 10% and so can usually be ignored. An exception is austenitic stainless steel, which is normally non-ferromagnetic, because it can become ferromagnetic if cold worked. This has a major effect on the eddy current signal, and prevents a conductivity reading being taken on conductivity meters.

Factors which affect the conductivity reading

(a) Lift-off

Conductivity meters and impedance display instruments which include a digital conductivity measurement facility normally provide lift-off compensation for lift-off values up to at least 0.08 mm, so the reading should not be affected by paint coatings up to this thickness or by minor surface roughness. If it is considered likely that the reading will be affected by a coating or surface roughness, conductivity readings should be made on a surface showing the

condition of the test part and on a flat, smooth surface to determine if a lift-off correction is required.

(b) Test part thickness

The conductivity reading will be affected if the test part thickness is less than the 'effective depth of penetration, which, for the coil diameter normally used for conductivity testing (approximately 10 mm), can be taken as 3 times the standard depth of penetration. If there is doubt as to whether the test part is thick enough, it should be tested, if possible, with and without a block of copper held against the far surface. Any difference in the readings indicates that the thickness is less than the effective depth of penetration. Most eddy current conductivity meters operate at a fixed, common frequency of 60 kHz. This is low enough to give sufficient penetration to avoid any contamination of the test surface having a significant effect, and high enough to allow testing of reasonably thin materials. Some conductivity meters have one or more, higher alternative test frequencies, and if so, a higher frequency may be selected to avoid excessive penetration. However, they should be operated at the lowest frequency possible for the test part thickness in order to avoid any contamination of the test surface having a significant effect. The second 'higher' frequency is commonly used to determine cladding thickness.

If the test part thickness is less than the effective depth of penetration, parts may be tested by determining a correction, or for sheet material, by stacking.

(c) Edge effect

Probes dedicated to conductivity testing are manufactured so that there is no edge effect if the area being tested is equal to or larger than the probe area and the probe is centered on this area. That is, if the edge (or hole) lies outside the area covered by the probe, there should be no edge effect. This should be verified by taking readings on a sample as the probe approaches an edge. If a smaller area is required to be tested, a smaller conductivity testing probe must be used, if available, or comparative testing with a standard eddy current instrument and a small diameter or shielded probe to determine the lift-off signal and compare it with those from known test samples must be used.

(d) Curvature

Curved surfaces with small radii of curvature may give an incorrect reading, the deviation increasing with increasing conductivity. If it is considered likely that the curvature will affect the reading, a correction must be determined.

Frequency selection

The frequency used for general conductivity measurement is 60 kHz, however where the ability to detect very small changes in conductivity is required, the frequency should be optimized, so that the change in coil impedance for a small change in conductivity is the greatest.

If lift-off compensation is important because of a rough surface or a non-conducting coating, the lift-off signal should be as close as possible to 90⁰ from the conductivity signal for change in conductivity, because signals are more easily suppressed if they are at 90⁰ to the signal of interest.

FIG. 5.19 shows the operating points for a number of materials at three different frequencies. It can be seen that, as the frequency increases, the operating point moves clockwise, further down the impedance curve. Furthermore, the greatest separation of the operating points for materials of different conductivity, and therefore the greatest sensitivity to conductivity is obtained if the operating point is in the central region of the impedance curve. If possible, conductivity testing and material sorting should therefore be carried out at a frequency which brings the operating points of the materials being tested to this central portion of the impedance curve. In addition, if lift-off compensation is important the operating point should be in the lower portion of this region, below the 'knee' of the curve. To allow the determination of an appropriate frequency, a relationship between frequency and operating point is required.

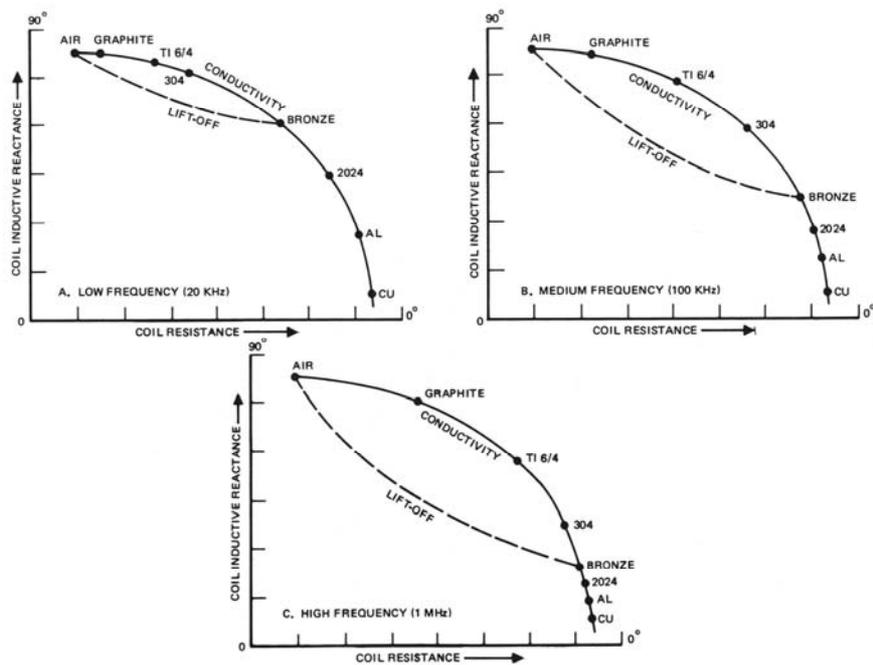


FIG. 5.19. Impedance diagrams and the conductivity curve at three different frequencies, showing that, as frequency increases, the operating point moves down the conductivity curve. It can also be seen that the angle θ between the conductivity and lift-off curve is quite small for operating points near the top of the conductivity curve, but greater in the middle and lower parts of the curve. The increased sensitivity to variations in conductivity towards the centre of the conductivity curve can also be seen.

The Characteristic Parameter (P_C) is a means of determining the operating point on the impedance curve. The formula for P_C depends on the units used, but the following is recommended:

$$P_C = 4.6 \times 10^{-3} f \mu_r \sigma r^2 \quad (5.3a)$$

Or

$$f = P_C / (4.6 \times 10^{-3} \mu_r \sigma r^2) \quad (5.3b)$$

where

P_C = characteristic parameter,
 f = frequency (kHz),
 μ_r = relative permeability,
 σ = conductivity (% IACS),
 r = mean coil radius (mm)

Note that the unit of frequency used in this formula, as in the other ‘applied’ eddy current formulae (for f_{90} and f/f_g) is kHz, unlike the basic theoretical formulae for depth of penetration and inductive reactance.

Calculations of P_C are used in conjunction with FIG. 5.20, which relates the value of P_C to the operating point on the impedance curve for surface probes.

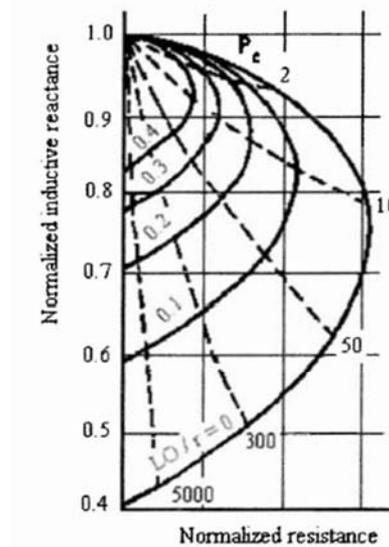


FIG. 5.20. Impedance diagram showing conductivity curves at a number of different values of lift-off to coil radius ratio (LO/r) (the solid curves) and a number of lift-off curves (dashed). Values of P_C are indicated for the zero lift-off conductivity curve. These values also apply to the corresponding locations on the other conductivity curves.

Example:

Calculate the optimum frequency for maximum sensitivity in sorting commercially pure titanium (conductivity approximately 2.5% IACS) from Ti-6Al-4V alloy (conductivity 1% IACS), using a coil with outer diameter 10 mm wound on a 6 mm diameter plastic core.

Calculation:

For maximum sensitivity to conductivity, and minimum response to lift-off, the operating point should be at or somewhat below the knee of the impedance curve. That is, P_C should be between 10 and approximately 200. The P_C value will be different for the two alloys, but, since P_C is proportional to conductivity, the two values will differ by a factor of $2.5/1 = 2.5$ (the ratio of the conductivities). Suitable values would be 30 for titanium and 75 for stainless steel, though other similar values within the range 10 to 200 could be chosen.

That is:

$$f = P_C / (4.6 \times 10^{-3} \mu_r \sigma r^2)$$

$$\begin{aligned} P_C &= 30 \text{ (for titanium),} \\ r &= (10 + 6)/2 = 8 \text{ mm, so } r = 4 \text{ mm,} \\ \mu_r &= 1 \\ \sigma &= 1\% \text{ IACS} \end{aligned}$$

Inserting these values into equation gives:

$$\begin{aligned} f &= 30 / (4.6 \times 10^{-3} \times 1 \times 1 \times 4^2) \\ &= 407.6 \text{ kHz or, rounding to a convenient figure:} \\ &= \text{approximately } 400 \text{ kHz} \end{aligned}$$

When eddy current conductivity meters are used, this approach is normally not possible, because they operate at one or more fixed frequencies. Normally, these instruments are designed to give an operating point in the region of the knee of the curve at the lowest frequency, normally 60 kHz, and higher frequencies are used only if the material is too thin for testing at the lowest frequency.

Test procedure using an eddy current conductivity meter

- (a) Locate the reference standards and the test part in the same area, and allow time for the temperature of both to equalize.
- (b) Switch on the instrument and allow it to warm up for a period of at least 5 minutes.
- (c) Calibrate the instrument in accordance with the instrument manufacturer's instructions. If possible, the calibration should be carried out or checked using reference standards with conductivity values similar to those to be measured. For aluminium alloys, the calibration should be carried out or checked using two reference standards which differ by at least 10% IACS, one in the range 25 to 32% IACS and the other in the range 38 to 50% IACS.
- (d) Perform conductivity measurements of the test part. Normally at least three readings should be taken on each test part to obtain a conductivity measurement, each reading being taken on a different area. The test areas should be flat, of sufficient area to avoid edge effects, of sufficient thickness that the thickness does not affect the reading, and, if a coating is present, it should be thin enough not to affect the reading. If any of these conditions cannot be met, with the instrument and frequency being used, alternative frequency, probe, or instrument which allows these conditions to be met should be used if this is not possible, a correction must be determined experimentally for the particular material and test conditions, and added to or subtracted from the instrument reading.

Test procedure using other eddy current instruments

If an impedance plane display instrument is being used to sort materials, lift-off signals should be obtained from suitable reference standards and the lift-off signals of the materials to be tested should be compared with these. For example, if it is required to sort material known to consist of two different known alloys or heat treatment conditions, lift-off signals should be

obtained from a number of samples of each material. It is important to have enough samples to assure that the range of conductivities of the two materials do not overlap. The instrument is adjusted so that the lift-off signals from one material are located towards one edge of the screen, and the lift-off signals from the other material are located towards the other edge of the screen.

Meter-indicating flaw detectors can be used for the same purpose, in this case adjusting the instrument so that the readings from one material lie towards one end of the scale, and the readings from the other material lie towards the other end of the scale.

Heat treatment of aluminium alloys and its verification

During age hardening of aluminium or titanium alloys, the hardness and conductivity of the material change simultaneously so that the degree of hardening may be obtained by measuring the conductivity of the test specimen and comparing it with a standard of that material with a known hardness. The operator must be aware of the effects of discontinuities and lift-off on the meter readings.

As can be seen from FIG.5.21 a typical conductivity of 35% IACS could have a Rockwell B hardness of either 20 or 85, from this we can see that conductivity measurements for heat damage must be accompanied with hardness testing to confirm true condition. In the manufacturing industry, conductivity alone can be used to confirm material Temper after heat treatment.

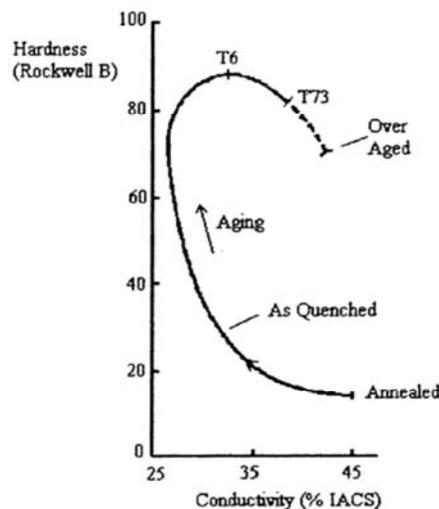


FIG. 5.21. Diagram showing the relation between hardness and conductivity at various stages in the heat treatment, aluminium-zinc alloys 7075. Other heat-treatable aluminium alloys show similar curves.

Sorting materials by magnetic permeability

In eddy current testing the test coil is sensitive to many test parameters, including magnetic permeability. Due to the amplification effect caused by magnetic permeability, measurement of permeability and high levels is generally not possible. However many paramagnetic alloys can exhibit permeability properties and almost any non-magnetic alloy can pick up magnetic inclusions or contamination during manufacture or service.

At normal eddy current test frequencies magnetic indications will often appear similar to discontinuities. Magnetic indications can be distinguished from discontinuities by re-testing at a reduced test frequency.

5.1.4 Thickness measurement of non-conductive coatings

Introduction

The thickness of non-conducting coatings on conductors is measured by measuring the amount of lift-off the coatings produce. The technique can be applied equally to ferromagnetic or non-ferromagnetic materials, and can also be used to measure the thickness of nonconductors like plastic sheet, by laying them on top of a flat conductor.

Most modern digital eddy current instruments when used in conductivity mode, provide a digital readout of both conductivity and lift off (non-conductive coating thickness).

Comparative measurements can also be made using the impedance plane and are summarised as follows.

Probe and frequency selection.

Any standard absolute or absolute reflection surface testing probe may be used, but to obtain stable and repeatable signals, a spot or spring loaded probe should be used. If a pencil probe is to be used, it should be fitted with a sleeve or shoe so that probe wobble is eliminated (see FIG. 5.22a). If curved surfaces are to be tested, a spring loaded probe in the form of a V block, or a V-block or specially contoured shoe should be used for the same reason (see FIG. 5.22b).

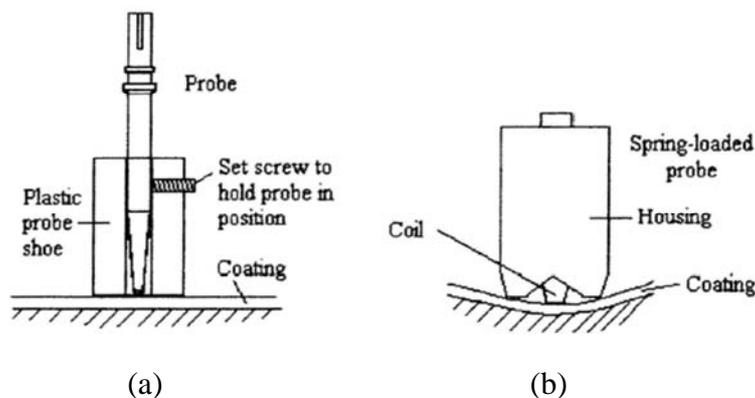


FIG. 5.22. Methods of obtaining stable and repeatable readings of coating thickness (a) Using a pencil probe with a probe shoe. The probe shoe can be contoured to fit a curved surface. (b) Using a spring loaded probe with V-notches on a curved surface. Convex surfaces can also be tested.

The preferred type of probe is an absolute reflection probe, preferably spring loaded, and with V-notches if curved surfaces are to be tested. Reflection probes are preferred because they show a more linear lift-off curve and they respond to a greater range of lift-off values. Note that differential probes should not be used because they eliminate or reduce the lift-off signal.

The coil diameter is important because the size of the magnetic field increases as the coil diameter increases. The magnetic field from a coil at a distance of one coil diameter from the

coil is only approximately 10% of that adjacent to the coil, and a very low eddy current intensity is produced at this distance. The magnetic fields of small diameter coils may not extend through a thick coating to the substrate. If this is the case, a lift-off signal cannot be obtained and measurement of coating thickness is not possible. In general, therefore, the thicker the coating to be measured, the larger the coil diameter should be. Note that the size of a probe is not necessarily a good guide to coil size. Some spot probes have a small diameter coil in a large diameter housing.

Non-conducting coating thickness measurement may be carried out over a wide range of frequencies, but it is preferable to select a test frequency which give an operating point on the lower portion of the impedance diagram. There are two reasons for this.

- (a) The signal for a given amount of lift-off is greater on the lower portion of the impedance curve. FIG. 5.20 shows this effect: for a P_C value of 300 (towards the bottom of the curve), the lift-off signal for a lift-off of 5% of the coil diameter (the curve labelled 0.1) is approximately 50% greater than for a P_C value of 10 (at the knee of the curve) and approximately 4 times greater than for a P_C value of 2 (towards the top of the curve).
- (b) When operating towards the bottom of the impedance curve, the change in signal for a given change in conductivity of the substrate is quite small (see FIG. 5.19), so that the effect of minor variations in conductivity of the substrate is reduced. In addition, in the lower portion of the impedance curve, the signals for lift-off and change in conductivity are reasonably close to 90° , so that any minor change in the substrate conductivity will have little effect on the lift-off signal. For the upper part of the impedance curve, the signals for lift-off and change in conductivity are separated by only a small angle, making them hard to distinguish.

A further consideration when selecting frequency is the depth of penetration of the eddy currents in the substrate. It is preferable to ensure that the effective depth of penetration of the eddy currents is significantly less than the thickness of the substrate, so that variations in substrate thickness do not affect the eddy current signal. Therefore, for thin material, the effective depth of penetration at the proposed test frequency should be calculated, and the frequency increased if required.

A typical operating frequency to measure a thickness of 0.15 mm of paint on an aluminium alloy substrate, conductivity approximately 30% IACS would be 300 kHz to measure the same thickness of paint on a magnesium alloy, conductivity approximately 15% IACS, a higher frequency, up to 1 MHz, would be preferred. This is because the operating point depends not only on frequency, but also on conductivity (and coil diameter). Lower conductivity materials therefore require higher frequencies to bring the operating point to a similar location as for high conductivity materials. Generally, as the thickness required to be measured increases, the coil diameter should be increased, as stated above. This moves the operating point further down the impedance curve, and therefore lower frequencies may be used. There is no difficulty with this because, in general, larger diameter coils are designed to operate at lower frequencies. In fact, lower frequencies are recommended for thicker coatings in order to avoid excessive sensitivity to lift off and to obtain a more linear response. For example, for a thickness of 1 mm on an aluminium alloy substrate, a frequency of approximately 80 kHz should be used.

Reference samples

The substrate reference sample for non-conducting coating thickness measurement should have the same conductivity, surface contour and thickness as the material to be tested.

For reference samples for the coating, stiff plastic shims of appropriate thicknesses are required. If the measurement is a go/no-go type, to verify whether the thickness lies within acceptable limits, only two shim thicknesses are necessary, one with the thickness of the lower limit and one with the thickness of the higher limit. However, a third shim, with thickness in the middle of the range, is desirable. If, however, the actual thickness of the coating is to be measured, at least three shim thicknesses are required. These should have thicknesses equal to the maximum and minimum expected thicknesses, and one approximately midway between these. If the coating required to be measured is thin, bare metal may be used for calibration. More shim thicknesses may be required if the response is notably nonlinear.

Measurement procedure

- (a) Connect the probe to be used to the instrument, switch on the test instrument and allow it to warm up for at least 5 minutes.
- (b) Ensure the test area is clean and free from dirt or other contaminants.
- (c) Select the frequency required, and set the gain to the middle of its range.
- (d) Apply the probe to the reference sample, either bare, or with the thinnest shim placed on it, balance the instrument, and adjust the phase so that the lift-off signal is horizontal to the left.
- (e) Adjust the spot to a location on the horizontal centre line near the right hand side of the screen.
- (f) Apply the probe to the reference sample with the thickest shim placed on it and, without rebalancing, check whether a signal is displayed. If visible, the spot should lie to the left previously obtained signal. Adjust the gain so that the spot is located towards the left hand edge of the screen. If the spot is not visible, first reduce the gain until it becomes visible, then further adjust the gain to locate the spot towards the left hand edge of the screen.
- (g) For some instruments, changing the gain changes the balance point, so steps (d), (e), and (f) should be repeated to ensure that the spot is located on the horizontal centre line, towards the right hand edge of the screen with the probe on the thinnest shim or bare metal, and towards the left hand edge of the screen with the probe on the thickest shim.
- (h) The position of the spot when the probe is located on the thickest shim can be marked.
- (i) Locate the probe on the other shims in turn, marking the position of the spot.
- (j) If measurement of the thickness is required, draw up a graph of the horizontal position of the spot, measured in millimetre or number of scale divisions from one edge of the screen, versus the coating thickness. If the graph is sharply curved, different frequencies should be tried to determine if a more linear response can be achieved. Alternatively, use more reference shims so that an accurate smooth curve can be plotted. Once a

satisfactory graph has been obtained, carry out thickness measurement by applying the probe to the test part, measuring the horizontal position of the spot from the edge of the screen, then using the graph to determine the thickness.

- (k) Alternatively, if the measurement is being carried out to verify whether the thickness lies between acceptable limits, move the spot vertically so that signals from the test parts do not overlay the reference shim signals, then apply the probe to the test part. The thickness is acceptable if the spot is located between the marks for the upper and lower thickness limits.
- (l) If a large number of measurements are required to be measured, the settings should be checked at least every 30 minutes.

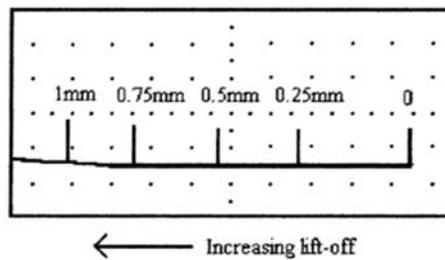


FIG. 5.23. The screen display for calibration to measure non-conducting coating thickness in the range 0 mm to 1 mm. The position of the spot is marked for each reference standard by using the Y position control to change the Y position then return it to its original position.

5.1.5 Thickness measurement of conductors

Introduction

The thickness of conducting materials can be measured because, provided the thickness is less than the effective depth of penetration, the eddy current signal depends on the thickness (see FIG. 5.24). Ultrasonic testing can also be used for thickness measurement, but eddy current thickness measurement is preferred for thin materials because it is easier to obtain accurate readings. The technique can also be applied to measure the thickness of a conducting coating on a nonconductor, for example, metal coatings on plastic.

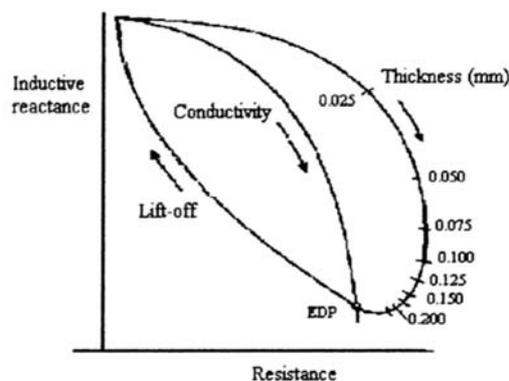


FIG. 5.24. Impedance diagram showing the conductivity curve and the locus of the operating points for thin red brass (conductivity approximately 40% IACS) at 120 kHz (the thickness curve). The thickness curve meets the conductivity curve when the thickness equals the Effective Depth of Penetration (EDP).

Probe and frequency selection

The types of probe most suitable for thickness testing of conductors are the same as the types used for measuring non-conducting coating thickness on conductors. Spot probes, absolute or reflection, with or without spring loading, are normally used, but pencil probes with a probe holder, preferably sprung to minimize lift-off, can also be used. Probes or probe holders in the form of a V-block or with a contoured face should be used on curved surfaces.

The basis for the selection of test frequency is the same as that for the selection of frequency for the detection of subsurface flaws. In fact the detection of corrosion and measurement of its depth is a thickness measurement problem. The frequency should be low enough so that the eddy current intensity at the far surface is relatively high, but low enough to give a relatively high degree of phase separation between signals from different thicknesses. Therefore, the operating frequency should be f_{90} . Normally, t in this formula would equal the maximum thickness to be measured.

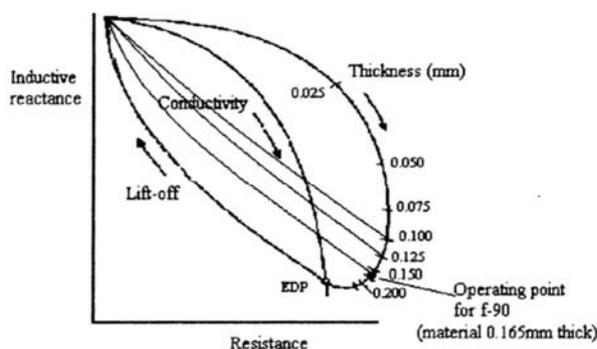


FIG. 5.25. Impedance diagram showing the conductivity curve, and the thickness curve for brass at a frequency of 120 kHz, the f_{90} frequency for a thickness of 0.165 mm. The operating point for this thickness is shown, and lift-off curves for this and various other thicknesses are also shown.

Signals from variations in thickness

If the test frequency is set to f_{90} for the thickest material to be tested, the operating point is far down the thickness curve, and the lift-off curve from this point is approximately 90° to the thickness curve, as shown in FIG. 5.25. For this diagram, the thickest material to be tested is 0.165 mm, and the frequency is 120 kHz. The eddy current instrument display is normally set up with the lift-off trace horizontal to the left. FIG. 5.26 shows part of the display shown in FIG. 5.25, rotated so that the lift off trace from the operating point is horizontal (for clarity, the conductivity curve is not shown). It can be seen that, if the probe is applied to thinner material, for example material 0.125 mm thick, the signal will be almost parallel to the lift-off signal for the 0.165 mm thick material, but will be further up the screen.

On the other hand, if material 0.165 is being scanned and the material gradually becomes thinner, the spot will move up the screen along the thickness curve.

Material significantly thicker than that for which f_{90} was calculated should not be thickness tested because the sensitivity to changes in thickness reduces rapidly below the f_{90} operating point, as shown in FIG. 5.25. This FIG. also shows that the thickness curve crosses the conductivity curve as the thickness approaches the effective depth of penetration. This means that, when operating in this region of the curve, the same lift-off trace would be obtained from two different thicknesses of material.

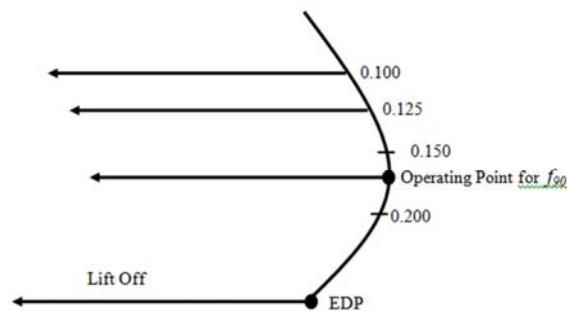


FIG. 5.26. Part of the display shown in FIG. 5.25, rotated so that the lift off trace from the operating point is horizontal, as it would appear on an eddy current instrument display. The lift-off traces are shown as straight lines, but they normally appear slightly curved

Reference specimens

Reference specimens should consist of shims or sheets of the material to be tested (or of a material of the same conductivity) which cover the expected range of thickness. As for non-conducting coating thickness measurement, if the measurement is to determine whether or not the test part thickness lies within a given range, one specimen with the thickness of the lower limit and one with the thickness of the higher limit should be used. However, a third specimen, with thickness in the middle of the range, is desirable. If, however, the actual thickness of the material is to be measured, at least three specimen thicknesses are required. These should have thicknesses equal to the maximum and minimum expected thicknesses, and one approximately midway between these. More shim thicknesses may be required if a wide range of thickness is being measured and the response is notably nonlinear.

Measurement procedure

- (a) Connect the probe to be used to the instrument, switch on the test instrument and allow it to warm up for at least 5 minutes.
- (b) Ensure the test area is clean and free from dirt or other contaminants.
- (c) Select the frequency required, and set the gain to the middle of its range.
- (d) Apply the probe to the thickest reference sample, balance the instrument, and adjust the phase so that the lift-off signal is horizontal to the left.
- (e) With the probe still on the sample, adjust the spot position to a location towards the lower right hand corner of the display (see FIG. 5.27).
- (f) Apply the probe to the thinnest reference sample and check whether a signal is displayed. Do not rebalance. If visible, the spot should lie above the previously obtained signal. Adjust the gain so that the spot is located towards the upper right hand corner of the screen. If the spot is not visible, first reduce the gain until it becomes visible, then further adjust the gain to locate the spot towards the upper right hand corner of the screen, as shown in FIG. 5.27.
- (g) For some instruments, changing the gain changes the balance, so steps (4), (5), and (6) should be repeated to ensure that the spot is located towards the lower right hand corner of the display with the probe on the thickest sample, and towards the upper right hand corner of the screen with the probe on the thinnest specimen.

- (h) Locate the probe on the other reference sample(s) in turn and note the signal, but without rebalancing.
- (i) If measurement of the thickness is required, draw up a graph of the vertical location of the trace, measured in millimetre or number of scale divisions from top or bottom of the screen along a suitable vertical line on the screen, versus the thickness. If the graph is sharply curved, more reference standards may be required so that an accurate smooth curve can be plotted. Once a satisfactory graph has been obtained, carry out thickness measurement by applying the probe to the test part, measuring the vertical position of the trace from the top or bottom of the screen, then using the graph to determine the thickness.
- (j) Alternatively, if the measurement is being carried out to verify whether the thickness lies between acceptable limits, note the positions of the trace from the upper and lower thickness values, then apply the probe to the test parts. The thickness is acceptable if the trace is located between the positions for the upper and lower thickness limits.
- (k) If a large number of measurements are required, the calibration should be checked at least every 30 minutes. The calibration should also be checked on completion of testing.

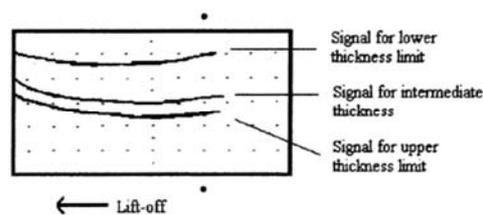


FIG. 5.27. The eddy current instrument display after setting up to verify that the thickness of the test samples lies between acceptable limits.

5.1.6 Thickness measurement of conducting coatings on conductors

The thickness of one conductor on a conducting substrate, for example, metallic plating on metals, can be measured by eddy current techniques provided the ratio of the conductivity of the metals is greater than 1.5. The technique is equally applicable to low conductivity coatings on a higher conductivity substrate and high conductivity coatings on a lower conductivity substrate. It can also be applied to non-ferromagnetic conducting coatings on a ferromagnetic substrate.

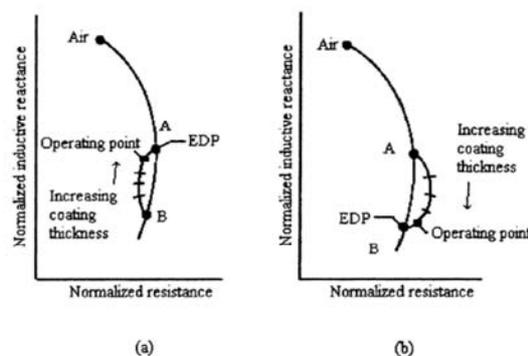


FIG. 5.28. Impedance diagrams showing the loci for variations in the thickness of one conductor on another. (a) shows the thickness of a lower conductivity metal (A) on a higher conductivity metal (B), (b) shows the thickness of a higher conductivity metal (B) on a lower conductivity metal (A).

FIG. 5.28 shows the impedance curves for the two cases involving non-ferromagnetic materials. The coating thickness curves meet the conductivity curve when the thickness of the coating equals the effective depth of penetration (EDP) of the eddy currents in the coating. As with the measurement of the thickness of a conductor, the test frequency should be f_{90} calculated on the thickness of the coating. This gives operating points at the locations marked on the curves. A further factor that needs to be taken into account when selecting test frequency is to avoid, if possible, the eddy currents penetrating through the substrate, as then substrate thickness will affect the reading. Frequencies higher than f_{90} may be required for this purpose. To determine if the eddy currents penetrate through the substrate, the material may be laid on a block of copper. If a signal is not obtained, the eddy currents do not penetrate.

The requirements for reference specimens and the test procedures are essentially the same as for measuring the thickness of conductors.

5.2. Tube testing

5.2.1 Tube testing using internal probes

Eddy current testing of tube using internal probes is one of the major applications of eddy current testing, and is used for testing tubular heat exchangers, for instance in condensers in power generation plants, and large air conditioning units. The testing is carried out to detect corrosion and cracking at the inside and outside surfaces, and estimation of the depth of any flaws is an important aspect of the testing so that action can be taken before tubes start leaking.

Tube testing probes and their sensitivity

The standard absolute internal probe for tube testing, commonly called a bobbin probe, consists of a short cylinder with a coil wound in a groove around its circumference (see FIG. 5.29a). Differential bobbin probes have two coils wound side by side (FIG. 5.29b). The tubes normally tested by this method generally have an outside diameter in the range approximately 12 mm to 30 mm, with wall thicknesses in the range approximately 0.7 mm to 3 mm. The probe diameter is matched to the internal diameter of the tube being tested, with a clearance of between approximately 0.8 mm to 1.5 mm on diameter, the larger clearance being for large diameter or damaged tubes.

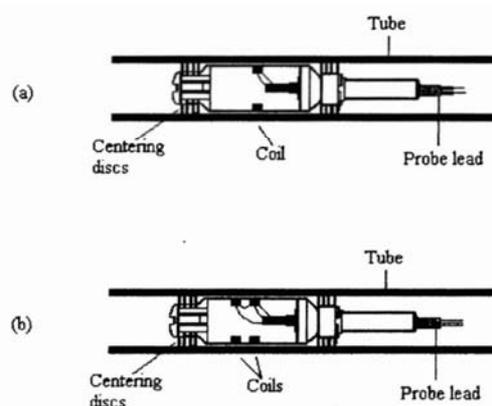


FIG. 5.29. Sections through a standard absolute bobbin probe (a) and a standard differential bobbin probe (b). Centring discs are not always present.

The coil(s) in bobbin probes produce magnetic fields similar to those produced by surface testing probes, but because the coil is concentric with material of the tube, the eddy currents flow circumferentially around the tube wall. Since flaws can be detected only if they distort the flow of eddy currents, this means that a lamination or other separation of the material parallel to the surface of the tube cannot be detected. Fortunately, this is not a common flaw in tubes, and is usually not very harmful to the service of the tube. However, it also means that narrow circumferential or transverse flaws cannot be detected, as shown in FIG. 5.30. Such flaws include fatigue cracks and stress corrosion cracks. Stress corrosion cracks are often branched rather than a single material separation, and, if so, may be detected. Fatigue cracks, however, are not branched, so the likelihood of detection is very low. Flaws which progress along the tube, like seams, and flaws which are relatively wide, like fretting grooves and corrosion pits, can be readily detected if they are of a significant size.

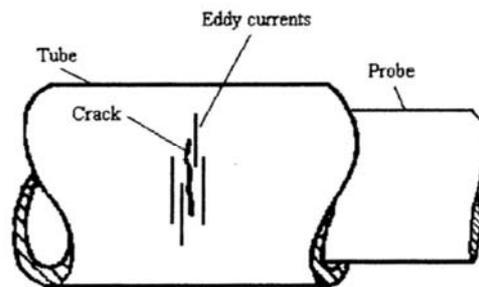


FIG. 5.30. Sketch of a tube being tested with a bobbin probe showing that a transverse crack does not distort the eddy currents, and so is not detected.

Other probe designs are available which are capable of detecting narrow transverse cracks as well as other flaws. These include zigzag probes, and differential probes with the two coils mounted with their axis normal to the tube axis and at right angles to each other (FIG. 5.31). One of these types of probe should be used when fatigue or stress corrosion cracking is a known problem or is suspected.

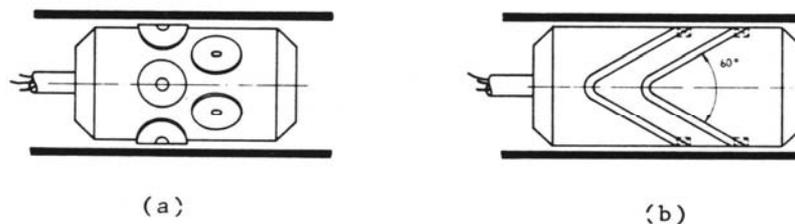


FIG. 5.31. (a) multi-coil pancake style probe and (b) zigzag style probe.

To obtain adequate sensitivity to flaws at the outside surface of the tube, the depth of penetration of the eddy currents must be adequate to obtain a relatively strong eddy current intensity at the outer surface. The depth of penetration can be increased by reducing the test frequency but, just as with surface testing, the coil dimensions have a major effect on the size of the coil's magnetic field and consequently on the depth of penetration of the eddy currents. For surface testing, the coil diameter can be increased to increase the penetration, but with tube testing, the coil diameter is controlled by the tube inner diameter, and it is the depth and particularly the axial length of the coil windings which are increased to increase the penetration. However, increasing either the depth or length of the coil reduces sensitivity to small discontinuities. For the best compromise between penetration and sensitivity, the coil

length and thickness (depth of the windings) should be approximately equal to the tube wall thickness. Note that, since probes with wide coils are designed for penetration, they are also designed to operate at low frequencies. Absolute probes have only one coil sensing the test material. The balance load may be within the probe, or elsewhere in the electric circuit. Differential probes have two coils sensing the test material, with the coils connected on adjacent arms of the bridge circuit. Because of this, differential probes give a signal only when the two coils sense different conditions. Therefore, identical conditions and gradually varying conditions, like gradual wall thinning, cannot be detected by differential probes. Long flaws, such as a seam in a tube, will give a signal only at their beginning and end. In addition, because they give more complex signals (discussed later), interpretation of signals can be much more difficult. Despite these disadvantages, they are more commonly used than absolute probes. This is largely because probe wobble noise is much less, and temperature drift and wandering of the spot because of changes in the conductivity of the tube are almost absent.

As for surface testing, the test sensitivity also depends on the degree of magnetic coupling. When testing with internal coils, the magnetic coupling is measured as the fill factor, given the symbol η (the Greek letter 'eta'), and defined as the ratio of the average area of the coil to the inside area of the tube.

The fill factor can also be expressed as a%. For maximum sensitivity, the fill factor should be as high as possible compatible with easy movement of the probe in the tube. Note that the fill factor can never exceed 1 (100%).

Selection of test frequency

The impedance diagram for testing tubes with internal probes is of the same general shape as the impedance diagram for surface testing of materials. Since detection of flaws at both the inner and outer surfaces is required, the test frequency is chosen so that the tube wall thickness is less than the effective depth of penetration. That is, the operating point is located on a thickness curve rather than on the conductivity curve. The location where each of the thickness curves meets the conductivity curve occurs when the tube wall thickness equals the effective depth of penetration. The location of this point on the conductivity curve depends on the test frequency, the conductivity of the curve and the tube diameter - as any of these increases, this point moves further down the conductivity curve. Note that this is similar to surface testing except that, for tubes, the tube diameter is the relevant parameter, not the coil diameter as for surface testing. The reason for this is that it is actually the diameter of the eddy currents that is the significant parameter. For surface testing with standard probes, the strongest eddy currents flow immediately beneath the coil, so the diameter of the eddy currents is essentially the same as the coil diameter. For tubes, the eddy currents flow in the tube and so their diameter is essentially that of the tube.

The basis for the selection of test frequency is the same as that for the selection of frequency for surface testing for subsurface flaws or thickness measurement. The frequency should be low enough so that the eddy current intensity at the outside surface is relatively high, but low enough to give a relatively high degree of phase separation between signals from different thicknesses. Therefore, the normal operating frequency should be the frequency which gives a f_{90} separation between the signals from a shallow inside surface flaw and a shallow outside surface flaw. However, because of the difference in configuration between surface testing and tube testing, this frequency is that at which the tube wall thickness equals approximately 1.1 standard depths of penetration.

$$f_{90} = 530 / (t^2 \sigma) \quad (5.4)$$

where

f_{90} = the operating frequency (kHz),

t = the tube wall thickness (mm), and

σ = the conductivity of the test material (% IACS)

An impedance diagram showing the signals from a shallow inside surface flaw and a shallow outside surface flaw is shown in FIG. 5.32. It can be seen that, as the frequency increases, the phase separation between the inside surface flaw and the outside surface flaw increases, but the amplitude of the outside surface flaw decreases relative to the inside surface flaw.

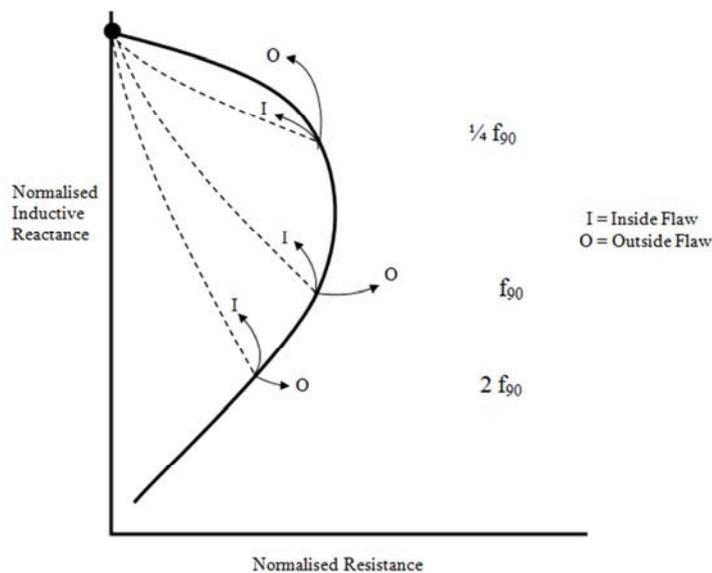


FIG. 5.32. Impedance diagram showing the signals from a shallow inside surface flaw and a shallow outside surface flaw at three different frequencies. The increase in the phase separation and the decrease in the amplitude of the outside surface flaw relative to that of the inside surface flaw can be seen.

Flaw signals from absolute probes

At f_{90} , the signals obtained using an absolute probe from a tube with a shallow inside surface flaw, a shallow outside surface flaw, and a through hole appear as shown in FIG. 5.33 when the display is rotated so that the orientation is similar to that obtained from the same conditions during surface testing. Note that a signal from decreasing fill factor is not normally obtainable. Instead, for tube testing, the phase control is adjusted so that the signal from a shallow inside surface flaw is approximately horizontal. Note that the illustration of absolute probe signals in the ASME code is rotated 180° and is therefore upside down with respect to FIG. 5.33. However the Code states that signals may be rotated to the upper quadrants at the convenience of the operator. Since it is standard practice internationally when performing surface testing to adjust the phase to give the signal orientation shown in FIG. 5.33, it is strongly recommended that the same orientation be used during tube testing to avoid possible confusion.

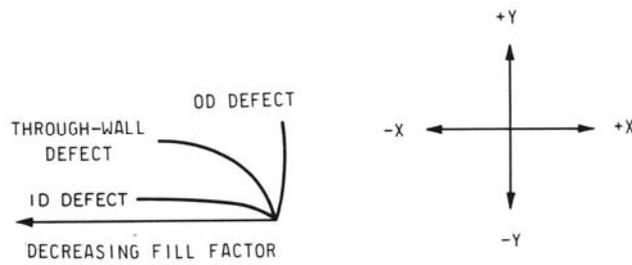


FIG. 5.33. The instrument display using an absolute probe for shallow inside and outside surface flaws and a through hole at f_{90} . The fill factor signal is not normally obtainable so is shown dashed.

At f_{90} , all flaw signals appear in the quadrant between the signals for a shallow inside surface flaw and those for a shallow outside surface flaw. Flaw signals which appear between those for a shallow inside surface flaw and a through hole indicate a flaw at the inside surface, and flaw signals which appear between those for a shallow outside surface flaw and a through hole indicate a flaw at the outside surface.

Absolute probe signals from other conditions

During testing of in-service tubes, signals from a number of conditions other than flaws are displayed on the screen. Some of these signals can appear at similar phase angles to those of flaws. It is therefore important to be familiar with these signals and how to distinguish them from flaw signals. These conditions include the following.

(a) Probe wobble

Probe wobble appears as a variation in fill factor and so gives an approximately horizontal signal either side of the operating point for all test frequencies, as shown in FIG. 5.34. This signal is readily distinguishable from flaw signals, but can add noise to other signals and so is undesirable. High frequencies increase the relative intensity of the inside surface eddy currents and so cause greater probe wobble signals. The signals can therefore be reduced by decreasing the test frequency. This may not be acceptable because of decreased sensitivity to the outside surface conditions, so if probe wobble noise is a problem, a slightly larger diameter probe should be used. Alternatively, the probe being used could be wrapped with adhesive tape to reduce wobble.

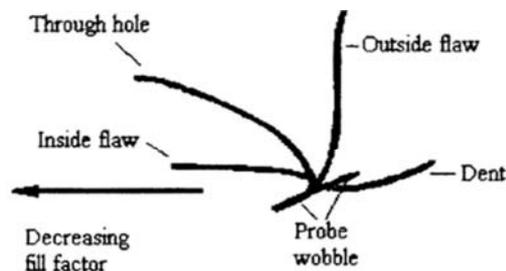


FIG. 5.34. The instrument display using an absolute probe for various flaws, probe wobble and a dent at f_{90} .

(b) Dents

Dents can be present in tubes in heat exchangers because of the buildup of corrosion products between the tube and a baffle plate or tube support sheet, and from other causes. The stresses associated with them can lead to stress corrosion cracking or fatigue cracking. A dent causes a reduction in inside and outside diameters without any significant thinning of the tube wall, and therefore appears as an increase in fill factor at all test frequencies, as shown in FIG. 5.34. This signal is readily distinguishable from flaw signals.

(c) Ferromagnetic conditions at the inside surface

A ferromagnetic inclusion at or near the inside surface of a nonferrous tube or an accumulation of iron oxide corrosion product give a similar signal. In both cases the ferromagnetic material increases the amount of flux which in turn increases the inductive reactance of the coil. The signal produced is therefore in the upwards direction on the impedance diagram, whatever the test frequency. However, although the direction on the impedance diagram varies little with frequency, the direction relative to the fill factor direction or the direction of flaw signals varies considerably. This can be seen in FIG. 5.35. At f_{90} (and at higher frequencies) the signal appears between the shallow inside surface flaw and shallow outside surface flaw signals, and so could be mistaken for a flaw signal (see the two lower operating points in FIG. 5.34).

A signal from a ferromagnetic condition at the inside surface can be distinguished from a flaw signal by retesting at a lower frequency, for example, $1/4 f_{90}$ or lower. As the frequency is reduced, the angle between the shallow inside surface flaw and the shallow outside surface flaw signals decreases, as shown in the upper operating point in FIG. 5.34. That is, the outside surface flaw signal rotates anticlockwise towards the inside surface flaw signal. However, a signal from a ferromagnetic condition at the inside surface will rotate slightly clockwise.

(d) Ferromagnetic conditions at the outside surface

A ferromagnetic condition at the outside surface gives the same signal as a ferromagnetic condition at the inside surface except that, because the eddy currents which are affected by it have a phase delay with respect to the inside surface eddy currents, the signal shows a phase shift. In addition, the eddy currents at the outside surface have a lower intensity than those at the inside surface, so the signal amplitude is less for a ferromagnetic condition at the outside surface. That is, the difference is the same as the difference between the signals from flaws at the outside and inside surfaces. At a test frequency of f_{90} , outside surface signals are rotated 90° clockwise with respect to inside signals. At lower frequencies, the phase rotation is less, but the signal amplitude is greater, whereas at higher frequencies, the phase rotation is greater, but the signal amplitude is less.

FIG. 5.36 shows the signal from a ferromagnetic condition at the outside surface. It could be confused with a signal from a dent, but the two can readily be distinguished if required by retesting at a different test frequency. The signal from a ferromagnetic condition at the outside surface will show phase rotation with respect to the signal from an inside surface flaw, as stated above, whereas a dent signal will remain approximately 180° from the inside surface flaw signal.

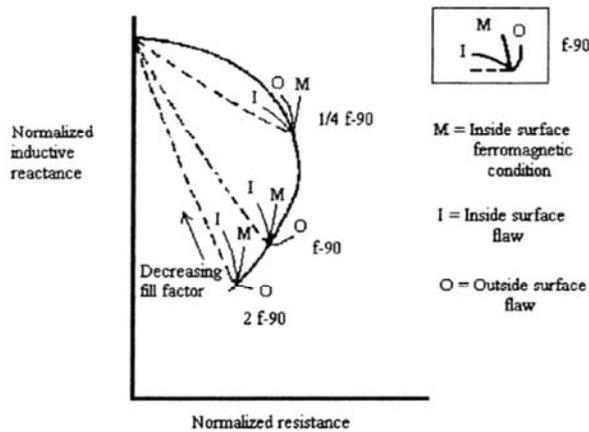


FIG. 5.35. Impedance diagram showing flaw signals and a signal from an inside surface ferromagnetic condition at three different frequencies. The insert shows the signals at 190 rotated to their approximate orientation on an eddy current instrument display.

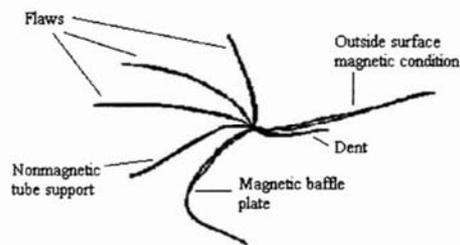


FIG. 5.36. The signals from a typical absolute probe from flaws, an outside surface ferromagnetic condition, a dent, a ferromagnetic baffle plate and a non-ferromagnetic support tested at f_{90} .

- (e) Non-ferromagnetic support or baffle plates and conducting deposits at the outside surface

A non-ferromagnetic tube support or baffle plate gives the combined effect of an increase in thickness of the tube, and, if the support has a different conductivity from that of the tube, a change of conductivity, rotated clockwise because of phase shift. At f_{90} the operating point is relatively low on the thickness curve, similar to that shown in FIG. 5.25 for surface thickness testing. The large increase in thickness (greater than the effective depth of penetration) caused by a support plate moves the spot to the EDP location on the conductivity curve, and so gives a signal in the lower left quadrant, as shown in FIG. 5.36. This signal will be modified by any difference in conductivity between the support and the tube. A change of conductivity will give a signal approximately parallel to the conductivity curve, which is approximately vertical. A decrease in conductivity will move the spot generally upwards, whereas an increase in conductivity will move the spot generally downwards. However, the conductivity change occurs at the outside of the tube, and is therefore phase shifted. At f_{90} , this phase shift is 90° clockwise, so if the conductivity of the support is less than that of the tube, the spot will move generally to the right. Whereas, if the conductivity of the support is greater than that of the tube the spot will move generally to the left. Consequently, the effect of a difference in conductivity between the support and the tube is to rotate the increase in thickness signal anti-clockwise if the support has a lower conductivity and clockwise if the support has higher conductivity.

This leads to the possibility of the support signal being rotated sufficiently clockwise to appear above the horizontal, at an angle similar to that for an inside surface flaw. One condition when this is possible is the deposition of copper on the outside surface of a tube. Copper can be leached out of copper alloys and redeposited on tube surfaces, particularly adjacent to tube supports. Even very thin copper deposits give a strong signal because of the high conductivity of copper. If this condition is suspected, retesting at a lower frequency, for example $1/2 f_{90}$, should be carried out. This will reduce the phase shift of the signal so that it appears in the lower left quadrant, easily distinguishable from inside surface flaws.

(f) Ferromagnetic support or baffle plates

The signal from ferromagnetic support or baffle plates is complex because it combines an increase of thickness, a phase shifted change of conductivity, and a phase shifted increase in permeability. The first two effects give a signal similar to that of a non-ferromagnetic baffle plate, and move the spot downwards and to the left. In fact, the signal from a ferromagnetic baffle plate commences in much the same way, because there is little magnetic response to the very weak magnetic field produced initially in the baffle plate. However, as the probe gets closer to the baffle plate, the magnetic effect increases, and the spot moves sideways to the right, as was the case for a ferromagnetic condition at the outside surface. The signal therefore usually has a distinct bend in it, giving rise to a characteristic hooked or curved signal (see FIG. 5.36).

Absolute probe signals from ferromagnetic baffle plates are below the horizontal and so are not readily confused with flaw signals. However, corrosion is common at the locations of baffle plates, and, if a flaw does occur at this location, the signal will be a combination of the two conditions, and may be difficult to interpret. Baffle plate signals should therefore be examined carefully, and any difference from the usual signal for the particular installation needs to be analyzed to determine if it incorporates a flaw signal. Fortunately this is often possible because eddy current signals are generally vectorially additive. This means, for instance, that if one condition causes the spot to move upwards and another concurrent condition causes the spot to move to the left, then the spot will move obliquely, upwards and to the left. FIG. 5.36 shows the vectorial addition of a baffle signal and the signal from a fretting groove (caused by vibration between the tube and the baffle). Vectorial analysis of non-ferromagnetic support plate signals is usually not possible because the support plate signal predominates and does not show the characteristic curve or hook, any variation or distortion of which is more readily recognized.

The best method of achieving reliable flaw detection at the location of baffles is to use multi-frequency testing, outlined later in this manual.

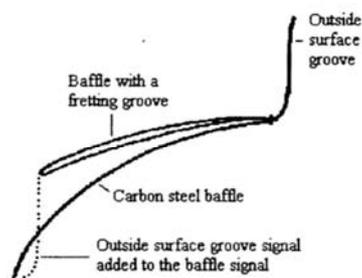


FIG. 5.37. The signals from a carbon steel baffle, an outside surface groove, and the two conditions occurring concurrently showing that the combined signal is produced by vectorial addition of the two component signals.

Signals from differential probes

The signals produced by a differential probe have a characteristic appearance as shown in FIG. 5.38. This is because only differences in the conditions sensed by the two coils are detected. As the probe is pulled along the tube, the first coil detects the particular condition, and so a signal very similar to that produced by an absolute probe is produced. However, as the probe is pulled further along, the second coil starts sensing the condition. The difference between the two coils is reduced, and so the signal amplitude decreases until, when the condition is detected equally by the two coils, the spot returns to the operating point. As the probe is pulled further along, the condition is sensed more by the second coil than the first coil, so the bridge becomes unbalanced in the opposite direction, and a signal in the opposite direction is produced.

It should be noted that absolute probe signals, which are close to 180° apart, such as a shallow inside surface flaw and a magnetic deposit at the outside surface, will give very similar differential probe signals. They may be distinguished only by observing the initial direction of movement of the spot, which is the same direction as the absolute signal. It should also be noted that if the probe is pushed rather than pulled, there is no change to absolute signals, but differential signals are traced out in reverse. That is, the initial direction of the spot movement is the opposite to when the probe is pulled, and opposite to the direction of the corresponding absolute probe signal. One other property of differential probe signals is that when a condition persists for some length along the tube, like a seam, the first half of the signal is produced when it detects the beginning of the condition, and the second half of the signal is produced when it detects the end of the condition. In between, when both coils are sensing the condition, there is no signal.

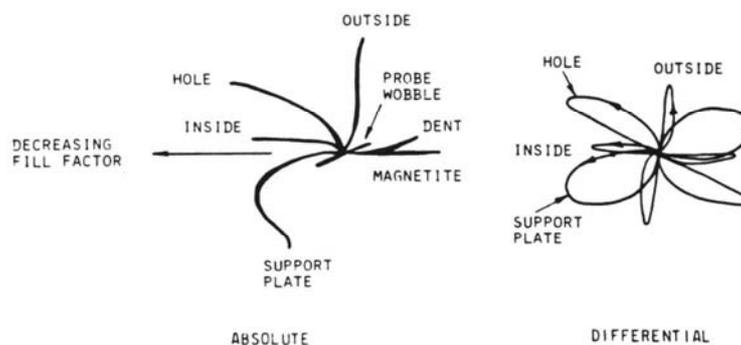


FIG. 5.38. Absolute and differential signals. The absolute signals are more complex and can be more difficult to interpret. For correct interpretation the initial direction of movement of the spot, shown by arrows, must be observed.

Correlating flaw depth and signal phase angle

Usually, evaluation of flaw depth is accomplished by measuring the phase angle of the flaw signal and comparing it to those obtained from a suitable reference standard. This is normally done by using a reference standard of the type indicated in Section V Article 8 of the ASME Boiler and Pressure Vessel Code, to prepare a graph correlating flaw depth and signal phase angle. The ASME reference standard contains flat bottom holes 20%, 40%, 60%, and 80% of the tube wall thickness from the outside surface, and a through hole. If these artificial flaws in the reference standard represent the flaws being analyzed, then reasonably accurate results can be obtained. However it should be realised that some flaws, for example, narrow

circumferential flaws like fretting grooves, and the grooves in the common British reference tube, will not show the kind of correlation of phase angle and flaw depth shown by the ASME reference tube.

A typical curve correlating flaw depth and phase angle is shown in FIG. 5.39. That is, higher frequency provides greater phase separation than the other frequencies shown. Analysis shows that the accuracy of flaw depth estimation by correlating flaw depth and phase angle increases with increasing frequency. The optimum frequency for evaluating flaw depth by relating it to signal phase angle has been found to be approximately $2f_{90}$, and this frequency is recommended for defect evaluation. (The optimum evaluating frequency, based on a 90° separation between the through hole and a flaw at 50% of the wall thickness at the outside surface, is $2.2f_{90}$).

Higher frequencies than $2.2f_{90}$ may give greater accuracy, but the signal from a shallow flaw at the outside surface will then approach the horizontal (180°) and so could be confused with a dent indication or probe wobble signals. Also, higher frequencies reduce the strength of signals from flaws at the outside surface. It should be noted that operating at $2f_{90}$ rotates signals from conducting non-ferromagnetic deposits at the outside surface to over 360° - that is, to the region occupied by flaws at the inside surface. Care must be taken therefore to correctly identify signals from such deposits at the frequency used for detection of signals (f_{90}) before changing to the evaluation frequency. The accuracy of flaw depth estimation increases with increasing flaw depth. This is advantageous because the greater flaw depths are of course more critical.

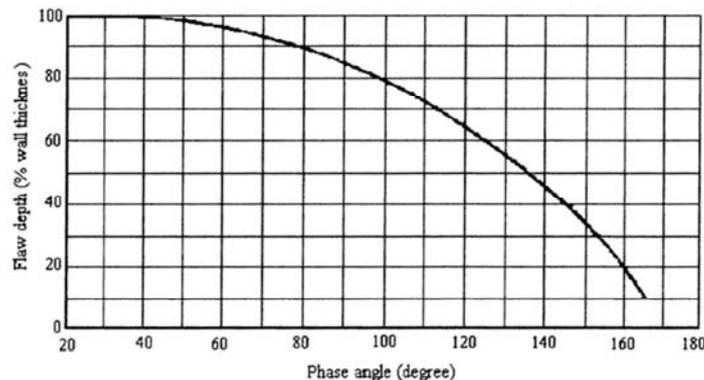


FIG. 5.39. Graph showing the correlation between signal phase angle and flaw depth for flaws which extend for some distance along the tube, like extended corrosion pitting.

Correlating flaw depth and signal amplitude

As mentioned previously, some flaws do not show the kind correlation of phase angle and flaw depth shown by the ASME reference tube. This can be the case for narrow flaws such as fretting wear at the tube support plates and anti-vibration bars. If it is known that the likely type of flaw shows correlation between signal amplitude and flaw depth, signal amplitude may be used to estimate flaw depth. A suitable reference standard containing artificial flaws simulating the type of flaw expected should be prepared and a graph correlating signal amplitude with flaw depth, such as shown in FIG. 5.40, should be prepared.



FIG. 5.40. Graph showing the correlation between signal amplitude and flaw depth for narrow circumferential flaws like fretting grooves.

5.2.2 Bar and tube testing using encircling coils

Bars and tubes are often eddy current tested during manufacture to detect flaws, or conductivity variations, and to measure their diameter. Both are tested using encircling coils, which can be absolute or differential. A common setup is to use differential coils with an external reference. A reference bar, known to have the required properties, is inserted in one coil, and the bars to be tested are passed through the balance coil. Any difference between the two bars gives a signal, which can be analyzed as required to determine its cause. Eddy current bar testing is usually highly automated, with signals recorded for analysis, or automatic marking of the product at locations showing signals from unacceptable conditions.

The following outlines bar testing using encircling coils, but it is a specialized application, and further information should be sought by those responsible for setting up or modifying such test systems. ^a The approach to testing bars with encircling coils is similar, but complicated by differences in the ratio of inside diameter to outside diameter, and so will not be considered further here.

The sensitivity of encircling coils

The eddy currents produced in a bar by encircling coils flow around the bar parallel to the coil windings, similar to the eddy currents produced in tube by internal bobbin coils. This means that planar discontinuities parallel to the surface of bar and planar transverse discontinuities will not be detected.

The depth of penetration of the eddy currents below the bar surface increases as the frequency, conductivity, and permeability are reduced, but the penetration is further limited because of the configuration, which results on the eddy current density falling to zero at the centre of the bar. FIG. 5.41 shows the eddy current density at various frequencies. It can be seen that the limiting condition is a linear decrease in the eddy current density from a maximum at the surface to zero at the centre of the bar. This means that, however low the frequency, flaws cannot be detected at the centre of a bar by eddy current testing, and ultrasonic testing should be used instead.

As for all eddy current testing, the test sensitivity also depends on the degree of magnetic coupling. When testing with encircling coils, the magnetic coupling is measured as the fill factor (η), as for testing tube with bobbin coils, and is defined as the ratio of the cross-sectional area of the bar or tube to the average area of the coil.

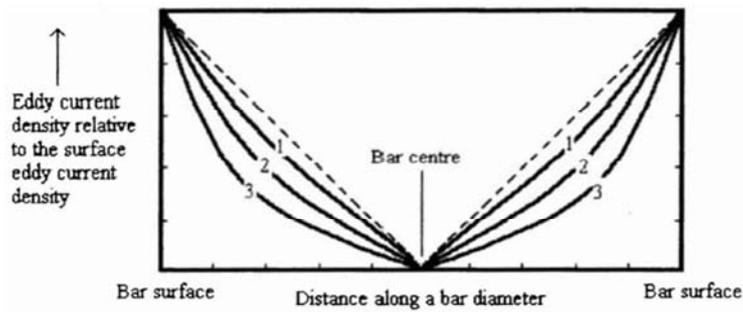


FIG. 5.41. The eddy current intensity along a diameter of a bar. Curves 1, 2, 3, show progressively increasing frequencies. The limiting condition is a linear decrease in the eddy current density from a maximum at the surface to zero at the centre of the bar, shown by the dashed line.

The fill factor can also be expressed as a% and cannot exceed 1 (100%). For maximum sensitivity, the fill factor should be as high as possible compatible with easy movement of the bar or tube through the coil. The clearance required to allow free movement depends on the diameter of the bar or tube, but is commonly 2-3 mm on the diameter.

Selection of frequency

For testing bars with encircling coils, the frequency is usually selected to give an operating point at a particular location on the impedance curve. For surface testing, the concept of the Characteristic Parameter (P_C) was developed for this purpose. Forster, who developed the theory of bar and tube testing using encircling coils, used a different approach and proposed the concept of the limit frequency (f_g). Forster's original formula was:

$$f_g = 5066 / (\mu_r \sigma d^2) \quad (5.5)$$

where

f_g = limit frequency (Hz),

μ_r = relative permeability,

σ = conductivity ($m/\Omega mm^2$), and

d = bar diameter (cm).

The limit frequency is not the test frequency, nor in itself does it have any practical significance for eddy current testing. Its importance lies in the ratio of the test frequency (f) to f_g , which allows determination of the position of the operating point on the impedance curve. This ratio, f/f_g , is therefore the equivalent to the Characteristic Parameter, and is used in the same way by referring to an impedance curve showing values of f/f_g (FIG. 5.42). It should be noted, however, that the value of f/f_g at a particular point on the impedance curve does not equal the value of P_C at the corresponding location (compare FIG. 5.42 with FIG. 5.20).

The value of f/f_g may be calculated for non-ferromagnetic materials using the following formula, which is derived from Forster's but with more practical units.

$$f/f_g = (f d \sigma)/873 \quad (5.8)$$

where:

f = the operating frequency (kHz),

d = bar diameter (mm), and

σ = conductivity (% IACS).

Associated with the f/f_g concept is the law of similarity. This may be stated that, if two test bars are tested at the same f/f_g ratio, the geometrical distribution and the eddy current density are the same. Thus, for instance, if two bars, which may differ in diameter, conductivity, and permeability, both have flaws of the same depth and width measured as a percentage of the bar diameter, the eddy current signals will be identical. This law can be helpful in that experience with bars of one material or diameter can assist in setting up to test and to interpret signals from bars of a different material or diameter. The law of similarity also applies to surface testing, using the Characteristic Parameter, but it is more commonly used to test bars and tubes during manufacture.

The optimum operating point depends on the test application, the general principle being to select a test frequency which optimizes the signal from the property of interest. Testing is usually not conducted near the top of the impedance curve (f/f_g less than 4), because the angle between signals from variations in diameter and variations in conductivity, is quite small, making their separation difficult. In addition, the angle between the signals from flaws at different depths is small, making depth determination difficult. Occasionally, a low frequency and a consequent high operating point may be used to improve penetration in a high conductivity material like copper. Common applications include measurement of diameter, measurement of conductivity, and flaw detection. These as applied to non-ferromagnetic bars are discussed in the following paragraphs. Testing ferromagnetic bars shows some differences and is discussed later in this manual.

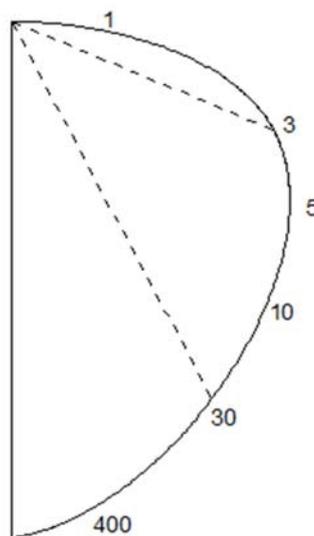


FIG. 5.42. Impedance diagram showing f/f_g values. Fill factor curves from $f/f_g = 3$ and $f/f_g = 30$ (solid curves).

Specific test applications for non-ferromagnetic bars

(a) Measurement of diameter

The main effect of variations in diameter is to vary the fill factor, but a significant second effect is to change the value of f/f_g . A decrease in diameter decreases both the fill factor and the f/f_g ratio, so the operating point follows a locus slightly above the fill factor locus, shown as a dashed line in FIG. 5.41a. For the accurate measurement of diameter, f/f_g should be greater than 4, so that the angle between signals from diameter variations and conductivity variations is reasonably large, allowing them to be reliably separated. If the sole purpose of the test is to measure the bar diameter, a very high frequency, giving an operating point well down the impedance curve, is preferred. Under these conditions, diameter and conductivity signals are well separated, the penetration is quite shallow, giving enhanced sensitivity to the bar surface and enhanced sensitivity to fill factor, as well as reducing conductivity variations in the material below the bar surface. In addition, at operating points low on the impedance curve, sensitivity to conductivity variations is quite low (see FIG. 5.42).

(b) Conductivity

If it is desired to measure conductivity or to compare the conductivity of bars with the conductivities of bars of known conductivity, the operating point should be in the vicinity of the knee of the curve. (For example, to verify the uniformity of heat treatment of aluminium alloy bars, or to sort mixed batches of bar material). That is, the operating point should be similar to that required for conductivity measurement using surface probes. This means that f/f_g should be in close to 6, but any value in the range approximately 4 to 20 could be used.

(c) Flaw detection

Surface flaw indications occur at a small angle to the fill factor signal, just as in surface testing, surface flaw indications occur at a small angle to the lift-off signal. Therefore, steps must be taken in automated testing to ensure that a variation in bar diameter does not register as a flaw. The simplest way of ensuring this is to monitor the component of the signals in a direction at right angles to that of bar diameter variations. That is, if the signal from bar diameter variations is set to be horizontal, the vertical component of any signal is monitored for flaw detection.

Experience has shown that, using this approach, the optimum frequency for the detection of surface-breaking flaws is that which gives an f/f_g ratio in the range 10 to 50, the lower values giving greater sensitivity for deeper flaws.

If subsurface flaws are required to be detected, it should be noted that, because of the relatively rapid decrease in eddy current density below the surface of the bar, flaws lying deeper than approximately 10% of the bar diameter below the surface are unlikely to be detected unless they are relatively large. Lower frequencies and therefore operating points higher on the impedance curve will maximize the penetration. Tests have shown that, if the component of the signals in a direction at right angles to that of bar diameter variations is monitored, an f/f_g ratio of 5 gives approximately equal sensitivity to a given size of flaw regardless of its depth location (up to approximately a depth of 10% of the bar diameter). In addition, f/f_g ratios in the range 5 to 15 give adequate sensitivity to flaws up to this depth, but higher f/f_g give rapidly reducing sensitivity to deeper-lying flaws within this range.

Testing ferromagnetic bars

The impedance curves for ferromagnetic bars are identical in shape to those of non-ferromagnetic bars, but are increased in magnitude by a factor equal to the permeability of the bar. As the permeability of the bar increases, the amount of magnetic flux in the bar increases, and so the inductive reactance increases proportionally. In addition, the increased flux causes an increase in the eddy current intensity, and so the resistive losses of the eddy currents and the effective resistance of the coil also increase proportionally. Therefore the operating point moves down the curve (FIG. 5.42). If the bar diameter increases, the amount of ferromagnetic material in which the magnetic field can be induced also increases, so the amount of magnetic flux in the bar increases. This is exactly the same effect as if the permeability has increased and therefore the two conditions cannot be separated.

Permeability variations in ferromagnetic material are quite common because of small variations in composition, heat treatment, amount of cold work, and residual stress, for example from straightening the bar, and, if the material has been magnetized, because of different degrees of magnetization. This leads to a noisy signal.

These two limitations, the inability to measure bar diameter and noisy signals, and a third limitation, the very restricted depth of penetration because of the high permeability, can be overcome by magnetizing the material to or close to saturation. In this condition, the material has an incremental permeability of, or close to, one, and therefore shows the same behaviour to eddy current testing as non-ferromagnetic material. In this case, the analysis used for non-ferromagnetic bars applies. Ferromagnetic bars and tubes are therefore often tested with two large coils carrying a large direct current, one either side of the eddy current coil(s). The current required is usually large enough to cause heating problems in the magnetizing coils, and pulsing the current and the use of water cooled jackets are often employed to overcome these problems.

Ferromagnetic material can be tested for flaws without magnetizing it, but to detect subsurface flaws, frequencies up to 100 times lower than those used for non-ferromagnetic bars of the same diameter need to be used. If surface flaws only are required to be detected, higher test frequencies can be used, and will improve the sensitivity to such flaws. Flaw signals in ferromagnetic bars show sufficient angular difference from the permeability/bar diameter locus to allow reliable interpretation.

In the lower part of the impedance diagram the directions of conductivity variation and of permeability or bar diameter variation are almost the same. If it is required to distinguish between these, an operating point high up on the impedance curve, where the angle between these two signals is close to 90° , should be chosen.

5.3. Multi-frequency testing

5.3.1 Principles

In multi-frequency testing, two or more sinusoidal signals of different frequencies are fed simultaneously to a single eddy current probe. Gain and phase of the output signal from each frequency can be separately controlled.

Multi-frequency testing allows signals from undesirable variables to be eliminated. Usually, two frequencies are mixed to suppress one variable in order to monitor a second variable. The

most common application is to eliminate unwanted signals, so that signals of interest give clear, easy to interpret indications.

Having obtained signals from the condition to be eliminated at the test frequencies, the amplitude and phase angle of the signal are adjusted and rotated to be nearly equal at the selected test frequencies. These signals are then vectorially subtracted by the instrument, resulting in a 'mixed' output which is insensitive to that condition. The primary frequency used in multi-frequency testing is usually f_{90} and, as a general rule, the second frequency should be no greater than half the primary frequency for external variables and no less than twice the primary frequency for the internal variables.

5.3.2 Equipment

Most modern eddy current systems can be operated at two frequencies, however specialized applications such as tube testing can use up to sixteen (16) channels operating at up to four (4) frequencies. Specialized probes are not required as two or more sinusoidal signals of different frequencies are fed simultaneously to a single probe.

5.3.3 Applications

It is most often used in tube testing, but some surface testing applications also make use of it.

For tube testing examples include, baffle plates, probe wobble and fill factor signals. For surface testing examples include fasteners, skin distortion/separation and geometry signals.

In tube testing a third frequency is sometimes used to eliminate probe wobble noise or signals from dents. In general, higher operating frequencies are used the suppression of internal variables like probe wobble or dents, whereas low and intermediate frequencies are used for the suppression of external variables like baffles.

6. PRESENTATION OF RESULTS

6.1. Eddy current testing codes and standards

There are many international, European, and national standards relating to eddy current testing, published by organisations and associations such as:

| | |
|------|--|
| ISO | International Organization for Standardization |
| AS | Australian Standard |
| ASME | American Society of Mechanical Engineers |
| ASTM | American society for Testing and Materials |
| CNS | Canadian National Standard |
| DIN | German National Standard |
| EN | European Norms |
| JIS | Japanese National Standard |
| SAE | American Society of Automotive Engineers |

These standards cover such topics as:

- The measurement of nonconductive coating thickness on metals: ISO 2360, ASTM B244, ASTM D1400.
- Sorting non-ferromagnetic metals: ASTM E703
- Conductivity testing: SAE AS 915
- Evaluation of corrosion: ISO 11463
- Testing welds: EN 1711
- Testing rod and bar: ASTM E215, ASTM E1606
- Testing tubes: EN 10246, ASTM E243, ASTM E571, ASTM E426, JIS H0515, DIN 54141, ASME V
- Testing aircraft structures: SAE ARP 4402
- Testing for surface flaws: AS 4544.1
- Equipment characteristics and verification: EN 13860, CNS Z8012900, JIS Z2314

6.2. Standards for equipment characteristics and verification

Different standards and procedures will specify the requirements for equipment verification. Due to the large numbers of variables associated with eddy current testing, and the majority of techniques being comparison based, the requirements for equipment verification are typically minimal.

The following example is taken from AS4544 (2005):

- (a) The test system shall be capable of generating an operating frequency suitable for conducting the specified eddy current test. It shall also be capable of displaying the test information in an acceptable format for interpretation.
- (b) The equipment shall be capable of detecting coil impedance changes due to variations in the conductivity of the material under test, and the presence of surface metallurgical and mechanical discontinuities.
- (c) The sensitivity of the system shall be such that a repeatable change in signal response of the magnitude specified can be detected when the test coil encounters a known specified natural or artificial discontinuity in the calibration reference.
- (d) The amplitude of the response to a natural crack or notch in the calibration standard used for system calibration shall be at least 20% of the full scale of the signalling device. The signal-to-noise ratio shall be 3 to 1 or better.

6.3. Written procedures for eddy current testing

Written procedures differ from standards in that they are much more limited in their application. They are prepared for testing one particular component, or a limited range of similar components or products. They are usually based on a particular standard, and apply the requirements of that standard to the particular product to be tested. They also include the

acceptance/rejection requirements for the particular product, and should give complete guidance on the performance of the test and disposition of the parts.

The general principle governing the preparation of written procedures is that they should be sufficiently detailed, and should specify sufficient control over the test variables, to enable all competent operators working to the procedure to achieve the same results.

The content of written procedures depends on a number of factors, including the purpose of the test (for example, whether flaw detection, material sorting, or thickness measurement) and the type of product it applies to, but they should normally include information on at least the following, if applicable.

- (a) Identification of the component(s) to be tested and description of the test area and flaws sought.
- (b) The type of eddy current instrument and probe(s) to be used. If a particular model of instrument or probe is nominated, acceptable alternatives should also be stated.
- (c) Reference standards.
- (d) Other related or referenced documents.
- (e) The operating frequency or frequencies.
- (f) Full set-up and calibration procedures, including the sensitivity required, and the frequency of calibration.
- (g) Full test instructions including scanning increments and scanning speed, if applicable, with precautions and notes, as appropriate.
- (h) Guidelines for the interpretation of signals.
- (i) Any safety precautions associated with the performance of the testing.
- (j) Disposition instructions for acceptable and unacceptable parts.

Written procedures should also include qualification and certification requirements, including the minimum level of certification, for those performing the testing, as well as identification of the organization which prepared the procedure, the persons who prepared and approved the procedures, and the date of issue and issue number.

Refer to Appendix C for example of written instruction.

6.4. Inspection techniques and their use

It is typical of many standards to include requirements for the test equipment, probes, and reference standards, the calibration procedure and frequency of calibration, information on scanning, and information on interpretation and evaluation of discontinuities. It also gives information on the preparation of a written procedure, which is required for some test applications. Many standards also give requirements for personnel qualification and certification for persons performing the testing.

In lieu of International, European, and national standards, many original equipment manufacturers (OEM's), in particular aircraft manufacturers, supply detailed instructions and procedures for the testing of their equipment.

6.5. Records and reports

6.5.1 Test records

The general principle governing recording of results of any testing is that sufficient detail should be recorded that the test could be repeated in exactly the same way as the original test, as far as this is possible. Much of the required information may be recorded by reference in the test record to the written procedure or other document, such as a company document controlling some aspect of non-destructive testing.

Essentially, the test record consists of information covering what was tested, how, when, where, and by whom it was tested, and the results. This should include at least the following

- (a) Name of the testing authority.
- (b) Identification of the component(s) tested.
- (c) Number of the product standard, if applicable.
- (d) Identification of the written procedure, standard, or other document to which the testing was performed.
- (e) Identification (manufacturer, model number, and serial number) of the eddy current instrument, and of the probes used. If the probes do not have a serial number, they should be given an in-house serial or plant number. The identification of any probe guides, or probe holders used should also be recorded.
- (f) Identification of the reference standards used during the test.
- (g) Any other relevant information on the test procedure, if not as specified in the written practice.
- (h) Results of the test.
- (i) Date and place of test.
- (j) Any other information which may assist in the assessment of the test results.
- (k) Identification and signature of the person performing the testing.

6.5.2 Test reports

A formal test report may be required, but often the results are communicated to the person responsible by other means, for example, tying an annotated 'UNSERVICEABLE' tag to the part, or stamping or signing documentation pertaining to the parts tested. However, if a test report is required, it should include at least the following information:

- (a) Name of the testing authority.
- (b) Identification of the component(s) tested.
- (c) Number of the product standard, if applicable.

- (d) Identification of the written procedure, standard, or other document to which the testing was performed
- (e) Identification of the calibration standards used during the test.
- (f) Results of the test.
- (g) Date and place of test.
- (h) Any other information the person responsible for the parts tested requires for assessment of test results.
- (i) Identification and signature of the person responsible for the test report.

Refer to Appendix C for example of test report.

6.6. Safety

6.6.1 Implementation of industrial safety standards in facilities and equipment in their operation.

The factors determining the safety requirements for any given eddy current inspection will depend upon the following:

- (a) Location of inspection
- (b) Inspection technique
- (c) Components under test
- (d) Working environment
- (e) Equipment used
- (f) Company specific requirements
- (g) National requirements

Specific safety requirements will be defined in the work instruction and or procedures.

Appendix I

EDDY CURRENT SYMBOLS AND UNITS

| <i>Quantity</i> | <i>Symbol</i> | <i>Unit</i> | <i>Unit Symbol</i> |
|--------------------------------|-----------------|--------------------------|--------------------|
| Cross-sectional area | A | metres squared | m ² |
| Radius | r | metre | m |
| Length | l | metre | m |
| Thickness | t | metre | m |
| Width | w | metre | m |
| Diameter | D | metre | m |
| Magnetic flux density | B | tesla | T |
| Capacitance | C | farad | F |
| Frequency | f | hertz | Hz |
| Optimum tube testing frequency | f ₉₀ | hertz | Hz |
| Characteristics frequency | f _g | hertz | Hz |
| Resonant frequency | f _r | hertz | Hz |
| Magnetic field intensity | H | ampere per metre | A/m |
| Current | I | ampere | A |
| Current density | J | ampere per metre squared | A/m ² |
| Self inductance | L | henry | H |
| Number of turns (windings) | N | | |
| Characteristic parameter | P _c | | |
| Resistance | R | ohm | Ω |
| Resistive load | R _L | ohm | Ω |
| Electric potential | V | volt | V |
| Depth below the surface | x | metre | m |
| Inductive Reactance | X _L | ohm | Ω |
| Capacitive Reactance | X _C | ohm | Ω |
| Impedance | Z | ohm | Ω |
| Standard depth of penetration | δ | metre | m |
| Permeability | μ | henry per metre | H/m |
| Resistivity | ρ | microhm-centimetre | μΩ•cm |
| Conductivity | σ | siemens per metre | S/m |
| Magnetic flux | Φ | weber | Wb |
| Fill factor | η | | |
| Phase lag | β | radian | rad |
| Angular frequency | ω | radians per second | rad/s |
| Angle | θ | degree | ° |

Appendix II

GLOSSARY OF TERMS FOR EDDY CURRENT TESTING

Absolute measurements made with a direct reference in contrast to differential measurements.

Absolute probe A probe having a single sensing coil.

Absolute signal The value of the amplitude of a signal without consideration of its relative phase, frequency, or wave form.

Alternating current AC amperes. A current flow changing in amplitude and direction with time.

Anomaly An unexpected, unclassified eddy current signal. A false defect indication.

Bridge Electrical circuit incorporating four impedance arms.

Calibration Standard A test standard used to estimate defect size and setup instrument. Also known as a reference sample.

Capacitive Reactance X_c , ohms. The opposition to changes in alternating voltage.

Characteristic Parameter dimensionless. It allows test coil operating point to be specified in terms of a single quantity rather than four independent variables.

Characteristic or Limit Frequency f_g hertz,

Characteristic Frequency Ratio f/f_g dimensionless. It allows the test coil operating point to be specified in terms of a single quantity rather than four independent variables.

Coil One or more turns of conductor wound to produce a magnetic field when current passes through the conductor.

Coil, Absolute A coil (or coils) that respond(s) to all electromagnetic properties of the test part.

Coil, Bobbin A coil or coil assembly used for electromagnetic testing by insertion into the test piece as in the case of an inside probe for tubing. Coils of this type are also referred to as inside coils or inserted coils.

Coil Circumferential see encircling and internal probes.

Coil Clearance The perpendicular distance between adjacent surfaces of the coil and test part.

Coils, Differential Two or more coils electrically connected in series opposition such that any electromagnetic condition which is not common to the areas of the specimen being tested or the test specimen and the standard will produce an unbalance in the system and, thereby, be detected.

Coil, Encircling Coil(s) or coil assembly which surround(s) the part to be tested. Coils of this type are also referred to as annular, circumferential, or feed-through coils.

Coil, probe A small coil or coil assembly which does not encircle the test specimen.

Coil, Search A probe coil which is used to measure local magnetic field intensities by virtue of the change of flux through the coil when it is moved from one position to another, or when the flux through it is changed by any other means.

Coil Size The geometry or dimension of a coil, for example, length, or diameter.

Coil Spacing The axial distance between two encircling coils of a differential system.

Conductivity σ (sigma), siemens/m. Measure of the ability of a material to conduct current (alternating or direct current)

Conductor Material capable of carrying electrical current.

Coupling An interaction between systems, or between properties of a system.

Current I, amperes.

Depth Of Penetration (Standard) δ (delta), millimetres. The depth at which the eddy current density has decreased to 1/e or 36.8% of the surface density. Also referred to as skin depth. The depth of penetration is an exponential function of the frequency of the signal, and the conductivity and permeability of the material. Synonymous terms are standard depth of penetration and skin depth.

Depth of Penetration, Effective The minimum depth beyond which a test system can no longer detect a further increase in specimen thickness. Eddy current density drops off to 5% of the surface density.

Defect A discontinuity that reduces a material's integrity or service capacity may involve a loss of material. Exceeds acceptance/rejection criteria.

Differential probe A probe having two sensing coils located side by side.

Differentiated An output signal which is proportional to the rate of change of the input signal.

Discontinuity Break in material structure. After detection requires evaluation to determine if it is a defect.

Discontinuity Artificial Reference Discontinuities, such as holes, grooves, or notches, which are introduced into a reference standard to provide accurately reproducible sensitivity levels for electromagnetic test equipment.

Distortion Harmonic Nonlinear distortion characterized by the appearance in the output of harmonics other than the fundamental component when the input wave is sinusoidal. Harmonic distortion is sometimes called amplitude distortion.

Direct Current — I_{DC} , amperes. A current flow that is constant in amplitude and direction with time.

Eddy Currents A closed loop alternating current flow induced in a conductor by a varying magnetic field.

Eddy Current Method An electromagnetic NDT method based on the process of inducing electrical currents into a conductive material and observing the interaction between the currents and the material.

Eddy-current Testing A non destructive testing method in which eddy-current flow is induced in the test object. Changes in the flow caused by variations in the specimen are reflected into a nearby coil or coils for subsequent analysis by suitable instrumentation and techniques.

Edge Effect Signal obtained when a surface probe approaches the sample's edge or geometric boundaries that makes it impractical to apply electromagnetic test methods to the associated regions of the sample..

Effective Depth of Penetration Depth at which eddy current density drops off to 5% of the surface density.

Electromagnetic Testing That non destructive test method for engineering materials, including magnetic materials, which use electromagnetic energy having frequencies less than those of visible light to yield information regarding the quality of the tested material.

End Effect Signal obtained when an internal or encircling probe approaches the end of a tube or rod (similar to edge effect).

Encircling probe (Coil) Also referred to as a feed through coil. A probe which completely surrounds test material; can be absolute or differential.

Feed Through Coil see encircling probe.

Ferrite Ferromagnetic oxide material. Used for cores in high frequency transformers.

Flaw A defect.

Ferromagnetic A material with a relative magnetic permeability greater than 1.0

Fill Factor η (eta), dimensionless. The ratio of the square of the diameter of a cylindrical test specimen to the square of the average diameter of the encircling coil. It is a measure of coupling between the coil and test object. Fraction of the test coil area filled by the test specimen.

Frequency f hertz. Number of cycles of alternating current per second.

Frequency (Angular) ω (omega), radians/second. Angular velocity, where $w = 2 \pi f$.

Frequency, Optimum That frequency which provides the highest signal-to-noise ratio obtainable for the detection of an individual property such as conductivity, crack, or inclusion of the test specimen. Each type of defect in a given material may have its own optimum frequency.

Frequency, Test The number of complete input cycles per unit time of a periodic quantity such as alternating current. The test frequency is always considered to be the fundamental whenever harmonics are generated in the process of testing certain materials such as ferromagnetic materials.

Hysteresis Magnetization curve.

IACS σ_{IACS} . International Annealed Copper Standard. Conductivity as a percentage of pure copper.

Inductance L , henries. Ratio of the total magnetic flux linkage in a coil to the current flowing through the coil.

Impedance Z , ohms. The total opposition in an electrical circuit to flow of alternating current. Represents the combination of those electrical properties that affect the flow of current through the circuit.

Impedance Analysis An analytical method which consists of correlating to changes in the amplitude, phase, or quadrature components, or all of these, of a complex test signal voltage to the electromagnetic conditions within the specimen.

Impedance Method Eddy current method which monitors the change in probe impedance; both phase and amplitude.

Impedance Plane Diagram A graphical representation of the locus of nt points indicating the variations in the impedance of a test coil as a function of basic test parameters.

Inductive Reactance X_L , ohms. The opposition to a change in alternating current flow.

Inductor A coil.

Internal probe (Coil) A probe for testing tubes (or holes) from the inside. The coil(s) is circumferentially wound on a bobbin.

Lift Off mm Distance between the coil of a surface probe and sample. It is a measure of coupling between probe and sample.

Level, Rejection The setting of the signal level above or below which all parts are rejectable or in an automatic system at which objectional parts will actuate the reject mechanism of the system.

Level, Test Quality The sensitivity at which a test is performed.

Material, Diamagnetic A material having a permeability less than that of a vacuum.

Material, Ferromagnetic A material which, in general, exhibits hysteresis phenomena, and whose permeability is dependent on the magnetizing force.

Material, Non-ferromagnetic A material that is not magnetizable and hence, essentially not affected by magnetic fields. This would include paramagnetic materials having a magnetic permeability slightly greater than that of a vacuum and approximately independent of the magnetizing force and diamagnetic materials having a permeability less than that of a vacuum.

Material, Paramagnetic A material having a permeability which is slightly greater than that of a vacuum, and which is approximately independent of the magnetizing force.

Magnetic Flux, webers.

Magnetizing Force H, amperes/metre. Magnetic field intensity.

Magnetic Flux Density B, tesla.

Modulation Analysis An instrumentation method used in electromagnetic testing which separates responses due to various factors influencing the total magnetic field by separating and interpreting individually, frequencies or frequency bands in the modulation envelope of the (carrier frequency) signal.

Noise Any undesired signal that tends to interfere with the normal reception or processing of a desired signal. In discontinuity detection, undesired response to dimensional and physical variables (other than discontinuities) in the test part is called 'part noise'.

Ohm's Law Electromotive force across a circuit is equal to the current flowing through the circuit multiplied by the total impedance of the circuit.

Operating Point Point on the impedance diagram that specifies the normalized inductive reactance and resistance of a coil.

Oscillator The electronic unit in an eddy current instrument that generates alternating probe excitation current.

Parameter A material property or instrument variable.

Performance Standard Also referred to as Reference Standard. A test standard used to qualify and calibrate test system for a particular test.

Permeability (Magnetic) — μ (mu), henry/metre. μ_r dimensionless, relative magnetic permeability. Ratio between flux density, B, and magnetizing force, H. Permeability describes the intrinsic willingness of a material to conduct magnetic flux lines.

Permeability, Effective A hypothetical quantity which is used to describe the magnetic field distribution within a cylindrical conductor in an encircling coil. The field strength of the applied magnetic field is assumed to be uniform over the entire cross section of the test

specimen with the effective permeability, which is characterized by the conductivity and diameter of the test specimen and test frequency, assuming values between zero and one, such that its associated amplitude is always less than one within the specimen.

Permeability, Incremental The ratio of the cyclic change in magnetic induction to the corresponding cyclic change in magnetizing force when the mean induction differs from zero.

Permeability, Initial The slope of the normal induction curve at zero magnetizing force.

Permeability, Normal The ratio of the normal induction to the corresponding magnetizing force.

Permeability, Variations of a Material Magnetic inhomogeneities of a material.

Phase Analysis An instrumentation technique which discriminates and between variables in the test part by the different phase angle changes which these conditions produce in the test signal.

Phase Angle The angular equivalent of the time displacement between corresponding points on two sine waves of the same frequency.

Phase Detection The derivation of a signal whose amplitude is a function of the deviation in phase of a single-frequency alternating quantity, such as voltage or current, from a similar quantity of a fixed phase.

Phase Lag β (beta), radians or degrees. A lag in phase (or time) between the sinusoidal currents flowing at the surface and those below the surface.

Phase Shift A change in the phase relationship between two alternating quantities of the same frequency.

Phasor A vector describing sinusoidal signals; it has both amplitude and phase.

Primary Field The magnetic field surrounding the coil due to the current flowing through it.

Probe Eddy current transducer.

Readout, Absolute The signal output of an absolute coil.

Readout, Differential A signal output obtained from a differential coil

Reference Coil Coil which enables bridge balancing in absolute probes. Its impedance is close to test coil impedance but does not couple to test material.

Reference Sample A test sample of known characteristics used to standardize the equipment.

Reluctance, Circuit The algebraic sum of the reluctances of each portion of the circuit.

Resolution, Defect A property of a test system which enables the separation of signals due to defects in the test specimen that are located in close proximity to each other.

Resonance. A circuit having an inductor and capacitor connected in series or parallel. When inductive reactance equals capacitive reactance the circuit is tuned or in resonance.

Resistance R, ohms. The opposition to the flow of electrical current. Applies to DC and AC.

Resistivity ρ (ro), microhm centimetre. Reciprocal of conductivity ($\rho = 1/\sigma$)

Response, Amplitude That property of the test system whereby the amplitude of the detected signal is measured without regard to phase.

Saturation The degree of magnetization produced in a ferromagnetic material for which the incremental permeability has decreased substantially to unity.

Saturation (Magnetic) A condition where incremental magnetic permeability of a ferromagnetic material becomes 1.0.

Secondary Field The magnetic field produced by induced eddy currents.

Selectivity The characteristic of a test system which is a measure of the extent to which an instrument is capable of differentiating between the desired signal and disturbances of other frequencies or phases.

Send Receive The variations in the test object which affect current flow within the test object can be detected by observing their effect upon the voltage developed across a secondary receive coil.

Sensing Head A probe unit containing a coil, magnet, or magnetic circuit from which a test signal is derived.

Signal A change in eddy current instrument output voltage; it has amplitude and phase.

Signal To Noise Ratio Ratio between defect signal amplitude and that from non relevant indications. Minimum acceptable ratio is 3:1.

Skin Depth See depth of penetration.

Skin Effect A phenomenon where induced eddy currents are restricted to the surface of a test sample. Increasing test frequency reduces penetration.

Standard (1) A reference used as a basis for comparison or calibration. (2) A concept that has been established by authority, custom, or agreement to serve as a model or rule in the measurement of quantity or the establishment of a practice or a procedure.

Standard, Reference A reference used as a basis for comparison or calibration.

Standardization The process of setting equipment parameters to meet procedure or specification requirements.

Surface probe A probe for testing surfaces, which has a finite coverage. The coil is usually pancake in shape.

System, Phase Sensitive A system whose output signal is dependent on the phase relationship between an input and a reference voltage.

Test Coil Coil coupled to test material. It senses geometric, electric and magnetic changes in test material.

Time, Recovery The time required for a test system to return to its original state after it has received a signal.

Voltage V, volts. Electric potential or driving force for current. Output signal from an eddy current instrument.

Vector A quantity having amplitude (magnitude) and direction. Normally represented as a line whose length represents the quantity's magnitude and the angular position the phase (relative to some reference).

Voltmeter The instrument used to measure voltage.

Wobulation An effect which produces variations in an output signal of a test system and arises from variations in coil spacing due to lateral motion of the test specimen in passing through an encircling coil.

Appendix III

EXAMPLE EDDY CURRENT PROCEDURE AND REPORT

III-1. EXAMPLE EDDY CURRENT PROCEDURE

Eddy Current Inspection of Stainless Steel 304 Elbows

SCOPE

Eddy Current Inspection of 72' Stainless Steel 304 Elbows to determine for the presence of surface cracking greater than 2 mm in length.

SAFETY

No objective takes priority over safety. All work undertaken must be carried out in accordance with specific client requirements. Isolation of equipment may be required prior to inspection.

REFERENCED DOCUMENTS

| | |
|--------------|--|
| AS1929 | NDT Glossary of Terms |
| AS 4544—2005 | Non-destructive testing—Eddy current testing for the detection of surface flaws—Ferromagnetic and non-ferromagnetic metallic products. |

PERSONNEL

Personnel performing ultrasonic examination have visual acuity meeting the requirements of ISO 9712.

Examination shall be performed by persons that have ISO 9712 Certification to level 2 minimum.

TEST EQUIPMENT

Facilities Control

You shall use a company supplied calibrated eddy current set with an Impedance Plane Display

- 1) Machine shall be able to operate at frequencies suitable and determined appropriate for inspection.
- 2) The probe shall be able to detect surface cracks greater than 2.0 mm in length.
- 3) Sensitivity shall be repeatable.(Indications from reference sample should be similar to those detected on the specimen under test)
- 4) Signal to Noise shall be better than 3:1
- 5) No probe shall give interfering responses from handling.

PROBE & INSTRUMENT

Probe - 500 kHz Unshielded Absolute Probe

Instrument - NORTEC 500

REFERENCE SAMPLES

Reference samples used to set sensitivity of the eddy current equipment for the detection of surface discontinuities shall have the following characteristics in common with the part under test:

- a. The same base metal type, preferably of identical chemical composition.
- b. Similar electrical conductivity.
- c. The same surface texture.
- d. Similar temperature.

The reference sample shall contain artificial discontinuities as shown in FIG. 1.

NOTES: Reference samples shall comply with the requirements of the purchaser and be traceable to a national standard for dimensional accuracy and material composition conformity. Reference samples shall be appropriately identified to ensure that their drawing or specification number, serial number, alloy type and size of discontinuity are known.

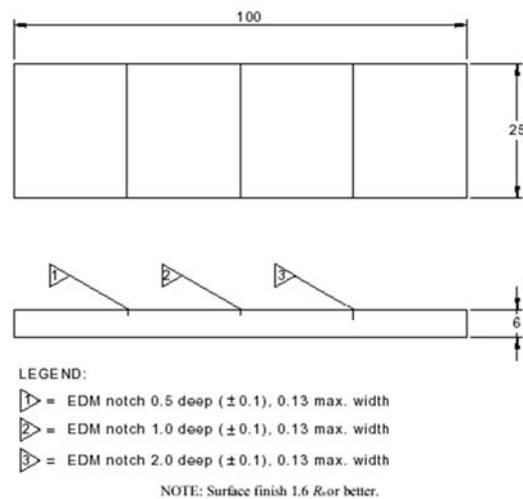


FIG. III-1. Calibration Sample

SURFACE CONDITION

The job shall be in a suitable condition for testing, free of contamination, excessive roughness or excessively heavy paint film. If this is not the case, the operator may request such cleaning as he deems necessary.

TESTING

GENERAL

Inspection of the component will be carried out on both inboard and outboard surfaces.

Inspection is required of 100% of surfaces.

STANDARDIZATION

Set Lift off to Horizontal

Set gain so signal from the 0.5 mm* deep artificial discontinuity = 40% screen range.

*Note: Suitable equivalent sensitivity reference is to be agreed upon in accordance with the clients requirements.

If protective Teflon tape is to be used during inspection, ensure calibration is carried out with this in place.

Set sensitivity of the equipment prior to use and at periodic intervals throughout the inspection. This procedure shall include battery condition checks and sensitivity checks, at approximately 15 minute intervals and at the completion of the inspection.

If an instrument is found to be out of sensitivity, all areas inspected since the previous calibration verification shall be rechecked.

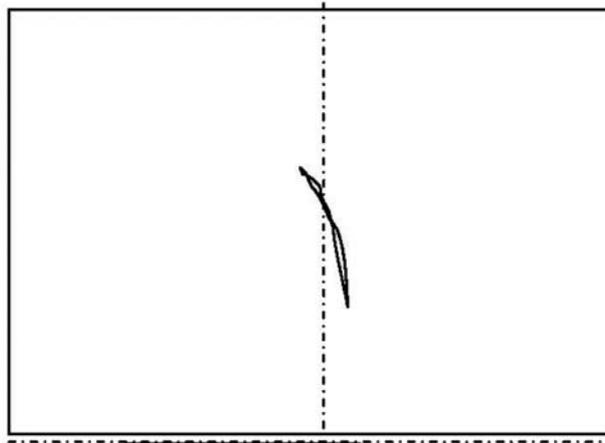


FIG. III-2. Showing Typical Signal from Calibration

SCANNING

Scanning shall be carried out over 100% of area.

Scanning shall be carried out by overlapping scans.

Ensure that the same probe scan speed is used during both instrument standardization and testing.

Do not perform test within 3m of AC fields.

Due to the large area to be inspected a detailed method of determining areas inspected is to be developed.

- a. Areas to be inspected is to be broken down into areas not exceeding 20cm × 20cm.
- b. Areas are to be inspected individually with a thick coating of Non Aqueous Wet Developed used to confirm scanning locations.
- c. Areas tested are to be clearly marked to ensure no area goes untested.

EVALUATION

Any reproducible signal that exceeds signal response from calibration notch and is not attributable to geometrical features (edge effect) shall be further evaluated.

Further Evaluation

Further Evaluation of surface breaking discontinuities may be carried out by

Visual Inspection (10× or 20× Magnification)

or

Fluorescent Dye Penetrant Inspection (level 3 or 4 Sensitivity)

ACCEPTANCE CRITERIA

Any Cracking that exceeds 2.0 mm in length shall result in non compliance.

Component is to be clearly marked and identified directly to client.

POST CLEANING

On completion of inspection component is to be cleaned.

REPORTING OF RESULTS

Shall be in accordance with specific client requirements, and as a minimum shall contain the following:

- Name of laboratory or testing authority.
- Identification of the component under test.
- Number of the product standard, if applicable.
- Identification of the calibration standards used during the test.
- Results of the test.
- Date and place of test.
- Any other information the purchaser requires for assessment of test results.
- Identification and signature of the person responsible for the test report.

Prepared by: Bob Smith ISO9712 level 2

Authorized by: Jon David ISO9712 level 3

Document Revision ET010.1

Dated: TODAY

III-2. EXAMPLE OF TEST REPORT

Trotter Independent Trading Eddy Current Inspection Report

Report No: TIT/ET/001

Inspection Date: 27 January 2009

Location: Aircraft Hanger 42

Component: Fatigue Stress Piece,

Identification: Part No: 11, Serial No. 12345

NDT Instruction No. TIT/ET/001 (Revision 0).

Flaw Detector: Nortec 2000 Eddy Current Flaw Detector, Serial No. 1234

Probe: Nortec high frequency, shielded probe, Serial No. 5647

Probe lead: Nortec Serial No. 126

Reference Sample: Aluminium Alloy, 34% IACS with 0.5 mm EDM slot, Serial No. 56173

Inspection Technique: Component inspected in accordance with NDT Instruction No. TIT/ET/001 (Revision 0).

Visual Examination: Surface finish, clean and smooth. No obvious visual faults apparent.

Inspection Results: One crack indication detected in the upper surface radiating from the centre hole. The indication length measured as 6 mm.
The indication was characterized as being a fatigue crack.

Accept/Reject Criteria: As per NDT Instruction No. TIT/ET/001, all fatigue cracks greater than 2 mm in length are to be rejected.

Disposal: Inspection surface cleaned.
Component tagged as Reject in accordance with NDT Instruction No. TIT/ET/001 (Revision 0) and returned to Quality Control.

Signed:

Name: A. N. Other

Certification No.: 123456

Date: TODAY

Appendix IV

DEVIATION FROM SYLLABUS FORMAT OF IAEA-TECDOC-628 REV 2. (2008)

Note 1:

This manuscript has been produced as a training manual and the sequence of presentations has been chosen to suit the needs of the trainees. While most of the contents of the manual conform to such needs of the trainees, only the contents of Section 5 (APPLICATIONS) need slight reorganisation.

Note 2:

Sections 5.6.3 and 5.6.4 have been re categorised as 5.7.1 and 5.7.2 respectively and brought under the main sub heading of 5.7.

The following Table IV-1 was produced to relate the contents of Subject 5 (Applications) for Eddy Current Testing, level 2, of TECDOC-628 Rev.2 (2008) with the contents in this book.

TABLE IV-1. RELATIONSHIP AND CONFORMANCE BETWEEN IAEA-TECDOC-628 AND THIS BOOK

| <i>Contents of Subject 5 (Applications) for Eddy Current Testing, Level 2, of IAEA-TECDOC-628. Rev.2 (2008)</i> | <i>Related contents in this book</i> |
|---|--------------------------------------|
| 5.1 Geometric defect characterization | 5.2.1, 5.2.2 |
| 5.1.1 Hypothesis of interrupted currents | 5.2.1, 5.2.2 |
| 5.1.2 Case of point defects | 5.2.1, 5.2.2 |
| 5.1.3 Case of large defects | 5.2.1, 5.2.2 |
| 5.1.4 Case of multiple defects | 5.2.1, 5.2.2 |
| 5.2 Coil with a long conductive product (bar or tube) | 5.2.1, 5.2.2 |
| 5.2.1 Impedance diagram | 5.2.1, 5.2.2 |
| 5.2.2 Influence of various parameters | 5.2.1, 5.2.2 |
| 5.2.3 Ferromagnetic products | 5.2.1, 5.2.2 |
| 5.3 Use of impedance diagrams | 5.2.1, 5.2.2 |
| 5.3.1 Definition of operating point | 5.2.1, 5.2.2 |
| 5.3.2 Choice of operating point according to sensitivity of parameter splitting | 5.2.1, 5.2.2 |
| 5.4 Electromagnetic properties of materials | 5.1.5 |
| 5.4.1 Electrical conductivity | 2.1.1, 5.1.5 |
| 5.4.2 Chemical analysis, temperature, grain size, texture influence, structure | 5.1.5 |
| 5.4.3 Magnetic permeability: chemical analysis, structure, grain size and texture influence | 2.2 |
| 5.5 Main types of discontinuities detected by eddy current testing | 5.1.2 |
| 5.5.1 Discontinuities arising from production | 1.3 |
| 5.5.2 Discontinuities arising during hot or cold processing | 1.3 |
| 5.5.3 Discontinuities arising during service | 1.4 |

| | |
|--|--------------|
| 5.6 Thickness measurement | 5.1 |
| 5.6.1 Thickness of a product | 5.1.5 |
| 5.6.2 Thickness of coatings | 5.1.4, 5.1.6 |
| 5.7 Measurement of product composition | 5.1.5 |
| 5.7.1 Measuring by electrical conductivity | 5.1.4, 5.1.5 |
| 5.7.2 Measuring by magnetic permeability | 5.1.5 |
| 5.8 Inspection of welds | 5.1.3 |
| 5.8.1 Characteristic probes and frequencies | 5.1.3 |
| 5.8.2 Defect reaction according to position and weld shape | 5.1.3 |
| 5.9 Multi-frequency eddy current testing | 5.3 |
| 5.9.1 Principles | 5.3.1 |
| 5.9.2 Equipment | 5.3.2 |
| 5.9.3 Applications | 5.3.3 |

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