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Training Guidelines in Non-Destructive Testing Techniques:

Manual for Visual Testing at Level 2

VIENNA, 2013

TRAINING COURSE SERIES 54

TRAINING GUIDELINES IN NON-DESTRUCTIVE TESTING TECHNIQUES:

MANUAL FOR VISUAL TESTING AT LEVEL 2

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TRAINING COURSE SERIES NO. 54

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MANUAL FOR VISUAL TESTING AT LEVEL 2

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FOREWORD

The International Atomic Energy Agency (IAEA) has been active in the promotion of non-destructive testing (NDT) technology for many decades. The prime reason for this interest has been the need for stringent quality control standards for safe operation of nuclear as well as other industrial installations. The IAEA has successfully executed a number of projects, including technical cooperation projects (national and regional) and coordinated research projects, in which NDT was an important part. Through these projects, a large number of persons have been trained in numerous Member States, leading to the establishment of national certifying bodies 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 these States.

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

The syllabuses for training courses have been published in the form of TECDOC publications. The first was IAEA-TECDOC-407 (1987), which contained syllabuses for the five basic NDT methods: 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, with the current version being IAEA-TECDOC-628/Rev.2 (2008), which includes additional and more advanced NDT methods.

The next logical step was to compile textbooks and training manuals in accordance with these syllabuses. Manuals on liquid penetrant, magnetic particle, radiographic, ultrasonic and eddy current testing have already been published in the Training Course Series. These play a vital role in training and certification of NDT personnel in Member States.

The compilation of this book was a continuation of that effort. The first draft of the book was prepared by the National Centre for Non-Destructive Testing, Pakistan. This was reviewed and finalized at a consultants meeting held in Vienna on 23–27 August 2010. The section in the previous Training Course Series publications on general knowledge related to NDT, comprising an introduction to basic NDT methods, materials, manufacturing processes and quality assurance, has been revised with updated information.

The IAEA wishes to express its appreciation to all those who contributed to the production of this book. The IAEA officers responsible for this publication were Joon-Ha Jin, A.A. Khan, B.P.C. Rao and P. Brisset of the Division of Physical and Chemical Sciences.

CONTENTS

1. GENERAL KNOWLEDGE

1.1. Basic principles of non-destructive testing (NDT)

1.1.1. Definition and methodology of applications of basic NDT methods

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.

d) It enables design of new products.

All of the above factors bring profitability to the manufacturer. NDT is also used widely for routine or periodic assessment of quality of the plants and structures during service life. This increases the safety of operation and eliminates any forced shut down of the plants.

1.1.2. NDT methods

For the purposes of these notes, NDT methods may be divided into conventional and non-conventional. To the first group belong commonly used methods like visual or optical inspection, liquid penetrant testing, magnetic particle testing, eddy current testing, radiographic testing and ultrasonic testing. The second group includes those NDT methods used only for specialized applications like neutron radiography, acoustic emission, infrared testing, microwave techniques, leak testing, holography etc. It must also be remembered that none of these methods provide solutions to all 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 conventional methods will now be briefly described.

1.1.2.1. Visual testing (VT)

Often overlooked in listings of NDT methods, visual inspection is one of the most common and 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 testing requires training (knowledge of product and process, anticipated service conditions, acceptance criteria, record keeping, for example). It is also a fact that all defects found by other NDT methods ultimately must be substantiated by visual testing. Visual testing can be classified as direct visual testing, remote visual testing and translucent visual testing. Often the equipment needed is simple. Fig.1.1. shows a portable light, a mirror on stem, a 2X or 4X hand lens, one illuminated magnifier with magnification 5X or 10X. 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.

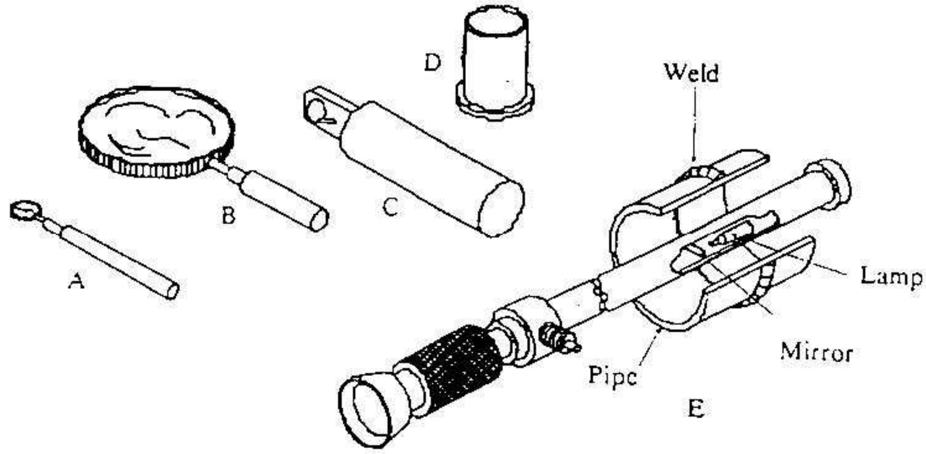


FIG. 1.1. Various optical aids used in visual inspection.(a) Mirror on stem (b) Hand magnifying glass (c) Illuminated magnifier (d) Inspection glass (e) Borescope.

The applications of visual testing include:

a) Checking of the surface condition of the component.
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.

Some of the advantages of visual testing are as follows:

a) Testing is simple
b) Testing speed is high
e) Testing is possible while test object is being used
f) Permanent records are available when latest equipment are used

Some of the limitations of visual testing are as follows:

a) Can detect only surface flaws
b) Eye resolution is weak
c) Eye fatigue

1.1.2.2. Liquid penetrant testing (PT)

This is a method that can be employed for the detection of surface-breaking defects in any industrial product 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 defect is absorbed by the developer to indicate the presence as well as the location, size and nature of the defect. The process is illustrated in Fig. 1.2.

Penetrants used are either visible dye or fluorescent dye. 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.

Liquid penetrant processes are further sub-divided according to the method of washing of the component. Penetrants can be: (i) water-washable, (ii) post-emulsifiable, i.e. an emulsifier is added to the excess penetrant on surface of the component to make it water-washable, and (iii) solvent removable, i.e. the excess.

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.

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) Applicable to a variety of materials.

f) Large area inspection.

The limitations of liquid penetrant testing are as follows:

a) Test surface must be free of all dirt, oil, grease, paint, rust, etc.

b) Detects surface discontinuities only.

c) Cannot be used on porous and 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.

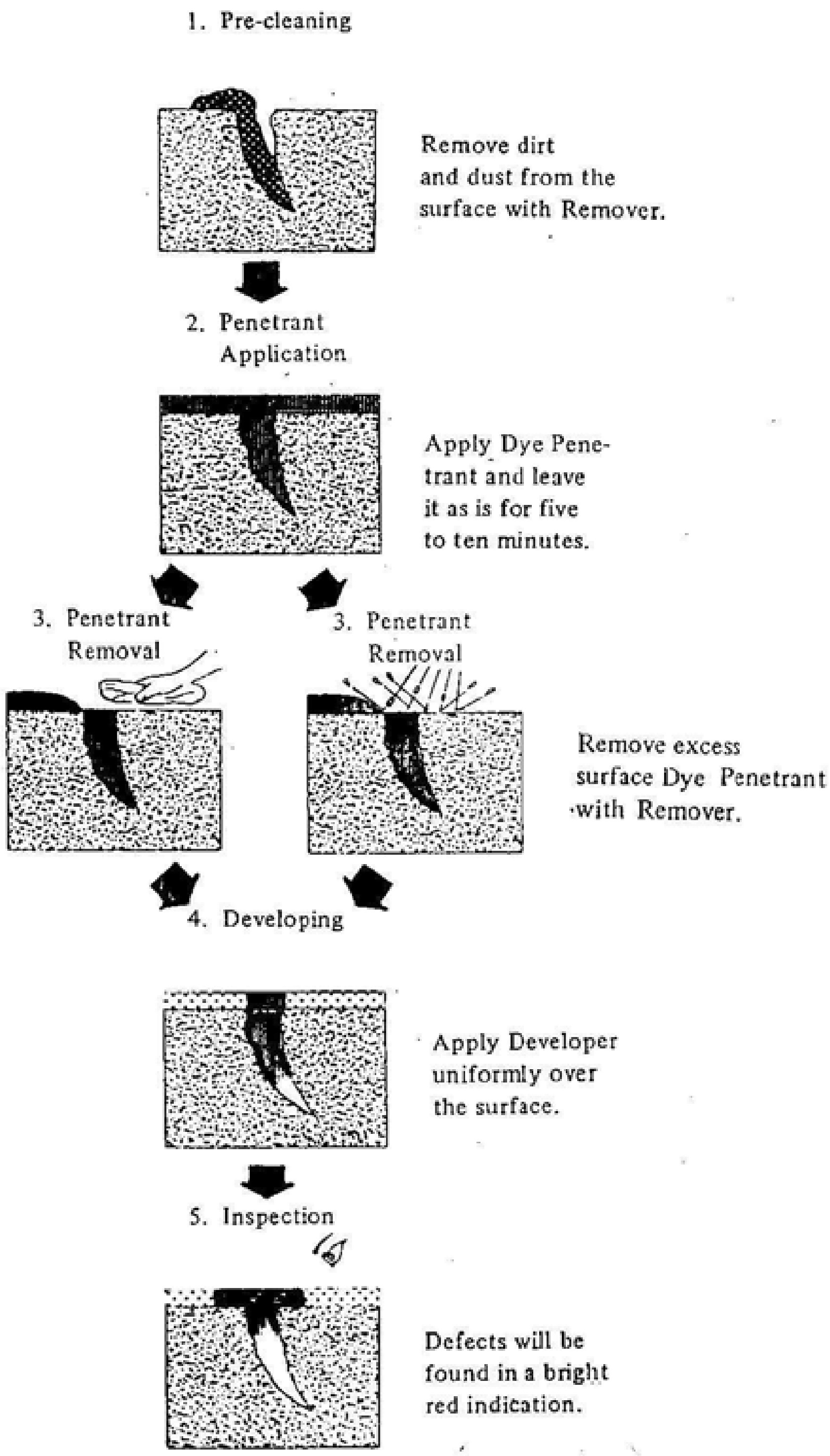


FIG. 1.2. Different stages of liquid penetrant process.

1.1.2.3. 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.

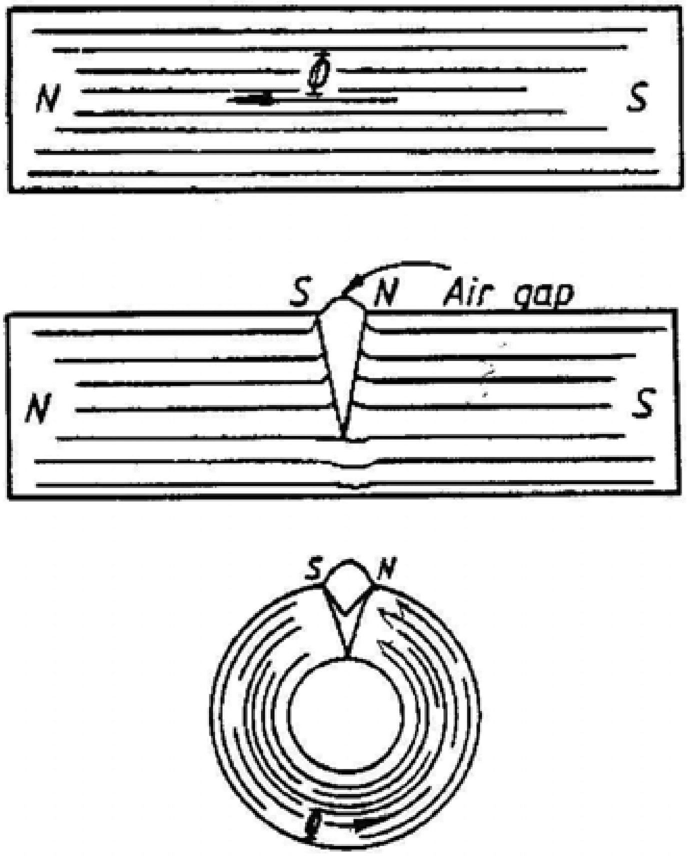


FIG. 1.3. Basic principle of magnetic particle testing.

Depending on the application, different magnetization techniques are used in magnetic particle testing which 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).

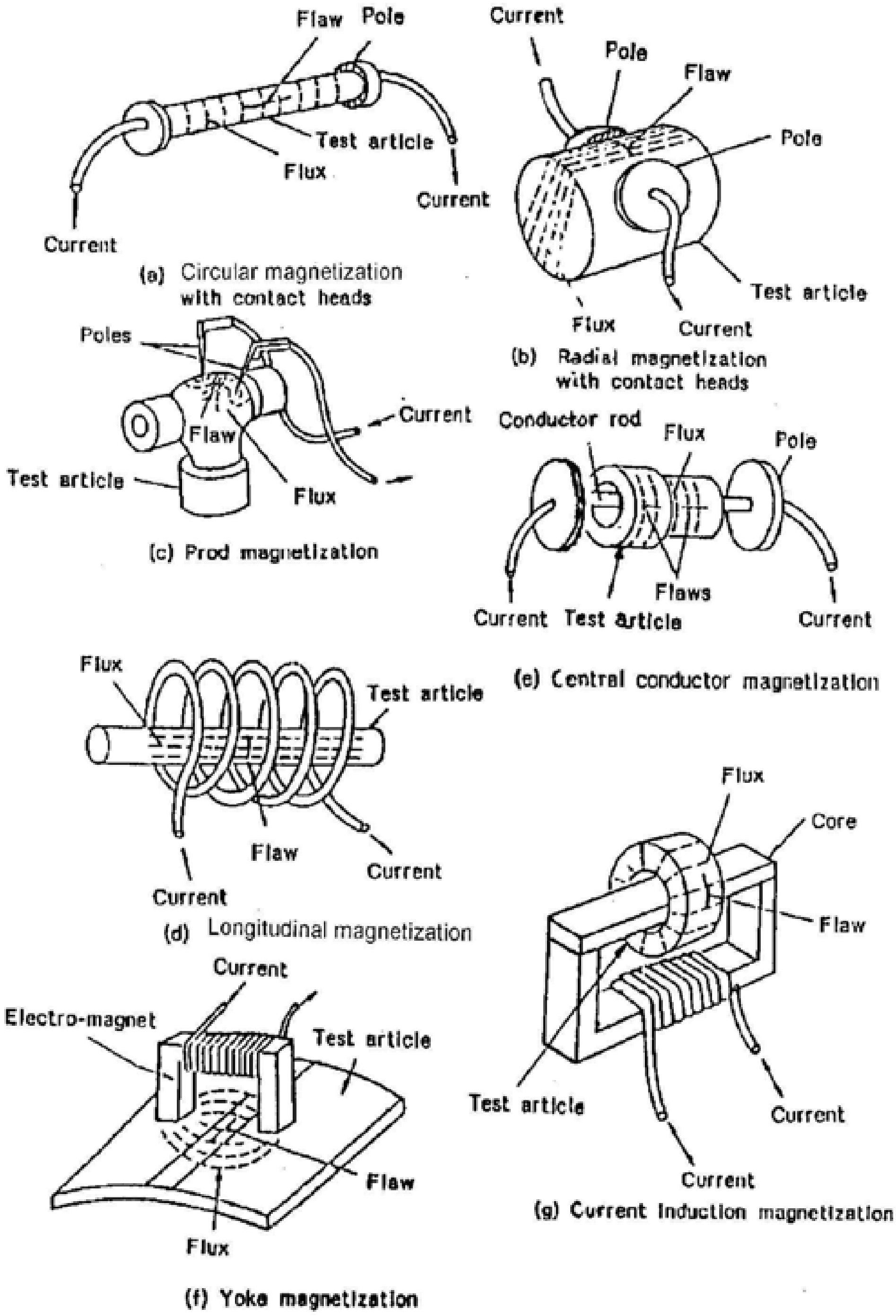


FIG. 1.4. Different magnetizations used in magnetic particle testing.

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) Will work through thin coating.
d) Inspection of complex geometries.
e) Portable NDT method.

The limitations of magnetic particle testing include the following:

a) Applicable only to ferromagnetic materials.
b) Orientation and strength of magnetic field is critical. There is a need to magnetise twice: longitudinally and circumferentially.
c) Large currents sometimes required and ―burning‖ of test parts is a possibility.
d) After testing the object must be demagnetized, which may be difficult sometimes.

1.1.2.4. Eddy current testing (ET)

This method is widely used to detect surface defects, to sort materials, to measure thin walls from one surface only, to measure thin coatings and in some applications to measure case hardening depth. This method is applicable to electrically conductive materials only. In the method, eddy currents are induced in the object 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 object near to the coil, is then shown as a meter reading or cathode ray oscilloscope presentation. Fig. 1.5 shows generation and distortion of eddy current.

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 in plates, sorting of materials, measurement of wall and coating thickness, and case depth measurement.

ET 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.

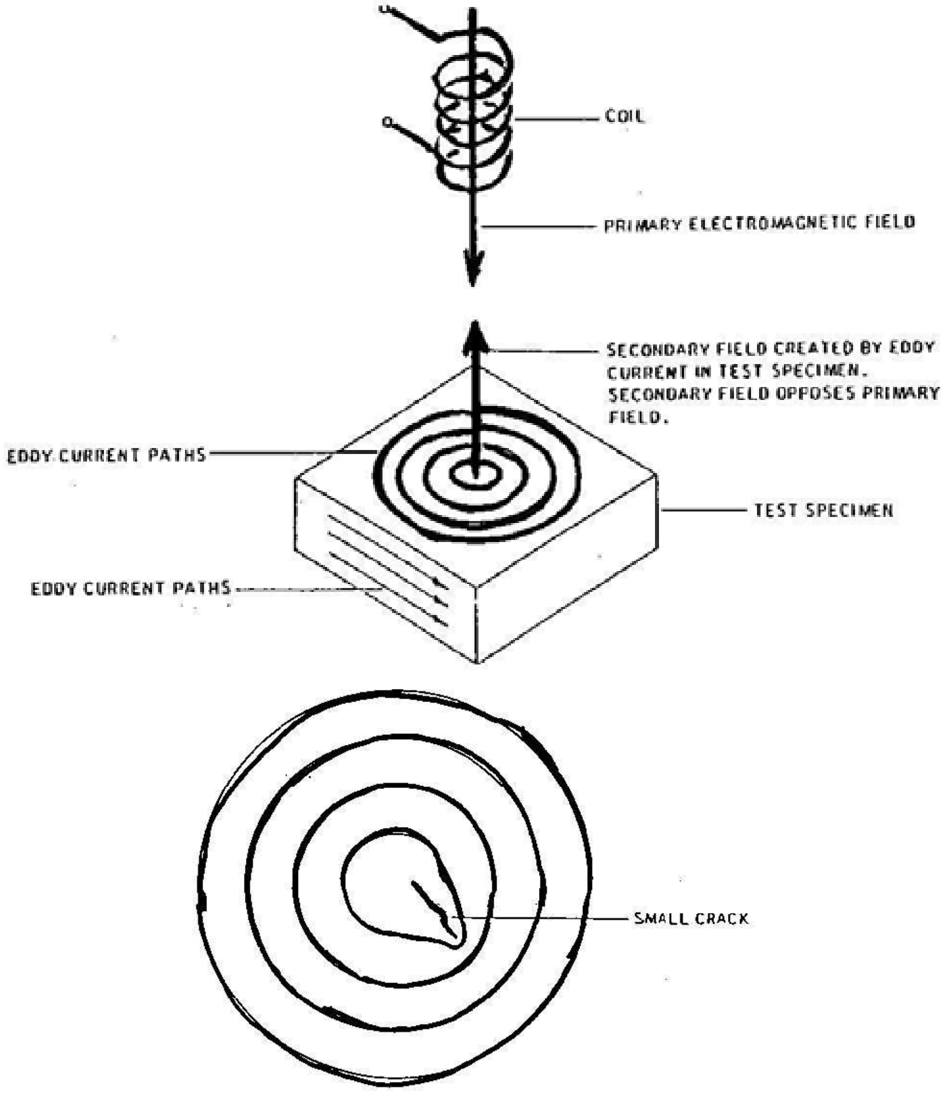


FIG. 1.5. (a) Generation of eddy currents in the test specimen, (b) Distortion of eddy currents due to defect.

The advantages of eddy current testing include that it:

a) Does not require couplant.
b) Gives instantaneous response.
c) Is extremely sensitive to surface cracks.
d) Allows use of high scanning speeds (as high as 10 m/s).
e) Accurate for sizing defects and coating thickness measurement.

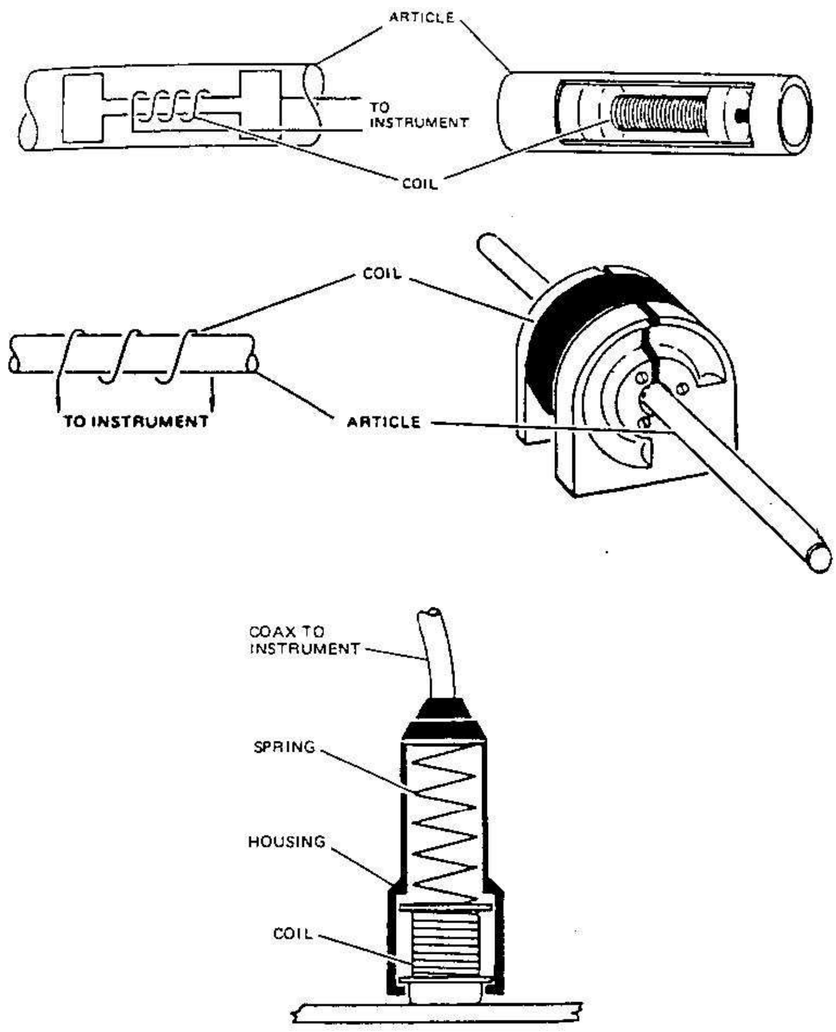


FIG. 1.6. Types of probes used in eddy current testing, (a) Internal Coil, (b) Encircling Coil, (c) Surface Probe.

The limitations of eddy current testing include the following:

a) Extremely sensitive to surface variations and therefore requires a good surface.
b) It is applicable to electrically conducting materials only.
c) Not reliable on carbon steel for the detection of subsurface flaws.
d) Its depth of penetration is limited to 8 mm.

1.1.2.5. 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.

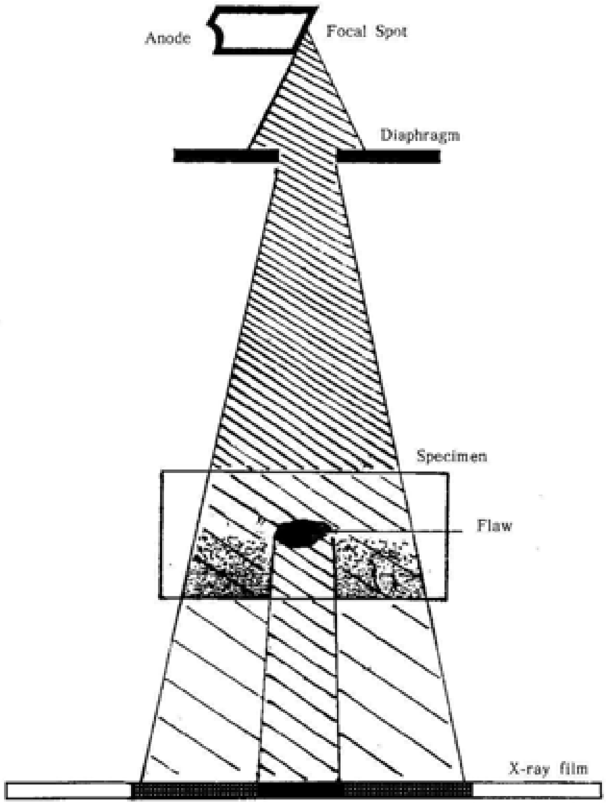


FIG. 1.7. Arrangement for radiographic testing method.

The advantages of radiographic testing include:

a) It is useful on wide variety of materials.
b) It can be used for checking internal malstructure, misassembly or misalignment.
c) It provides permanent record.
d) Devices for checking the quality of radiograph are available.

Some of the limitations of this method are:

a) Access to both sides of the object is required.
b) It cannot detect planar defects readily.
c) The thickness range that can be inspected is limited.
d) Sensitivity of inspection decreases with thickness of the test object.
e) Considerable skill is required for interpretation of the radiographs.
f) The depth of defect is not indicated readily.
g) X rays and gamma rays are hazardous to human health. The iaea‘s radiation safety series are referred for personal safety and radiation protection.

1.1.2.6. Ultrasonic testing (UT)

Ultrasonic inspection is a non-destructive method by which high frequency sound waves are introduced into the object being inspected. Most ultrasonic inspection is done at frequencies between 0.5 and 20 MHz. 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. Partial reflection occurs at metal-liquid or metal-solid interfaces. Ultrasonic testing has a higher penetrating power than radiography and can detect flaws deep in the test object (up to about 7 metres 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.

The ultrasonic testing method is:

a) Used for detection of flaws in materials and for thickness measurement.
b) Used for the determination of mechanical properties and grain structure of materials.

Some of the advantages of ultrasonic testing are that:

a) It has high sensitivity which permits detection of minute defects.
b) It has high penetrating power 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 object causes problems during inspection.
b) Inspection of materials having coarse grain microstructure is difficult.
c) It requires the use of a couplant.
d) Defect orientation affects defect detectability.
e) Reference standards and calibration are required.
f) Rough surfaces can be a problem and surface preparation is necessary.

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.

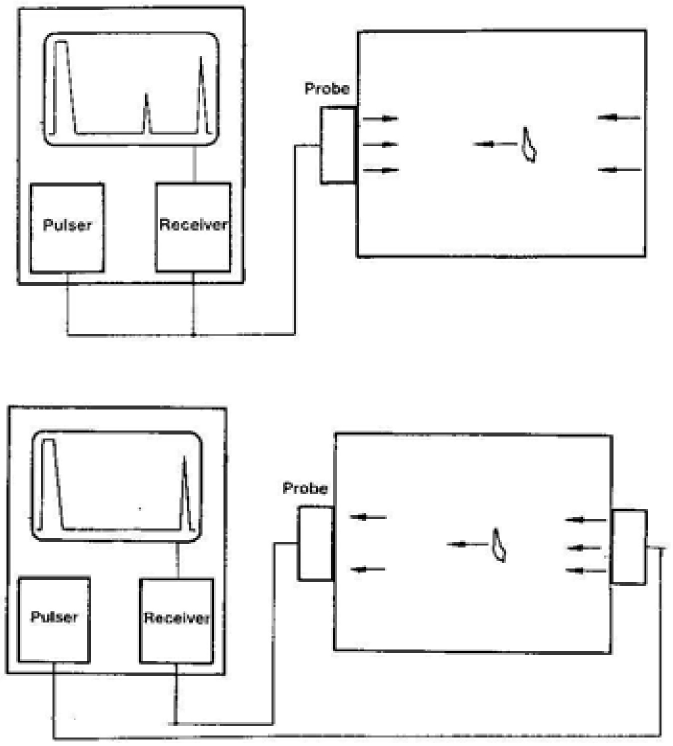


FIG. 1.8. Basic components of an ultrasonic flaw detection system, (a) Pulse echo method, (b) Through transmission method.

1.1.3. Comparison of different NDT methods

It is frequently necessary to use one method of NDT to confirm the findings of another. Therefore, various methods must be considered to be complementary rather than in competition with each other. Each method has its particular advantages 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.

1.1.4. New developments in NDT

Modern developments in all areas of technology especially aerospace, mass transit systems such as railways, petrochemicals, oil and gas explorations and processing, entertainment, bio-materials, industrial and conventional and nuclear power plants, nano-materials, micro-electronic components, composites and multi-layered structures etc. which are dependent on using materials which are stronger, lighter, have other exotic properties and use minimum possible raw materials. All this is aimed at increasing the efficiency, durability and reliability of machines containing components made from such materials. There are stringent requirements of dealing with these exotic new materials and for detecting and characterising the extremely small sizes of flaws. Consequently there is a great challenge to improve upon the existing techniques for non-destructive testing and develop new ones where required.

NDT has continued to play a vital role for quality control of industrial products in the highly aggressive and competitive world markets. It may not be totally out of place to say that the relative share of a particular country in the world market depends more and more on its investment in quality control and quality assurance, which in real terms and in most cases means an investment in NDT.

NDT equipment has been made more reliable and sensitive with a trend to make it as independent of operator errors as possible. This has seen a greater use of computers and automation. We see most of the modern NDT with microprocessors and computers with enhanced capabilities for image processing, data acquisition and analysis. There is a growing trend towards using multiple transducers and multi-channel systems both for ultrasonic and eddy current testing. Similarly the concept of simultaneously using multiple methods of inspection is increasing, for example for the inspection of reactor pressure vessels. On-line and continuous monitoring of plant and equipment inspection is now commonly applied. To cope with the increased use of composite materials high sensitivity test methods such as micro-focus radiography and high frequency ultrasonic testing are now well established.

NDT has been increasingly applied in process control as a means to fulfilling the requirement of a good quality assurance concept of making the products right the first time. Such a shift towards use of NDT for process control has simultaneously demanded development in several related fields such newer and faster NDT techniques, computers and data handling which make it easier to analyze NDT data rapidly and use it in a feedback loop to modify, control and optimize the process. Thus we see development of large installations employing automated radiography, tomography, ultrasonic testing, eddy current testing, optical-visual testing and infra-red testing. But, increasing the degree of automation also increases the consequences of error. Therefore, a high degree of automation requires a high degree of (automated) monitoring and control. Consequently, a steady need for automated NDT is observed in industry. Process integrated NDT has to fulfil the requirements of today’s industrial production concerning integrate-ability, automation, speed, reliability and profitability.

A confluence of developments in the fields of electronics, computer technology, simulation tools and signal processing is contributing to the excitement and fuelling some of the most compelling advances. Technology is indeed breathing new life into the field and there is much to look forward to in this important scientific endeavour. Some recent developments in the individual areas of NDT are briefly reviewed below:

1.1.4.1. Radiographic testing (RT)

Radiographic testing has seen rapid development of digital methods. Starting with laser-based digitization of conventional film radiographs, the technology has moved fast to the development of Imaging plates (IP) and digital detector arrays (DDA) also called flat panel detectors using semiconductors such as Europium-doped BaFBr and CMSO or amorphous Si and a-Se or CdTe. These have the capability of directly converting the X or gamma rays into electrical signals which can be fed to the computer for further processing and formation of images. The images can also be erased and the detectors re-used, for example, for close to 1000 times. The conventional fluoroscopic methods have moved into the digital domain through the use of high quality image intensifiers the images from which can be directly photographed using the charge coupled device (CCD) cameras which convert visual signals to electrical signals which can be processed by a computer. This offers a distinct possibility of producing low cost digital radiographic systems as against more expensive systems. Computed tomography (CT) having the capability of producing three-dimensional images of internal structures of specimens is now in use. The high resolution digital micro-radiography is in the market. These use X-ray machines with micron level focal spots. Corresponding to characteristics of conventional radiographic images similar characteristics have been defined for the digital images. The equivalent of optical film density is Signal to Noise Ratio (SNR), that of film contrast is Contrast to

Noise Ratio (CNR), that of film resolution and granularity is Basic Spatial Resolution (SRb) and that of dynamic range is Specific Material Thickness Range (SMTR). Standards such as ASTM E2597 have been developed to study the characteristics of digital radiographic systems.

Digital radiography offers numerous benefits over conventional radiography including:

a) Radiation dosage and exposures are reduced resulting in less risk to the operator.
b) Reduces radiographic inspection time, cost and improves productivity.
c) Eliminates chemicals, chemicals disposal and chemical storage costs.
d) Allows radiographic data to be archived and analyzed using image processing algorithms.
e) Storage costs are minimized and images can also be accessed and interpreted remotely.Significant cost savings due to use of DIR systems have been reported from industry.

1.1.4.2. Ultrasonic testing (UT)

Automated and remote control systems of ultrasonic examination have seen rapid development and are now used in wide range of industries in many different applications. Such systems comprise of handling and guiding of test objects, mechanical and remote operation of probe or probes, automatic supply of couplant, automatic gain control, automatic distance amplitude correction, self-checking or monitoring system, UT data processing system, application of B-scan, C-scan , P-Scan etc. and feedback and corrective actions. Such automated systems reduce the operational variables and personal errors, the data obtained is more accurate and reliable, can be applied in difficult and hostile environments (such as reactor pressure vessels in nuclear power plants) and can be very fast, saving working time and manpower costs. The analysis and evaluation of results can be done through computerized systems thereby increasing the efficiency and reliability of data processing.

We have seen increased use of time of flight diffraction (TOFD) technique for flaw characterization. It depends on the principle that when ultrasound is incident at linear discontinuity such as a crack, diffraction takes place at its extremities in addition to the normal reflected wave. This diffracted energy is emitted over a wide angular range and is assumed to originate at the extremities of the flaw. This is quite helpful in sizing such flaws. A more accurate technique for flaw sizing may, however, be based on signal processing based on a semi-empirical approach of Weiner filtering with autoregressive spectral extrapolation using ultrasonic B- and S-scans.

Another area which has seen many applications is the phased array technique which is a process wherein UT data is generated by constructive phasal interference formed by multiple elements controlled by accurate time delayed pulses. The arrays can perform beam sweeping through an angular range (S-scans), beam scanning at fixed angle (E-scans), beam focusing, lateral scanning and a variety of other scans depending on the array design and programming. Each element consists of an individually wired transducer, with appropriate pulsers, multiplexers, A/D converters, and the elements are acoustically isolated from each other. The phased array system is computer-controlled, with software typically user-friendly such that the operator can simply programme in the required inspection parameters. Usually, a wedge is used to optimise inspection angles and minimise wear. Phased arrays are particularly useful for regions with limited access, rapid inspection of components such as welds, inspection of test objects of complex shapes such as the turbine blades, imaging and storing data, and sizing cracks by tip diffraction.

While the majority of ultrasonic tests are performed with liquid couplants or immersion in water there is an increasing need for tests without conventional coupling, especially in situations where liquid may damage the test material, when cost of couplant removal is excessive or when high scanning speeds are to be achieved. Such air coupled transducers have been developed in many categories such as bimorphic, electrostatic, piezoelectric and ceramic types each for specialized applications.

Acoustic microscopy is the high resolution, high frequency ultrasonic testing techniques that produces the images of features beneath the surface of a test object. Acoustic microscopes operate up to and beyond 1 GHz frequencies have been developed. Because of such high frequencies it is possible to obtain very high resolution and therefore study of internal structure and defects in materials at micron levels.

1.1.4.3. Acoustic emission (AE)

Acoustic Emission is another technique finding increased applications. It is commonly defined as generation of transient elastic waves within a material caused by the release of localized stress energy which can be caused by sources not involving material failure including friction, active corrosion, leakage, cavitation and impact. Additionally, events can also come quite rapidly when materials begin to fail, in which case AE activity rates are studied as opposed to individual events. AE events that are commonly studied among material failure processes include the extension of a fatigue crack, or fiber breakage in composite materials.

AE tools have been designed for monitoring acoustic emissions produced within the material during failure and part failure can be documented during unattended monitoring. The monitoring of the level of AE activity during multiple load cycles forms the basis for many AE safety inspection methods that allow the parts undergoing inspection to remain in service. In materials under active stress, such as some components of an airplane during flight, transducers mounted in an area can detect the formation of a crack at the moment it begins propagating. A group of transducers can be used to record signals and then locate the precise area of their origin by measuring the time for the sound to reach different transducers. The technique is also valuable for detecting cracks forming in pipelines transporting liquids under high pressures.

1.1.4.4. Ultrasonic guided waves

Use of ultrasonic guided waves is a suitable method for inspection of pipes over long distance and can be efficiently used instead of conventional ultrasonic methods which are based on point by point inspection. It offers many advantages such as high speed inspection over long distances, in service inspection of underwater or buried gas and oil pipelines, inspection of heat exchanger tubes and bends and the possibility of inspecting parts and joining with complex geometry.

1.1.4.5. Eddy current testing (ET)

ET equipment has been developed combining high speed testing capabilities, with multi-channel, multi-frequency apparatus utilizing spatial high quality filtering and multiplexing offering excellent signal-to-noise ratios making inspections faster and easier to perform. Equipment enabling a wide variety of tests on aircraft structures, engine components, and wheels is available. Similarly state-of-the-art eddy current instruments and systems are available for testing of critical mass-produced components coming from processes such as forming, heat treating, machining and finishing, testing for cracks and other surface flaws and material properties such as hardness, case depth, mixed structures and alloy integrity. Typically tested components include engine, transmission and drive train components; steering, chassis and suspension components; valve train components; gears; shafts; bearings and bearing components; fasteners, etc. Both external and inner surfaces can be inspected and inspection can be performed at production line speeds. Eddy current imaging using array coils, pulsed eddy current testing and remote field eddy current testing are some of the recent advances in this technique.

1.1.4.6. Thermal non-destructive testing

Infrared Thermography involves measurement of emissions and temperature variations on a component. Application of IRT include predictive maintenance especially in aerospace, condition monitoring, several aspects of night vision, inspection of electrical installations and building envelopes, inspection of welds for defects as well components for fatigue cracks. Further development of IRT has been motivated by the introduction of composites and surface-protected metals in aerospace, power production and some other fields of cutting-edge technologies. IRT enables detection of defects in the above-mentioned materials and allows rapid inspection of relatively large areas.

The Photothermal Camera is an inspection instrument that can be used to replace more conventional surface inspection techniques such as ET or PT. Photothermal testing is a contactless NDT technique that detects infrared emission following a transient thermal excitation of the inspection target. An infrared sensor is combined with a scanning laser excitation source. The focused laser scanning beam almost instantly heats a line on the target surface to be inspected. The infrared detector measures the IR emission of the surface adjacent to the heated area as the thermal wave propagates away from the line of initiation. On-line analysis of the image clearly shows the cracks, acting as a thermal barrier, with their characteristic flaw footprint. The method is also relatively quick and therefore the operator exposure to hazards of the general inspection area may be minimized. Thus the method is ideal for situations where surface contact can be hazardous to the operators (like contaminated nuclear components) or materials and environments that may be sensitive to chemical exposures. Other important applications may include inspection of primary system components for power plants (reactor, steam generators and reactor coolant pipes), high temperature inspection surfaces (up to 250°C), and inspection of in-core components of nuclear reactors.

1.1.4.7. NDT of concrete structures and other ceramic materials

NDT of concrete structures including buildings, bridges, roads and pavements has received due attention during the recent years. Building diagnosis using non-destructive test methods is a key contributing factor to decide needed repairs. The objective of condition assessment in existing buildings is to detect concealed damage and its extent. In new buildings non-destructive diagnosis methods are used for quality assurance. In the field of service life determination the current building conditions are assessed and the potential development is estimated to effectively manage the service life of buildings.

Most of the conventional NDT methods have been adapted for use in this sector. These include visual vesting, electrical potential method, Schmidt rebound hammer Test, Windsor probe test, electromagnetic covermeters, radiographic testing, ultrasonic testing, infrared testing, ground penetrating radar (GPR), aadioisotope thickness, density and moisture gauges. Special bridge scanners using a combination of several non-destructive test methods which enable testing and imaging of bridge surfaces of several square metres have been developed along with a non-destructive method for fixing the scanners to the structure. Portable equipment has been developed for the measurement of damaging salts (e.g. chlorides and sulfates). The analysis uses the LIBS-method (laser induced breakdown spectroscopy). The equipment represents an alternative to conventional chemical analysis of building material samples, because the results are directly available on site. Its use is intended both for damage assessment and quality assurance.

1.1.4.8. Surface methods

The photothermal camera is an inspection instrument that can be used to replace more conventional surface inspection techniques such as ET or PT. Photothermal testing is a contactless NDT technique that detects infrared emission following a transient thermal excitation of the inspection target. An infrared sensor is combined with a scanning laser excitation source. The focused laser scanning beam almost instantly heats a line on the target surface to be inspected. The infrared detector measures the IR emission of the surface adjacent to the heated area as the thermal wave propagates away from the line of initiation. On-line analysis of the image enables the cracks, acting as a thermal barrier, to be clearly shown by their characteristic flaw footprint. No chemicals are required for the process. Photothermal inspections generate no environmental waste in contrast to alternative surface inspection likeliquid penetrant or magnetic particle testing. The method is also relatively quick and therefore the operator exposure to hazards of the general inspection area may be minimized. Thus the method is ideal for situations where surface contact can be hazardous to the operators (like contaminated nuclear components) or materials and environments that may be sensitive to chemical exposures. Other important applications may include inspection of primary system components for power plants (reactor, steam generators and reactor coolant pipes), high temperature inspection surfaces (up to 250°C), and inspection of in-core components of nuclear reactors.

The new small and lightweight videoscopes, which are used for a wide range of remote visual inspections of parts or structures where access is limited, offer portability, ease of use, durability, and a host of practical features. These are ideal for applications where operator access is limited, such as inside boiler rooms, airplane fuselages, or wind turbine gear boxes. They can be operated safely in many difficult field environments and in dusty or sandy conditions. Some of these offer far more than just on-site inspection. From image archiving to defect measurement and image management on a PC, post-inspection tasks are made easier. They feature high-quality still images and movies that record directly to a removable USB flash drive. Saving or retrieving images requires a single button press while the thumbnail view allows instant review of inspection results. The accompanying software features image data management and precise measurement (or re-measurement) of objects in recorded images.

1.1.4.9. Process compensated resonance testing (PCRT)

Process compensated resonance testing is a relatively new approach in NDT. PCRT is based on the physics fundamental that any hard component will resonate at specific frequencies that are a function of its mass, shape, and material properties. Material changes or flaws change the normal resonance pattern. Resonant ultrasound spectroscopy (RUS), the analysis of the resonant frequencies of a component, has been used to detect major flaws in metal components for decades. This technique lacks the resolution to find small defects and cannot effectively be used to qualify production parts or detect the onset of fatigue. However, the analytical tool of RUS, coupled with advances in computer based analytical software, has resulted in PCRT, an analytical tool of great power. The technology is achieving growing acceptance (over 150,000,000 automotive parts tested with PCRT in 2006) in inspection of wide range of manufactured components such as connecting rods, crank shafts, suspension arms, composites, ceramics and super alloys, turbine blades etc. Also, the size and geometry of components does not limit the application PCRT.

1.1.5. Inspection Methodology

1.1.5.1. Probability of detection (POD)

Detection of flaws by NDT methods depends on large number of variables. Consequently there is always a chance (probability) that a certain flaw present in the test object will be missed. The best possible level of confidence with which flaws present in the tested object can be actually detected is calculated with the help of probability of detection (POD). The factors on which the POD for a particular test depends include:

a) Human factors such as application conditions, access and approach to the object.

b) Equipment, its sensitivity, resolution and complexity.

c) Process and materials interactions.

d) The capability of various NDT techniques can be quantitatively compared using POD data.

POD data collection & analysis tools include the following:

a) Background on NDE Reliability.

b) Measurement Practice.

c) Vetting and assessing existing databases of POD capability.

d) Calibrations & transfer functions.

e) Selecting a model.

f) Understanding capability relationships behind POD curves.

g) Understanding & addressing experimental variation.

1.1.5.2. Risk-based inspection (RBI)

A concept that has gained considerable importance lately is that of risk-based inspection (RBI) which is a realistic approach to an overall inspection programme. It defines the risk of failure for all critical components in a system and establishes the appropriate schedules (periods) for their inspection and testing. Advancement in NDT resulting in improved probability of detection (POD) has facilitated an increase in the use of RBI.

The European Network for Inspection Qualification (ENIQ) comprising of utilities, vendors, R&D institutions etc. continues to develop harmonized approaches for inspection qualification and for risk-informed in-service inspection (RIISI). The widespread use of the ENIQ documents has been confirmed by an official survey on nuclear safety, performed under the European Council, as well as by Western Nuclear Regulators Association (WENRA).

1.1.5.3. Life assessment studies

NDT has proved to be of great value to perform the condition evaluation and subsequently the lifetime assessment of components. To do that, we need a combination of non-destructive evaluation (NDE), metallurgical evaluations and computational skills. A combination of these evaluations can provide information that is needed to evaluate the severity of flaws in components and with proper engineering analysis, sometimes provide an estimate of component's remaining life. This cycle of evaluation can help to provide plant operators the ability to continue the operation of their equipment in a prudent manner even beyond the originally designed life.

1.1.5.4. Performance based qualification

The concept of performance based qualification is becoming a necessity in view of the stringent inspection requirements imposed by the new materials and machines. It is based on the fact that second party (employer based) qualification and approval (for example in accordance with ANSI/ASNT CP-189) or independent qualification and third party certification (for example, in accordance with ISO 9712 or EN 473), followed by on-the-job training may not provide the required degree of confidence for safety critical inspections. Performance-based qualification requires personnel to demonstrate that they can do a job that meets certain standards consistently under real working conditions. It places candidates in situations where they must demonstrate their knowledge and skills to reliably detect relevant discontinuities.

1.1.6. Responsibilities of levels of certification

Commonly used standards for qualification and certification of personnel define the responsibilities of certified persons as follows.

1.1.6.1. Level-1

An individual certified to Level 1 has demonstrated competence to carry out NDT according to written instructions as 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:

a) set up NDT equipment;

b) perform the tests;

c) record and classify the results of the tests in terms of written criteria;

d) report the results.

However, a person having a Level-1 certificate shall not be responsible for the choice of the test method or technique to be used not for the assessment of test results.

1.1.6.2. Level-2

An individual certified to Level 2 has demonstrated competence to perform NDT 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 practical testing 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 or specifications;

g) prepare written 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) organize and report the results of non-destructive tests

1.2. Materials and defects - Physical and mechanical properties of materials

1.2.1. 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. 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.

1.2.1.1. 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. 1.9. 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.

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.

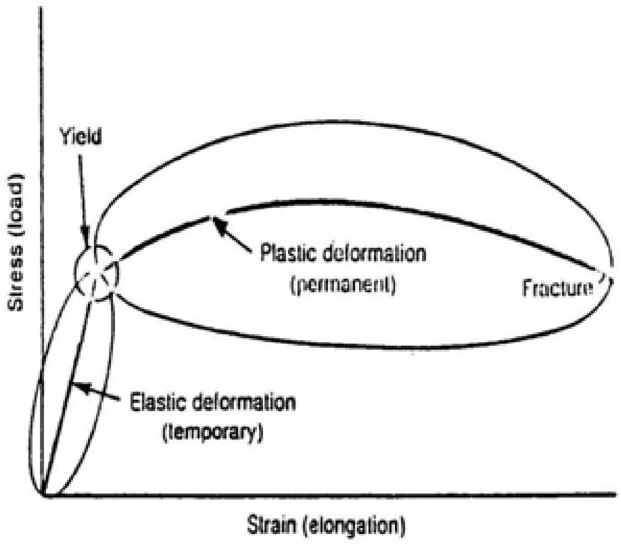


FIG. 1.9. Stress-strain curve showing elastic and plastic portions of a typical curve.

1.2.1.2. 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:

Tensile strength = (Maximum load) / (Original cross - sectional area) (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.

1.2.1.3. 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.

1.2.1.4. 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.

1.2.1.5. 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.

1.2.1.6. 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).

1.2.1.7. 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.

1.2.1.8. Electrical Conductivity

Electrical 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.

1.2.2. Non-metallic materials

1.2.2.1. 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.

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.

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.

1.2.2.2. 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.

1.2.2.3. 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.

1.2.3. Structures 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", formed among similar metal atoms, 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. 1.10).

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.

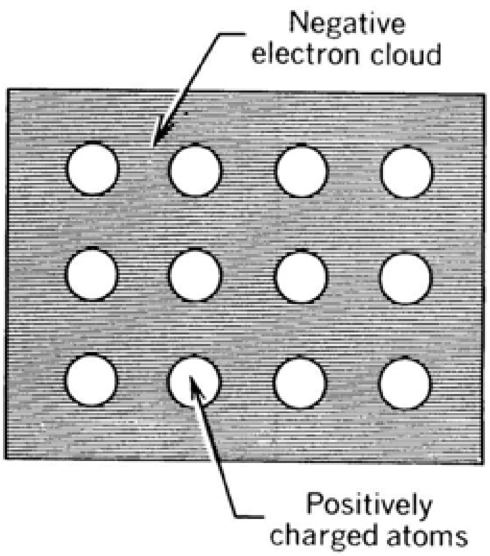


FIG. 1.10. Schematic illustration of a metallic bond.

1.2.3.1. 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 on-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-centered 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. 1.11 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 ^{o}C also has this structure, and is called alpha iron or ferrite.

b) Face-centered 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. 1.11 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^{o}C to 1400^{o}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. 1.11 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.

1.2.3.2. 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. 1.12 illustrates the process of the formation of grains and grain boundaries.

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.

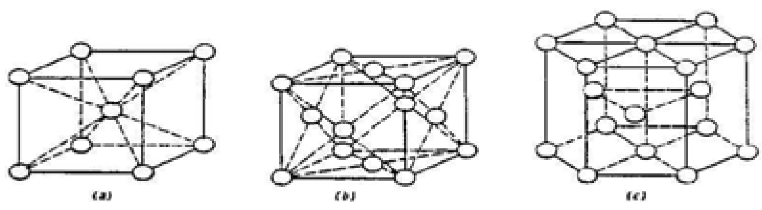


FIG. 1.11. Crystal types
(a) Body-centred cubic (BCC)
(b) Face-centred cubic (FCC)
(c) Hexagonal close-packed (HCP)

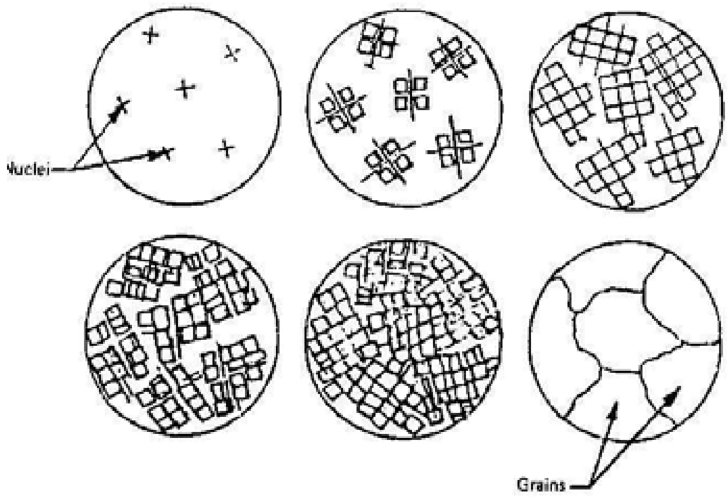


FIG. 1.12. Growth of crystals and grains during solidification.

1.2.3.3. 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 element. 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 another 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.

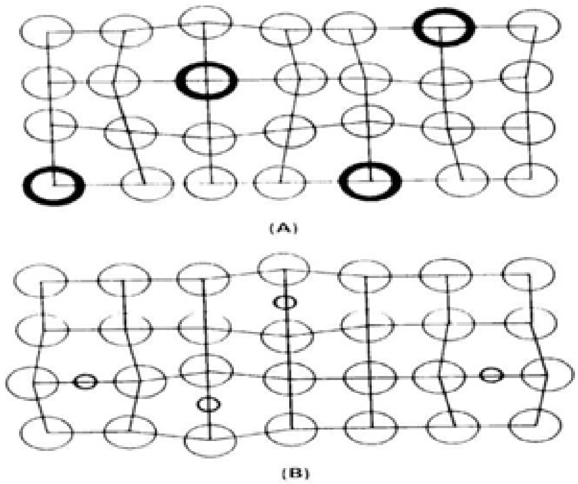


FIG. 1.13. Illustration of (a) substitutional and (b) interstitial solid solutions.

c) 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. 1.13 (a). Examples of substitutional solid solutions are gold dissolved in silver, and copper dissolved in nickel.

d) 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 1.13 (b). Small amounts of carbon, nitrogen, and hydrogen can alloy interstitially in iron and other metals.

e) 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 inter-metallic compounds are very hard and brittle due to their complicated crystal structure.

1.2.3.4. 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 1333^{o}F or 723^{o}C), FCC (above 1670^{o}F or 911^{o}C), and delta iron (between 2550^{o}F or 1398^{o}C and 2800^{o}F or 1538^{o}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 effect 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. 1.14. On cooling, delta ferrite to austenite transformation occurs at 2535^{o}F (1390^{o}C) in essentially pure iron, but in steel, the transformation temperature increases with increasing carbon content to a maximum of 2718 °F (1492°C). Steels with more than 0.5 per cent carbon freeze directly to austenite at a temperature below 2718°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. 1.14. 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 0 (775°C). Thus, both at high and low temperatures 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 (Fe_3C), called cementite. Ferrite and cementite in adjacent platelets form a lamellar structure, known as pearlite.

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.

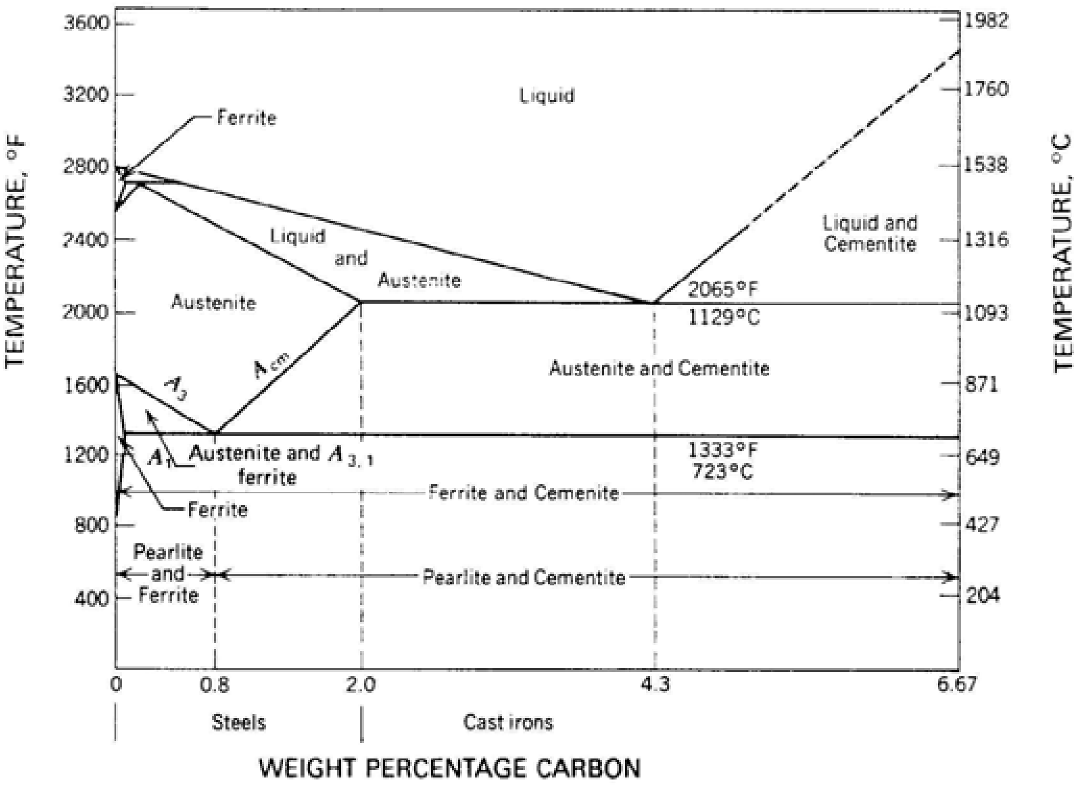


FIG. 1.14. The iron-carbon phase diagram.

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.

1.2.4. Indications, discontinuities and defects in 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 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. Based on these considerations all discontinuities found during NDT tests should be evaluated in the light of applicable standards or procedures. If the discontinuities turn out to be rejectable according the criteria specified in these applicable documents then these are termed as 'defects'.

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

Manufacturing and in-service discontinuities are respectively dealt with in the relevant Sections 1.3 and 1.4.

1.3. Processing and defects

1.3.1. Casting

1.3.1.1. 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.

1.3.1.2. 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.

(a) 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.

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 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.

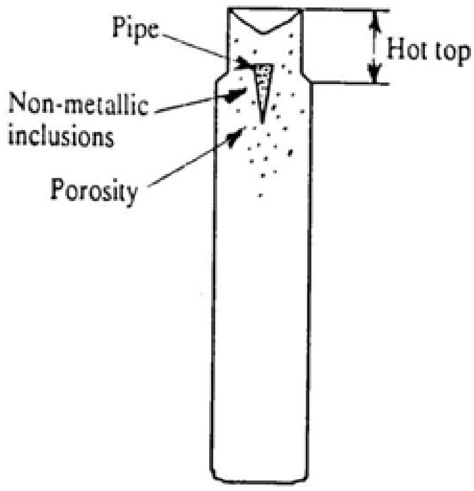


FIG. 1.15. Typical defects in an ingot.

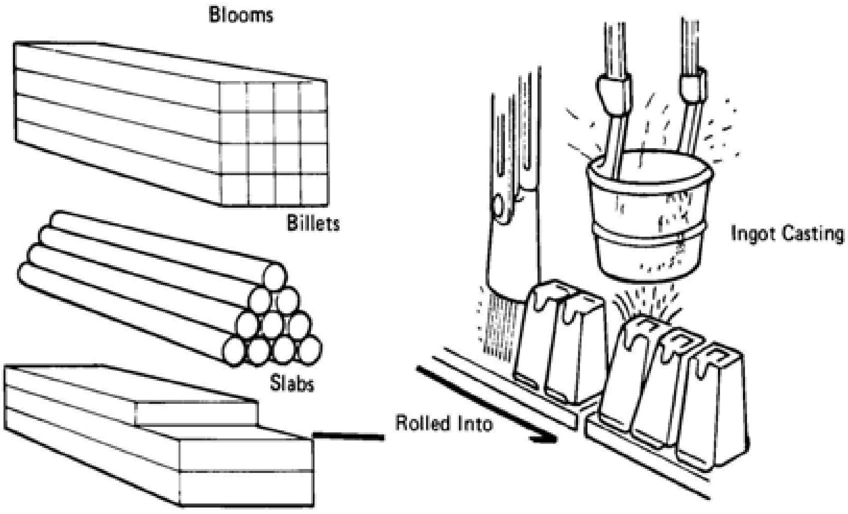


FIG. 1.16. Typical primary material processes.

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.

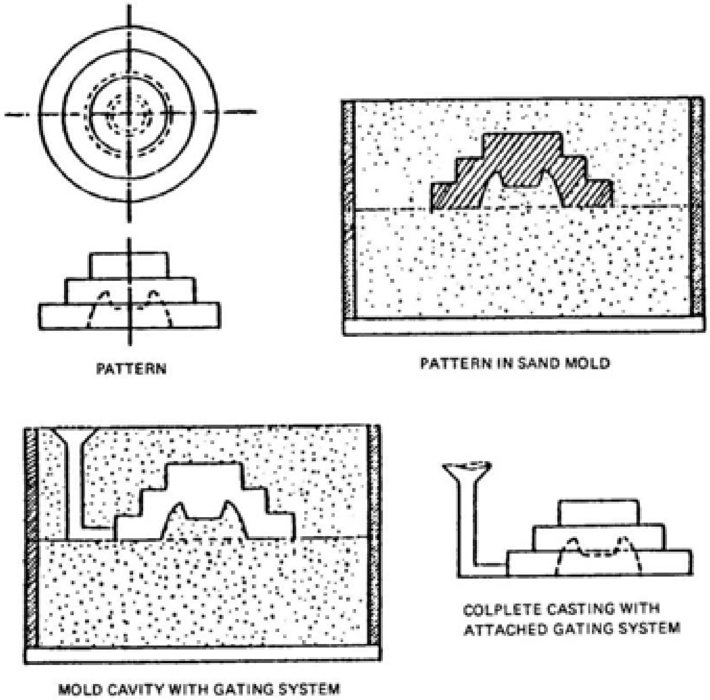


FIG. 1.17. Typical casting steps.

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.

(b) 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 with large graphite flakes is the most commonly used material 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.

(c) 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.

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 3.5 to 41 MPa (500 to 6000 psi). An average of approximately 14 to 17 MPa (2000 to 2500 psi) is common. Air injection pressures are normally limited to about 4 MPa (about 600 psi). Fig. 1.18. shows hot chamber die casting.

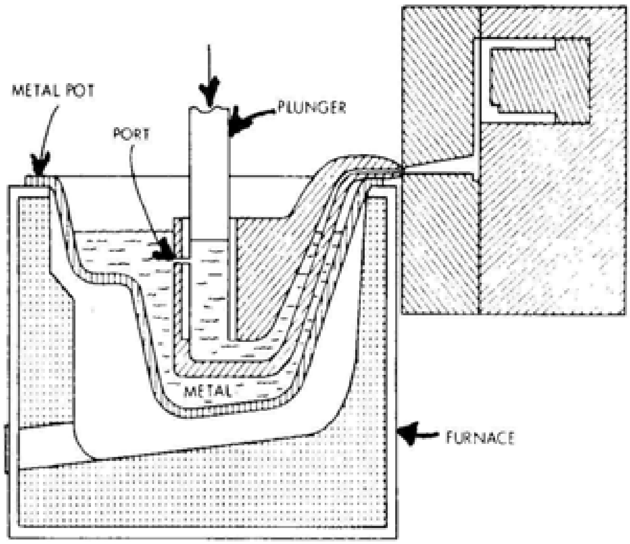


FIG. 1.18. Hot chamber die casting.

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 semi-molten condition. Pressure on the casting metal in cold chamber die casting machines may vary from 20.5 MPa (3000 psi) to as high as (172 MPa (25 000 psi) and in some cases may reach (690 MPa (100 000 psi). Metallic alloys cast in a semi-molten 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.

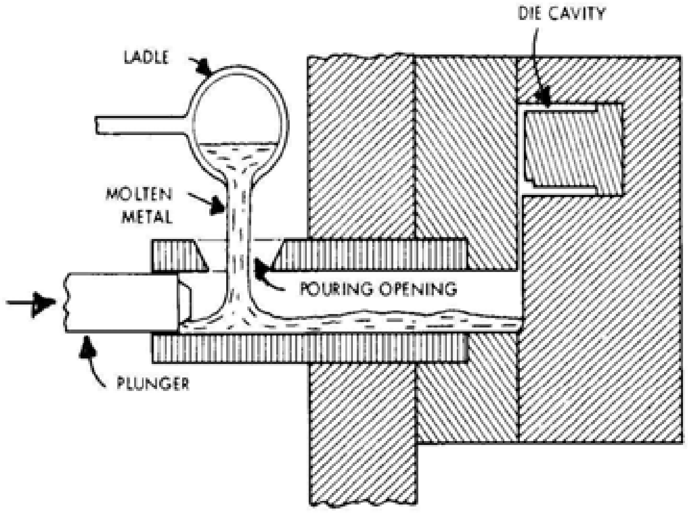


FIG. 1.19. Cold chamber die casting.

(d) 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.

Centrifuged 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.

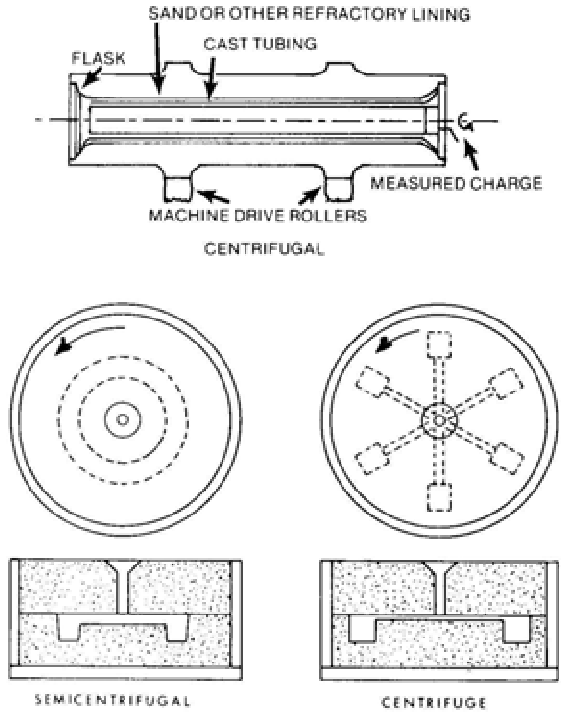


FIG. 1.20. Centrifugal casting.

(e) 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.

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 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 200ºF. 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 1300–1900ºF. This removes all wax residue, if any, sticking to the investment mould. The mould is then heated to the casting temperature.

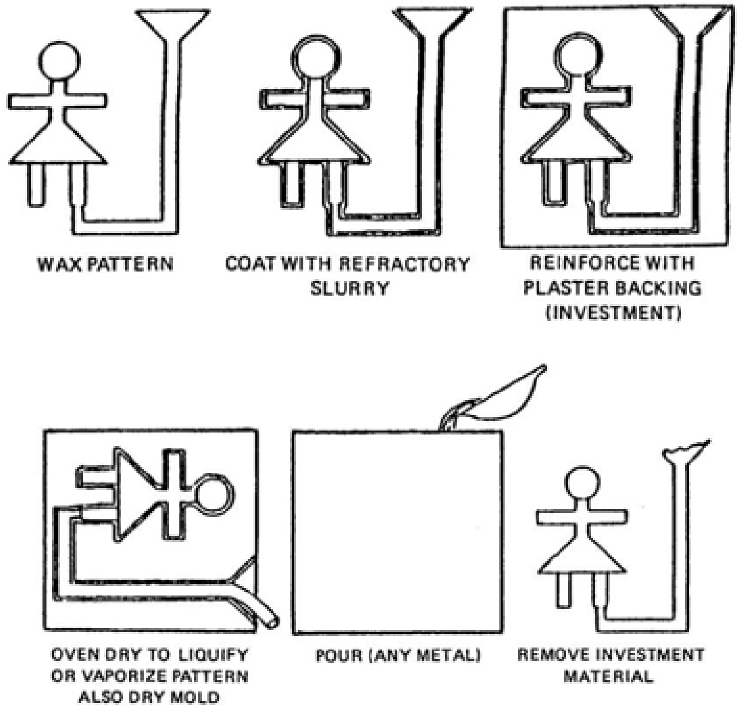


FIG. 1.21. Steps for investment casting.

(f) 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 1,000ºF. 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 phenol formaldehydes, 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 600ºF. 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.

(g) 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.

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	Unlimited
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

1.3.1.3. 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.

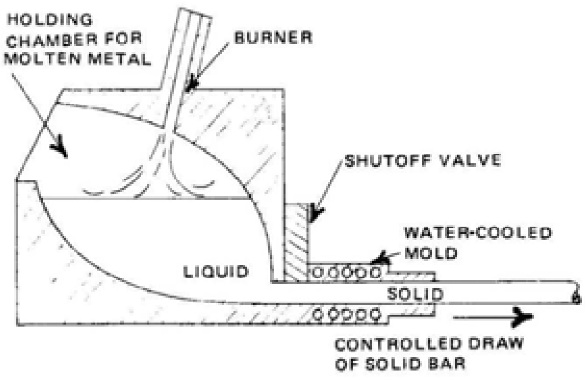


FIG. 1.22. Schematic diagram of continuous casting process.

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:

(a) 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.

(b) 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.

(c) Piping

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

(d) 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.

(e) 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.

(f) 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.

(g) 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.

(h) 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.

(i) 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.

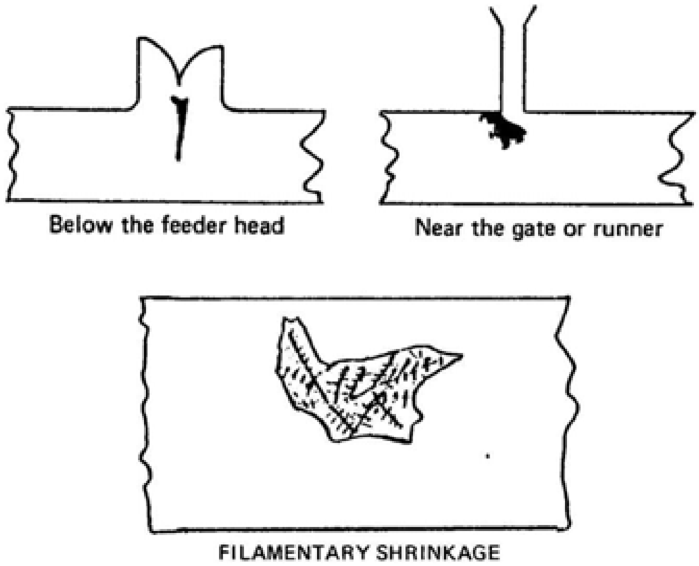


FIG. 1.23. Formation of shrinkage defects.

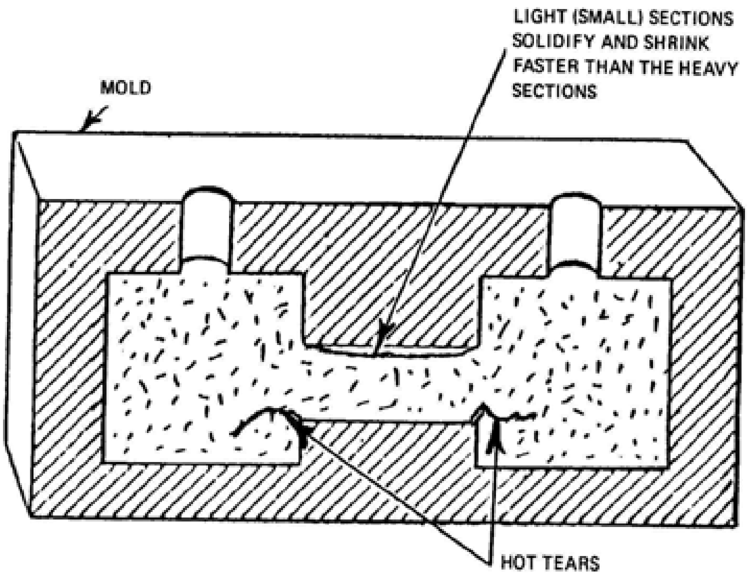


FIG. 1.24. Hot tears.

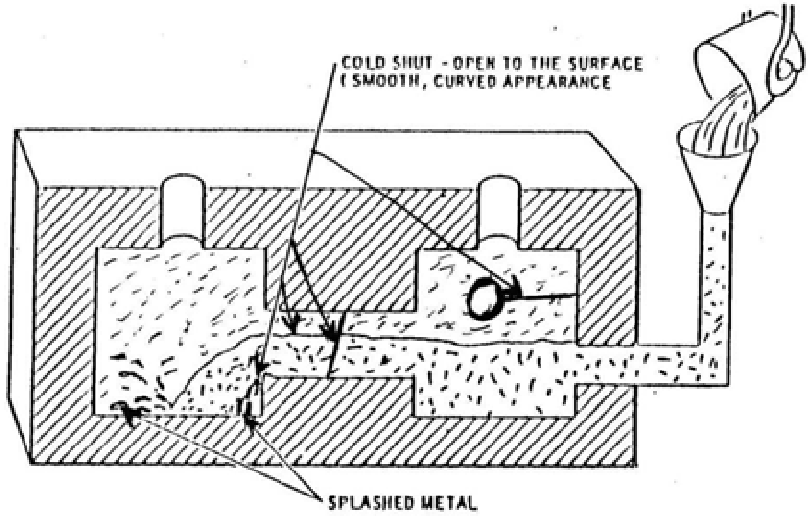


FIG. 1.25. Types of cold shuts.

(j) 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.

(k) 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.

(l) 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.

1.3.2. 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. 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.

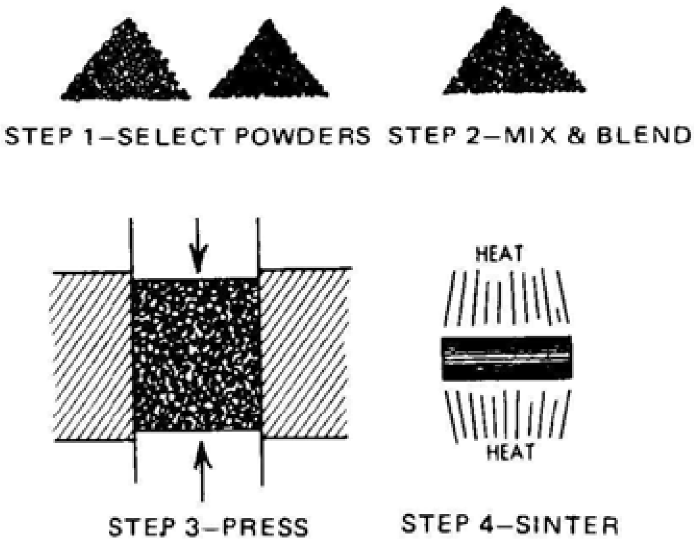


FIG. 1.26. Elements of powder metallurgy.

1.3.2.1. 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.

1.3.2.2. Compaction or 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.

1.3.2.3. 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.

1.3.2.4. 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. Repressing, 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.

1.3.2.5. 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.

1.3.2.6. 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.

1.3.2.7. 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.

1.3.2.8. 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^{o}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.

1.3.3. 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.

1.3.3.1. 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°±5°) and not rotating during welding Fig. 1.28 (F).

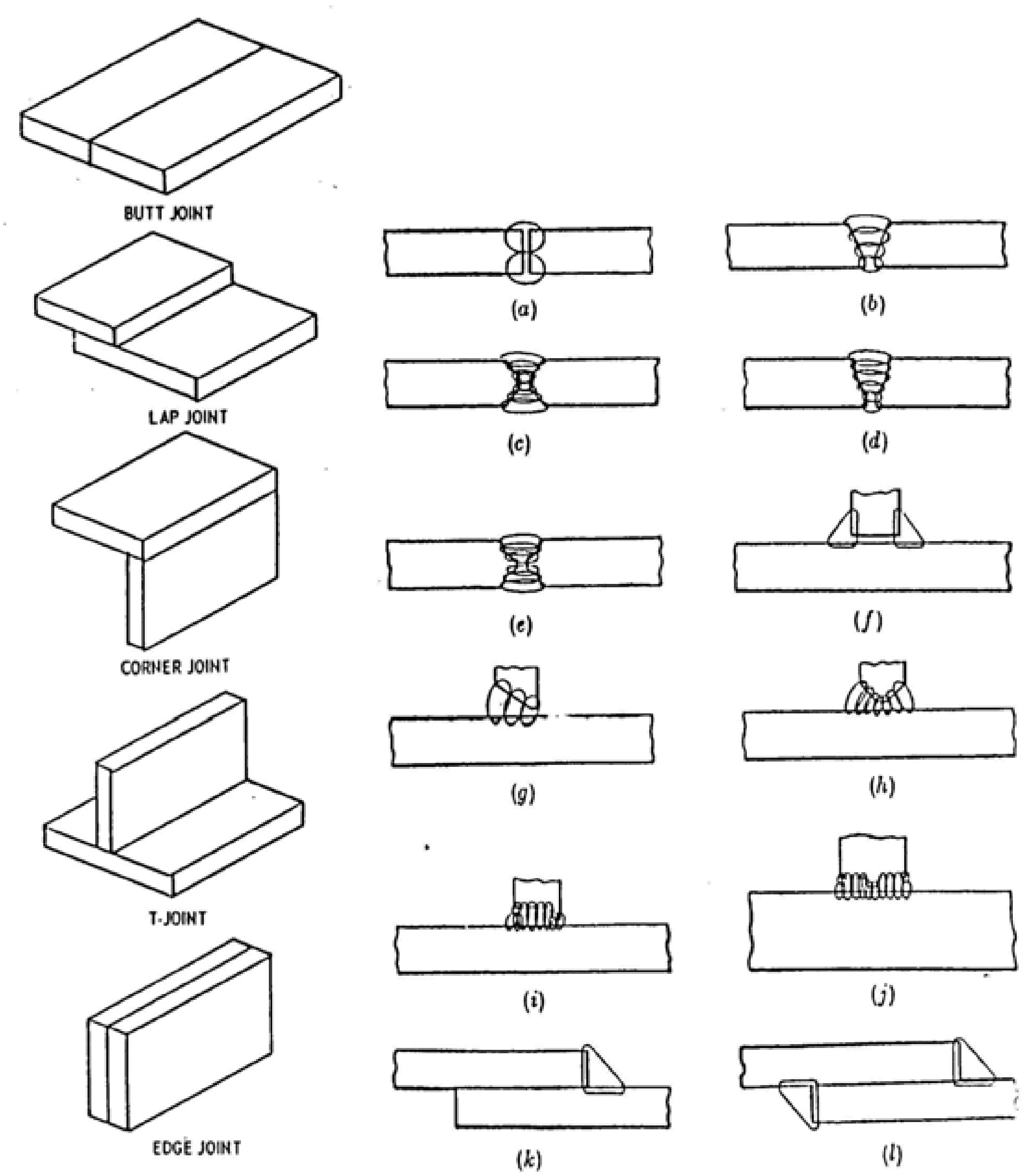
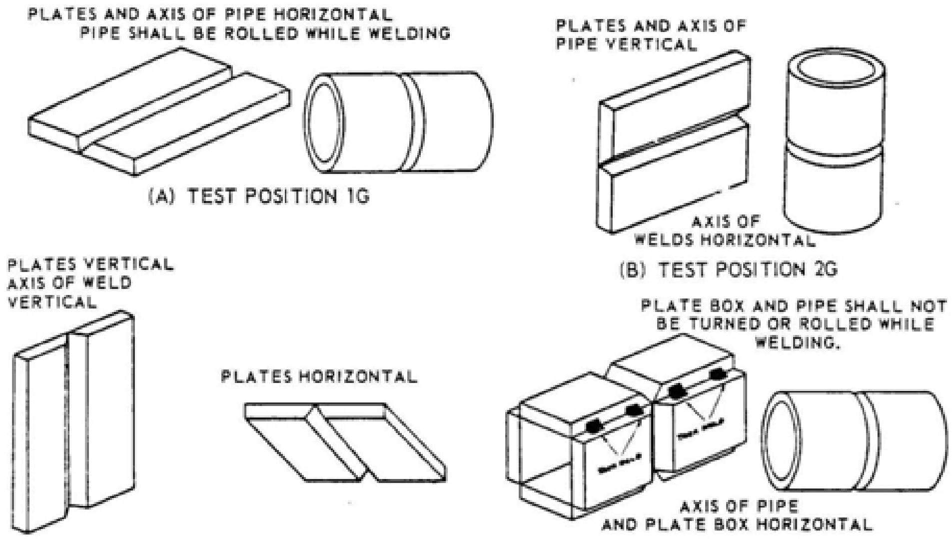


FIG.1.27. Types of welding joints: (a) square butt , (b) single-v butt , (c) double-v butt , (d) single-u butt , (e) double-u butt , (f) square-t , (g) single-bevel t , (h) double-bevel t , (i)single-u t , (j) double-u t , (k) single-bead lap , (l) double-bead lap.



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

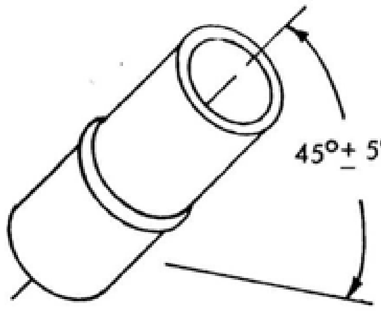


FIG.1.28. Positions of plates and pipes for groove weld.

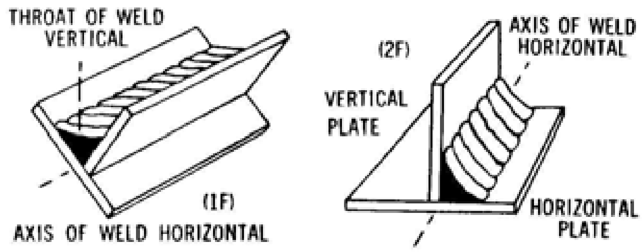
For fillet welds in plates, different positions are defined as below:

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).

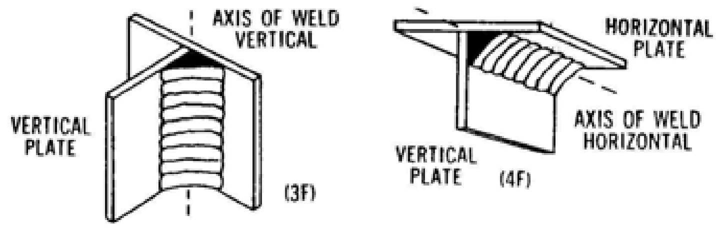
Horizontal position (2F). The test plates are so placed that each fillet weld is deposited on the upper side of the horizontal surface and against the vertical surface Fig. 1.29 (B).

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

Overhead position (4F). Plates are placed such 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.

(a) 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.

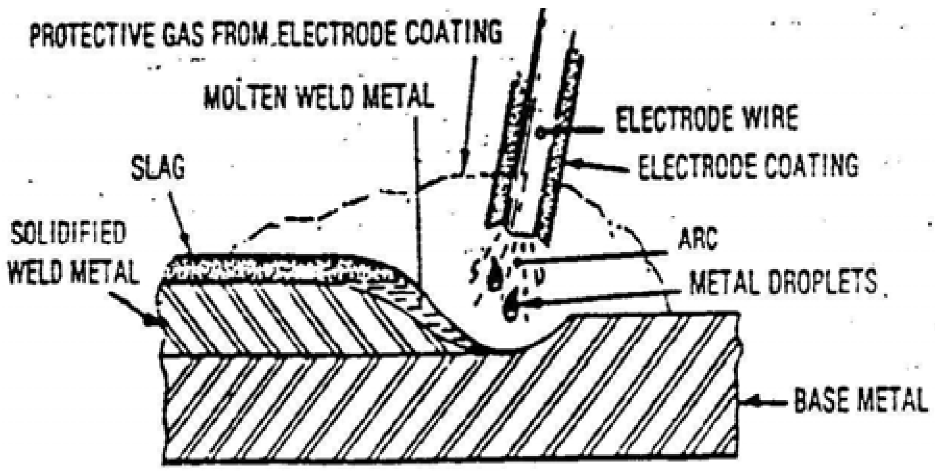


FIG. 1.30. Shielded metal arc welding process.

Covered electrodes are produced in a variety of diameters normally ranging from 2 mm 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.

(b) 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.

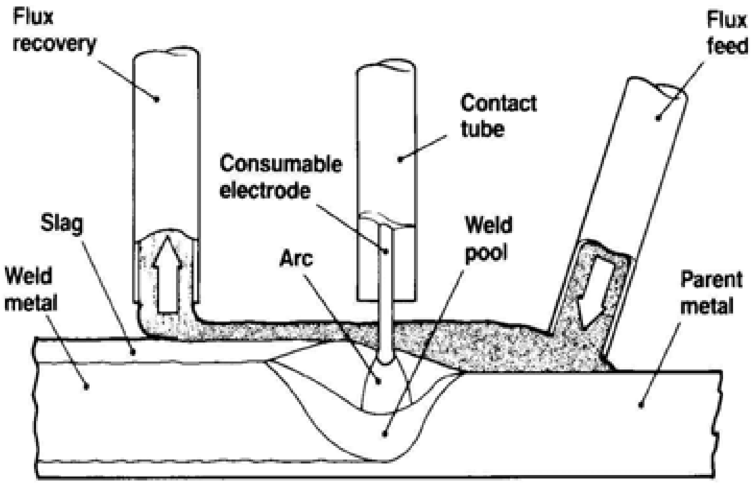


FIG. 1.31. Submerged arc welding process.

(c) 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.

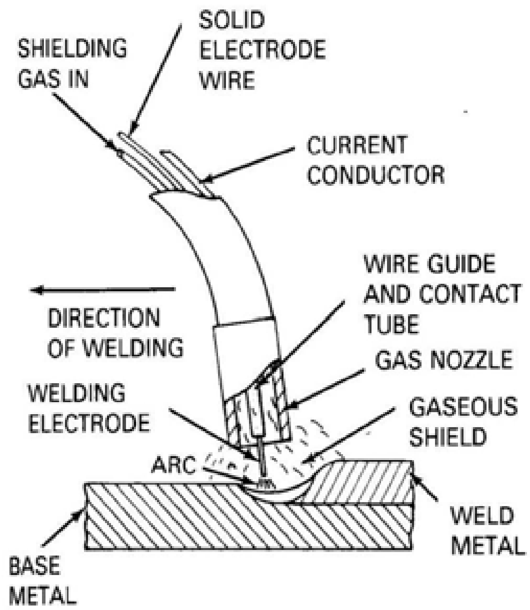


FIG. 1.32. Gas metal arc welding process.

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.

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.

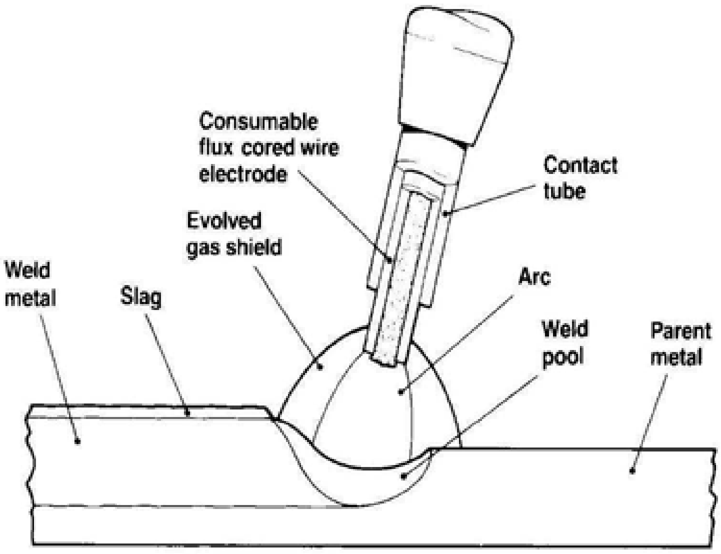


FIG. 1.33. Flux cored arc welding.

(d) 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.

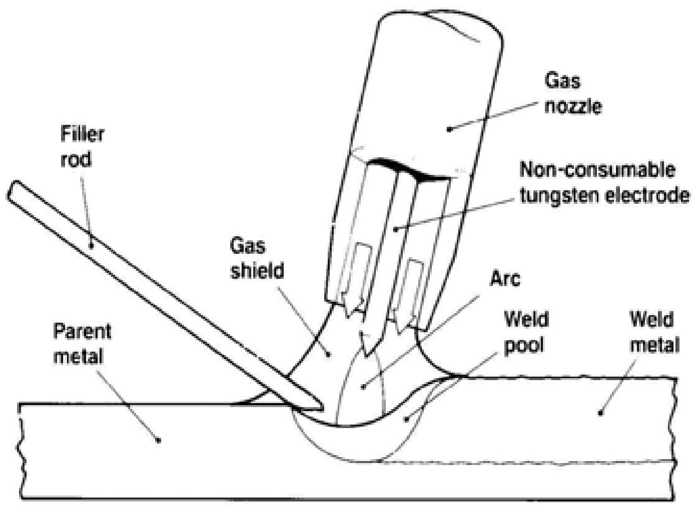


FIG. 1.34. Gas Tungsten arc welding.

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 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 restrictions on disposal of used thoriated electrodes by conventional means.

(e) 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 electroslag 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.

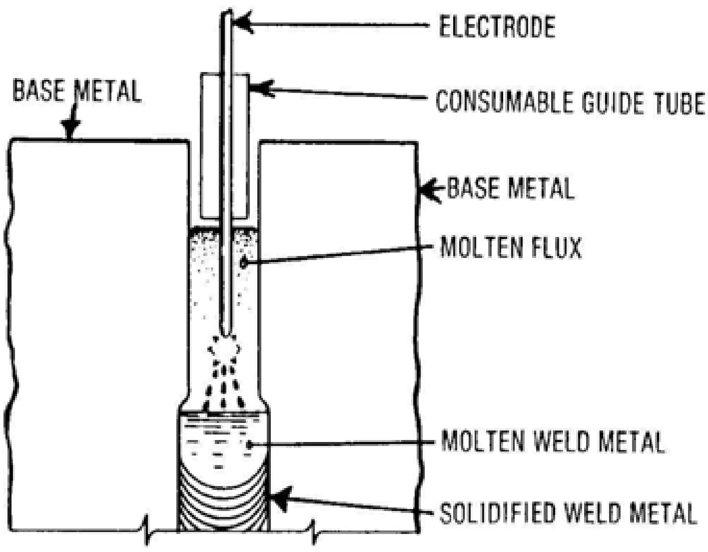


FIG. 1.35. Electroslag welding process.

(f) 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.

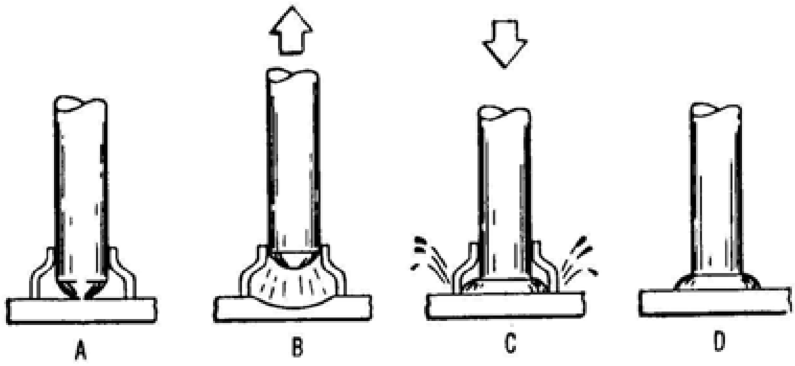


FIG. 1.36. Stud welding sequence.

(g) Plasma arc welding (PAW)

The plasma arc welding process provides a very stable heat source for welding most metals from 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.

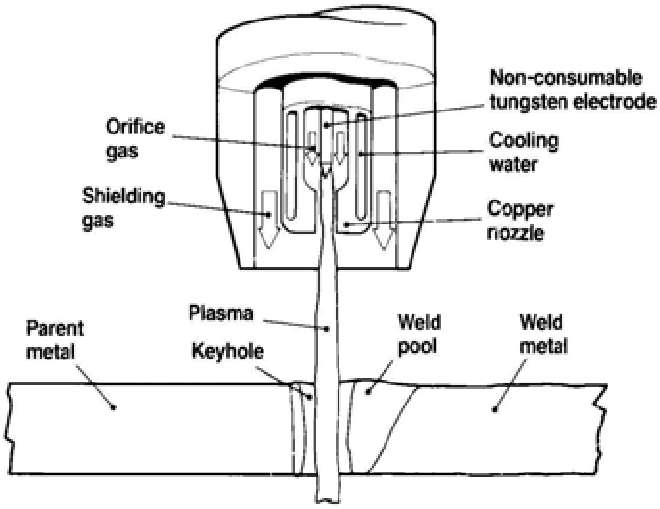


FIG. 1.37. Plasma arc welding.

(h) 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.

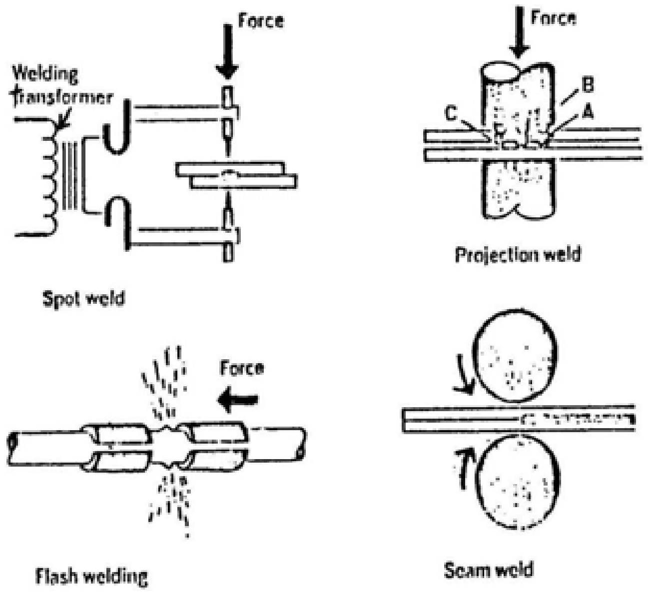


FIG. 1.38. Basic resistance welding methods.

(i) 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.

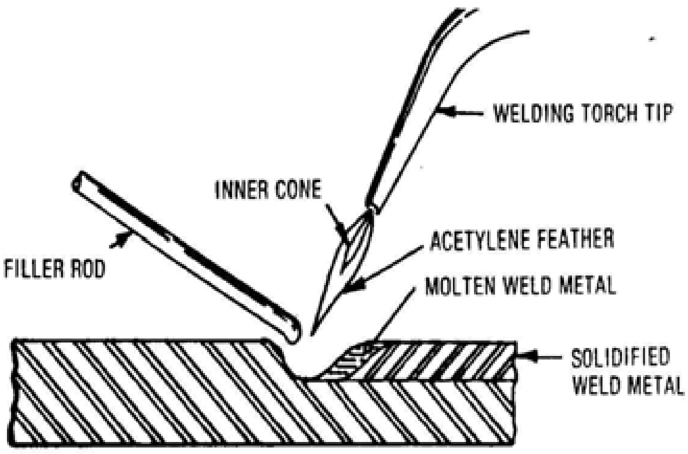


FIG. 1.39. Oxyfuel gas welding process.

Oxyfuel gas welding is normally done with acetylene fuel gas. Other fuel gases, such as methyl acetylene propadience 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 6 mm maximum thickness.

(j) 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.

(k) 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.

(l) 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.

(m) 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.

1.3.3.2. 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.

(a) 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.

(b) 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.

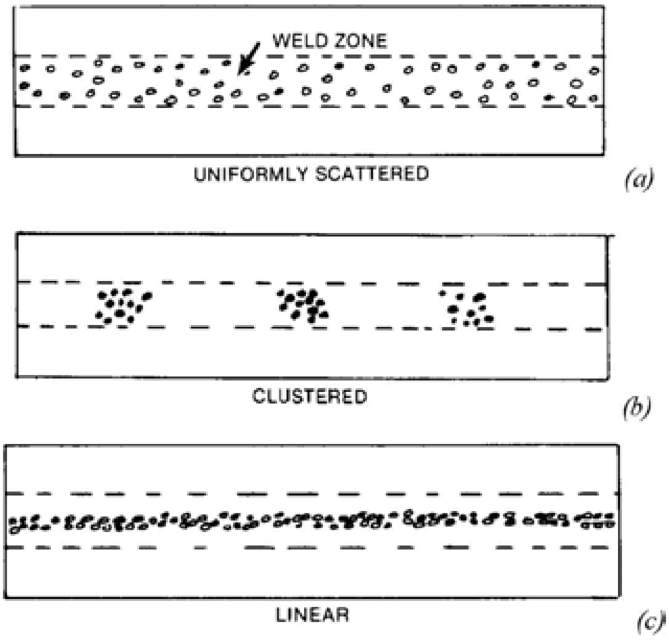


FIG. 1.40 Three types of weld porosity (a) Uniformly scattered porosity, (b) Clustered porosity (c) Linear porosity.

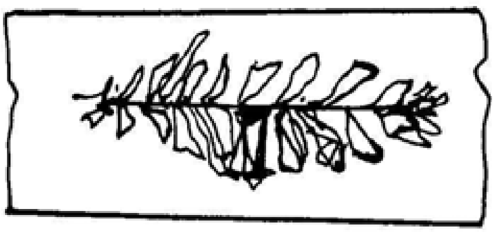


FIG. 1.41. Piping in weld.

(c) 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.

(d) 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.

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

TABLE 1.4. COMMON CAUSES AND REMEDIES OF SLAG INCLUSIONS

Causes	Remedies
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

(e) 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

(f) 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).

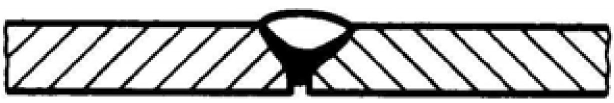


FIG. 1.42. Incomplete root penetration.

(g) 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.

- 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 inter-granularly 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.

- 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).

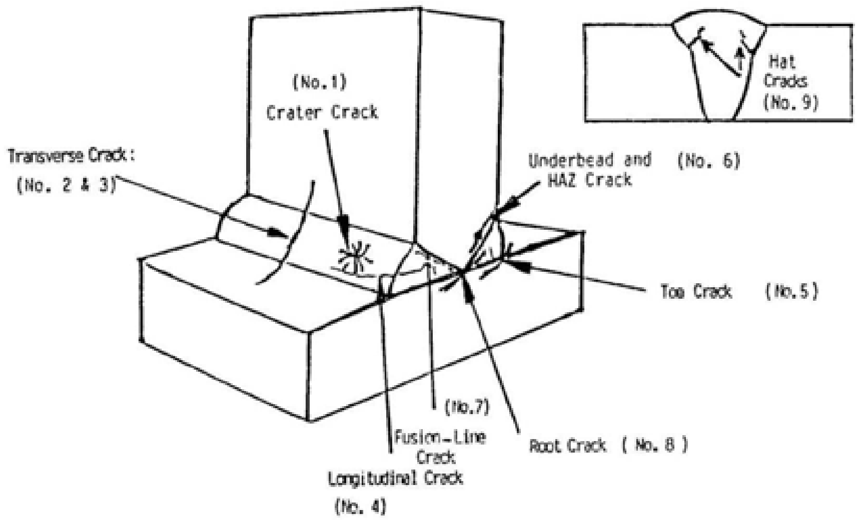


FIG. 1.43. Different types of cracks located in and around a welded joint.

- 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.

- 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.

- 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.

- 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).

(h) 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.

(i) 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 down hand 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.

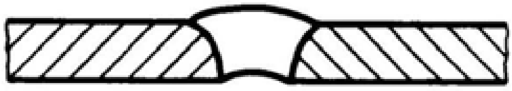


FIG. 1.45. Root concavity.

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	welding or post-weld 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
High hardenability	Apply intermediate stress-relief heat treatment temperature
Brittle phases in the microstructure	Solution heat treat prior to welding

(j) 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.

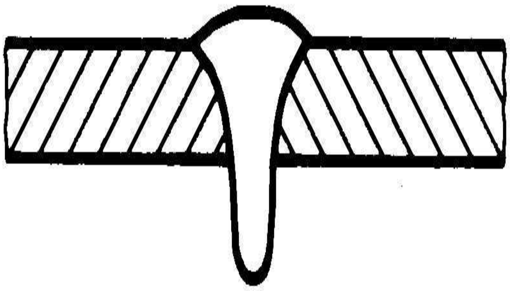


FIG. 1.46. Excessive penetration.

(k) 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.

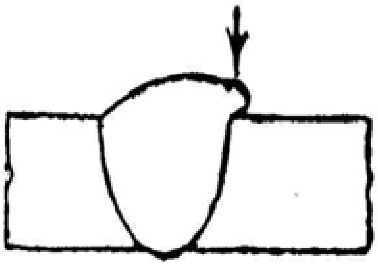


FIG. 1.47. Overlap.

(l) 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. These results initially in de-cohesion of non-metallic inclusions and then ductile tearing at about 45^{o} 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.

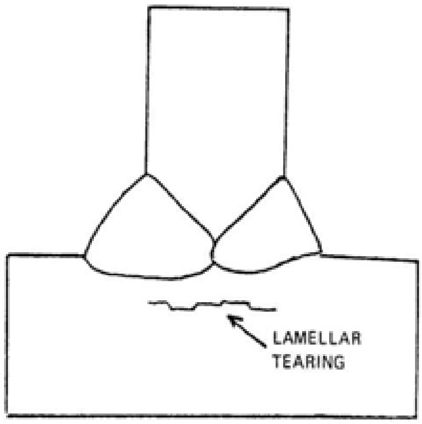


FIG. 1.48. Lamellar tearing.

(m) 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.

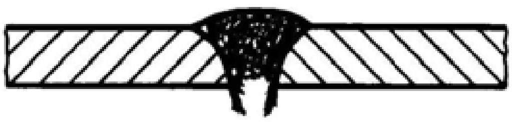


FIG. 1.49. Burn through.

(n) 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.

1.3.4. 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.

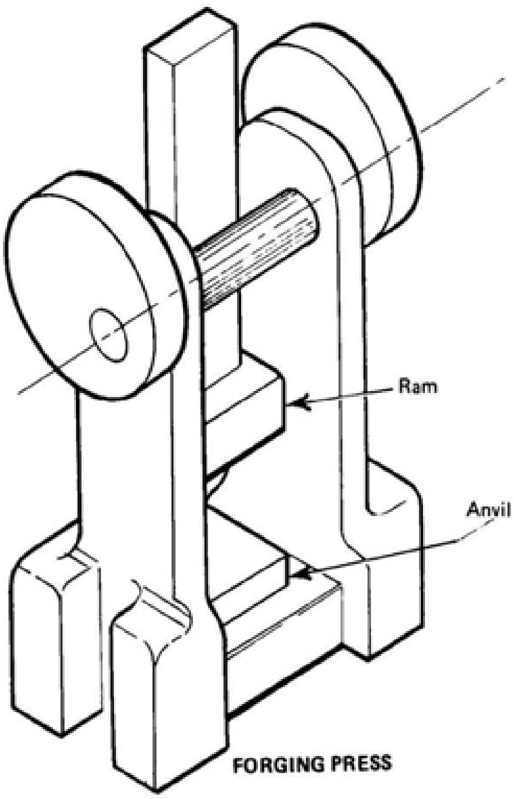


FIG. 1.50. Vertical forging press.

Forging may be considered in 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.

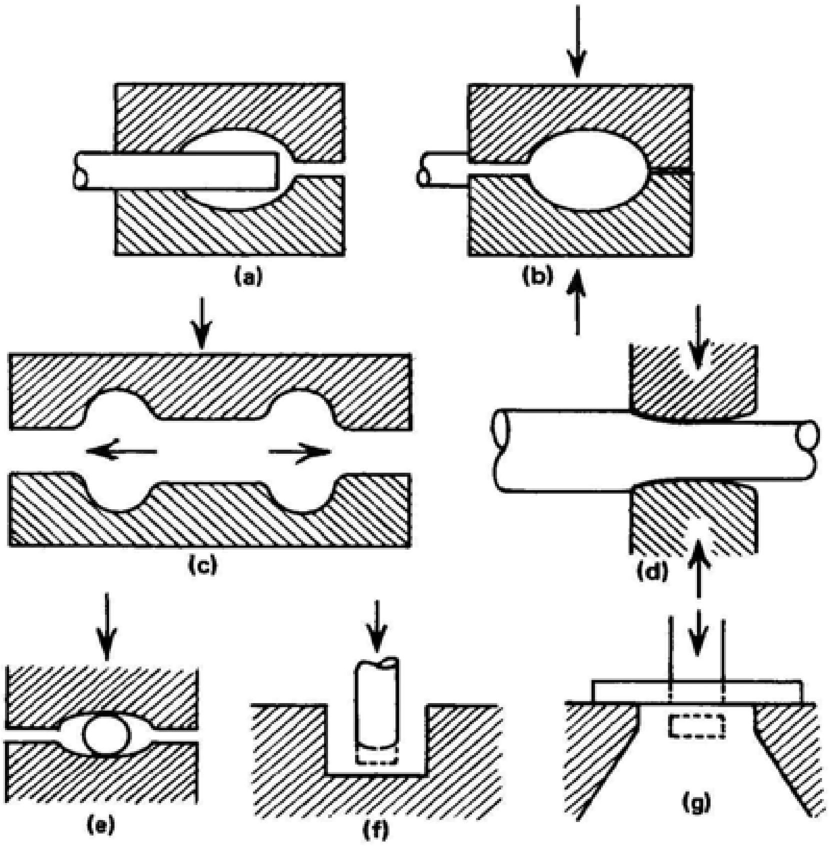


FIG. 1.51. Forging operations; (a, b) edding; (c) fullering; (d) drawing, (e) swaging (f) back extruding; (g) punching.

1.3.5. 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.

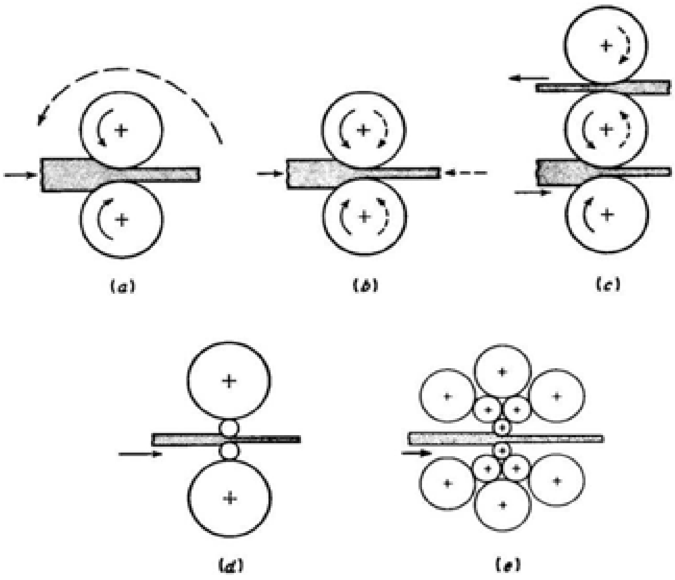


FIG. 1.52. Typical arrangements of rolls for rolling mills; (a) Two-high pullover, two-high reversing, (c) three-high, (d) four-high, (e) cluster.

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 joints are often laid out to provide a continuous train Fig. 1.53.

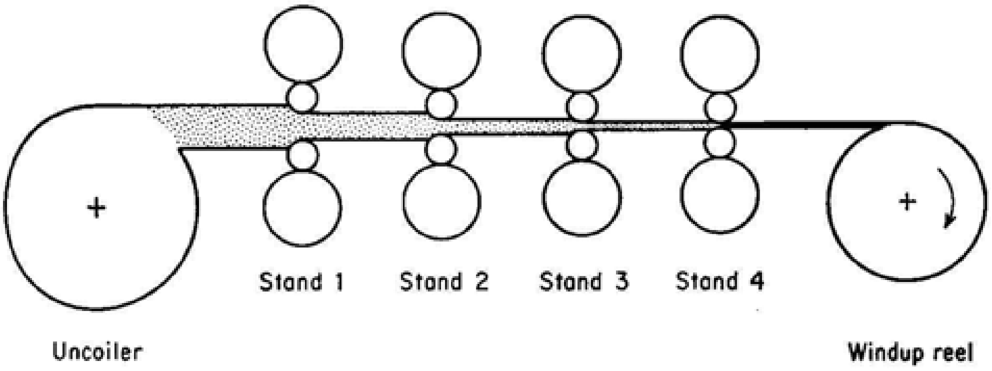


FIG. 1.53. Schematic drawing of strip rolling on a four-stand continuous mill.

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.

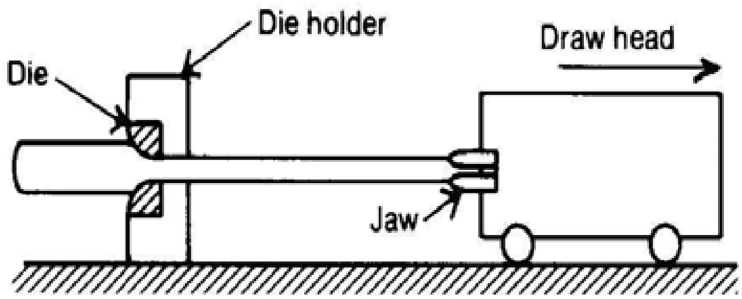


FIG. 1.54. Schematic drawing of a draw bench.

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.

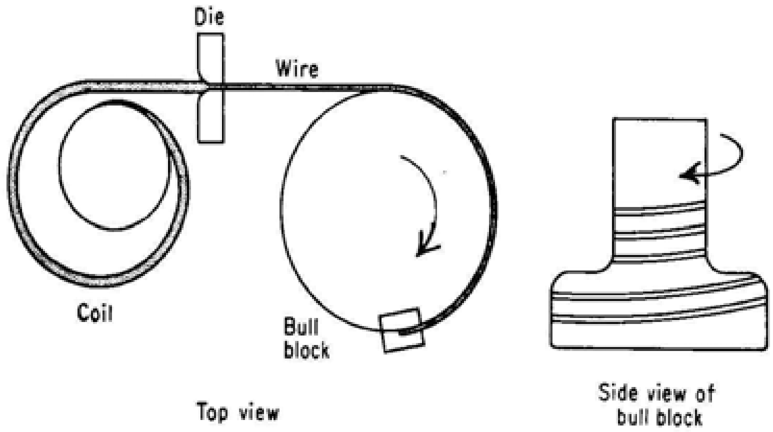


FIG. 1.55. Schematic wiredrawing equipment.

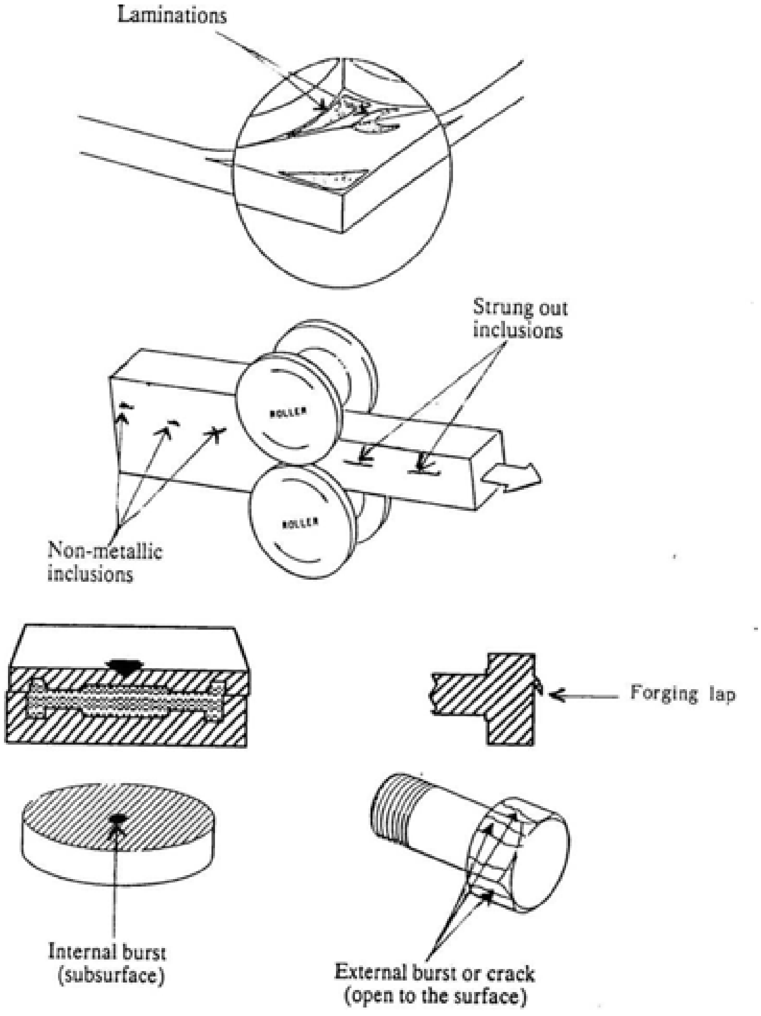


FIG. 1.56. Forging and rolling defects.

1.3.6. 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.

a) 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. 1.56.

b) 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.

c) 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. 1.56.

d) 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. 1.56.

e) 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.

f) 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.

g) 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.

h) 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.

i) 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.

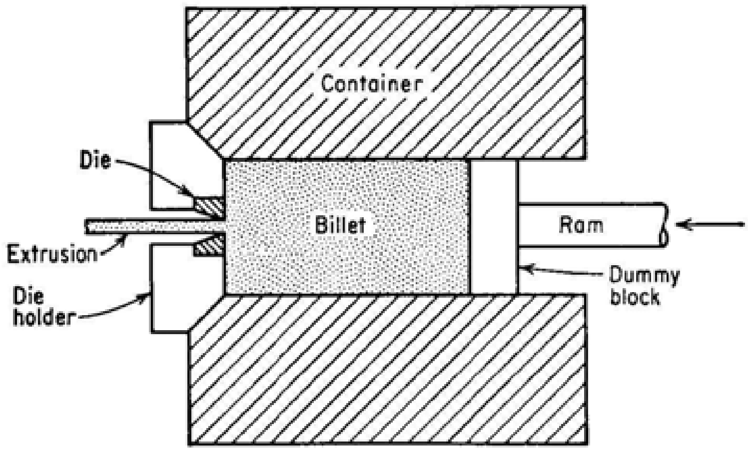
j) Pipe

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.

1.3.7. 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 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. 1.57 (a, b).

The Mannesmann mills, plug rolling mills, three-roll piercing mills, and reeling mills are also used for producing seamless pipe and tubing Fig. 1.58. The Mannesmann mill Fig. 1.58 (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 centre 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. 1.58 (b), have been widely adopted. This has led to the development of three-roll piercing machines Fig. 1.58 (c) which produce more concentric tubes with smoother inside and outside surfaces than the older Mannesmann design. A reeling mill Fig. 1.58 (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.



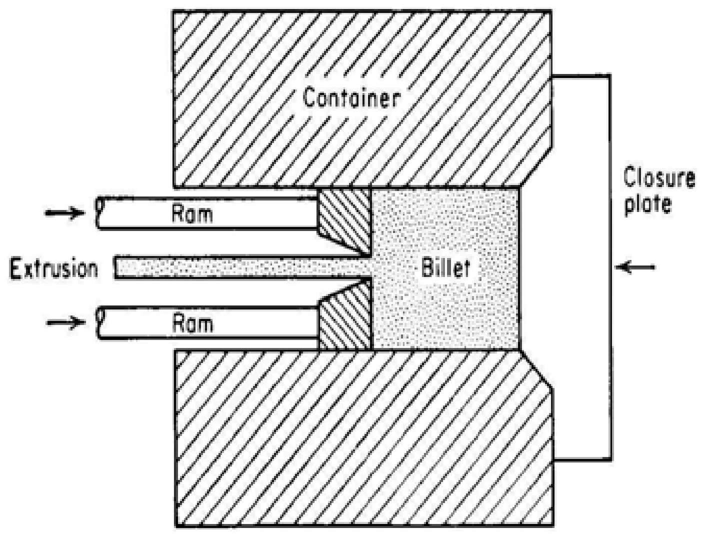


FIG. 1.57. Types of extrusion.

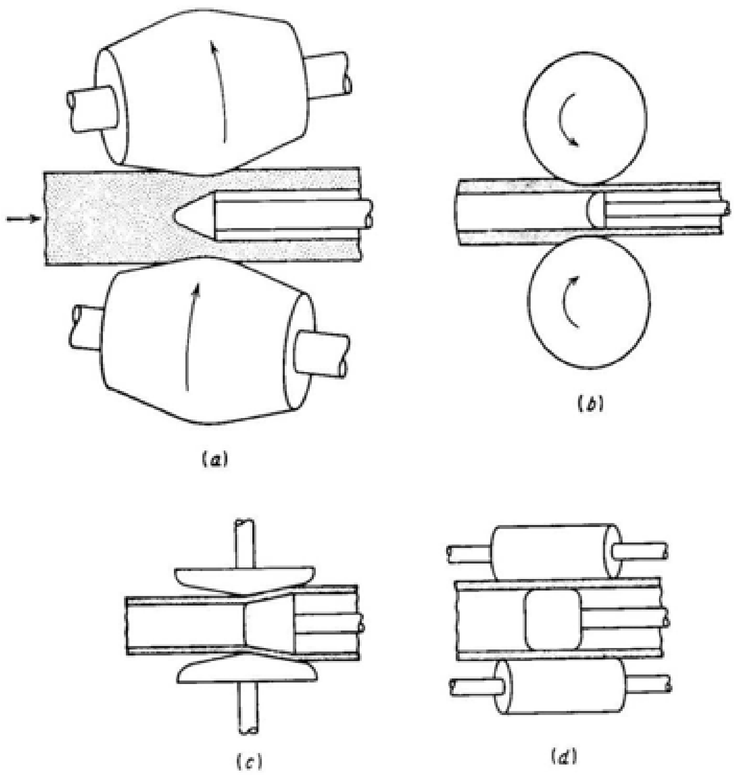


FIG. 1.58. (a) Mannesmann mill (b) plug rolling mill (c) three-roll piercing mill (d) reeling mill.

1.3.8. Spinning processes

A method of making tank heads, television cones, and other deep parts of circular symmetry is called spinning Fig. 1.59 (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. 1.59 (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, $t = t_o \sin \alpha$. 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.

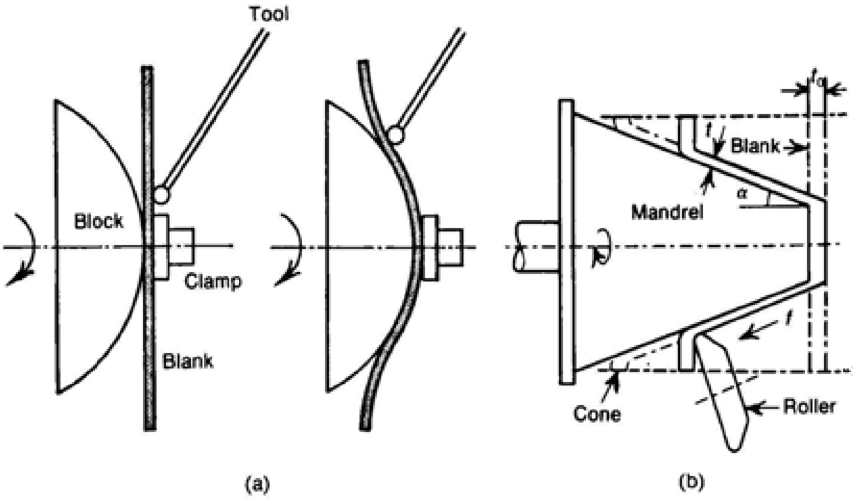


FIG. 1.59. Schematic representation of spinning processes (a) manual spinning (b) shear spinning.

1.3.9. 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 offering 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.

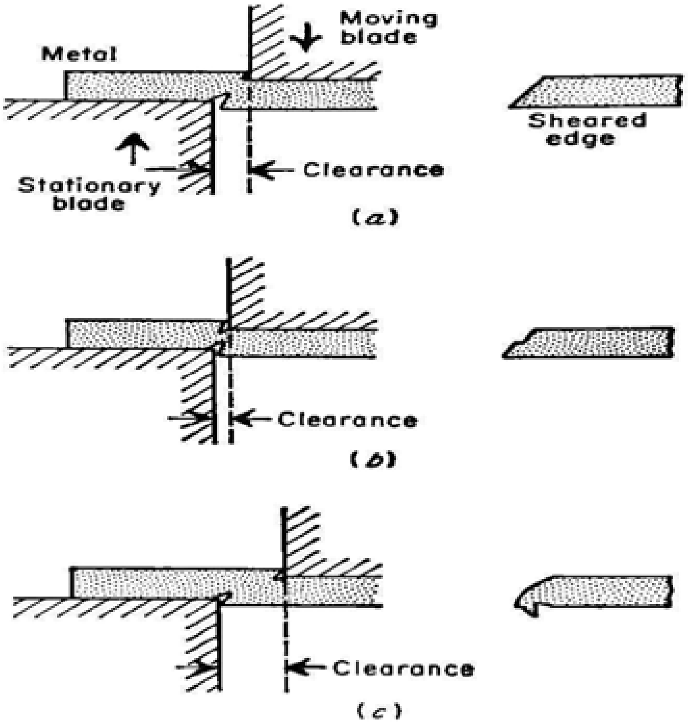


FIG. 1.60. Shearing of metal; (a) proper clearance (b) insufficient clearance (c) excessive clearance.

1.3.10. 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 definitions 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.

1.3.11. 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.

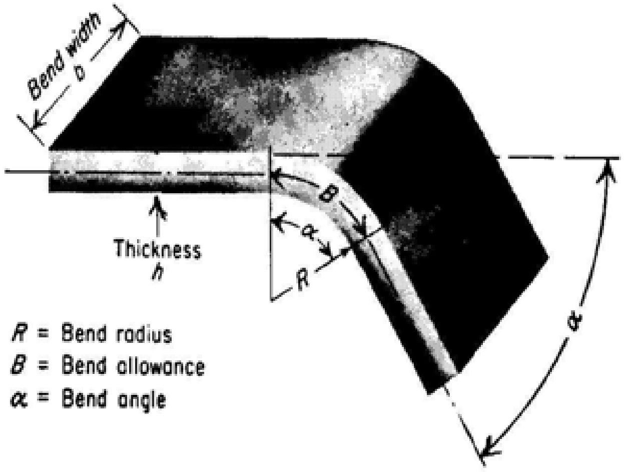


FIG. 1.61. Definition of terms used in bending.

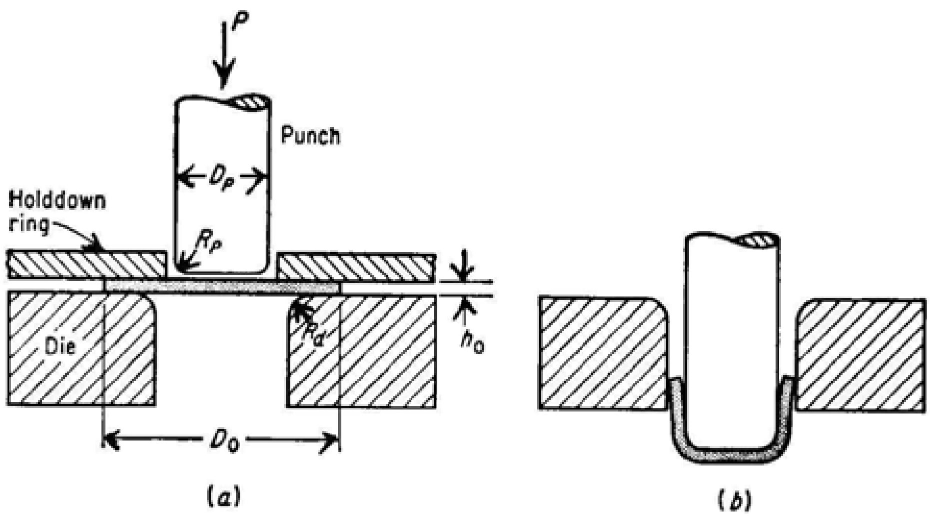


FIG. 1.62. Deep-drawing of a cylindrical cup; (a) before bending, (b) after drawing.

1.3.12. Finishing processes and related defects

1.3.12.1. 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.

1.3.12.2. 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.

1.3.12.3. 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.

1.3.12.4. 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.

1.3.12.5. 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.

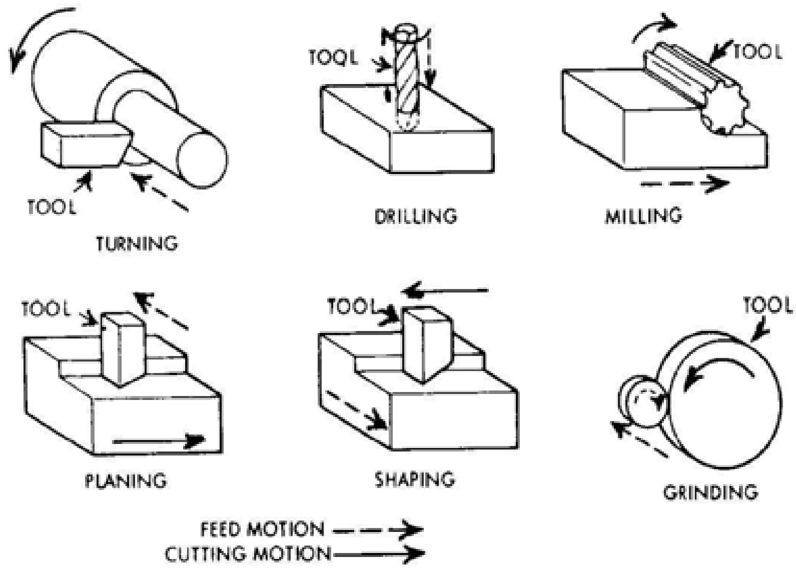


FIG. 1.63. Feed and cutting motions.

1.3.12.6. 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.

1.3.13. 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.

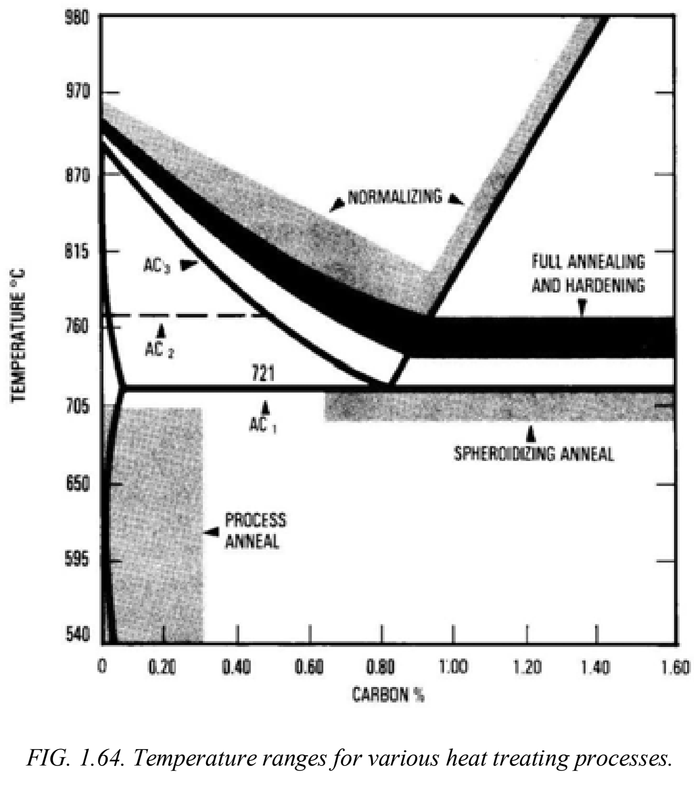


FIG. 1.64. Temperature ranges for various heat treating processes.

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 austentization.

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).

1.3.13.1. 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.

1.3.13.2. 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.

1.3.13.3. 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 shown in Fig. 1.65.

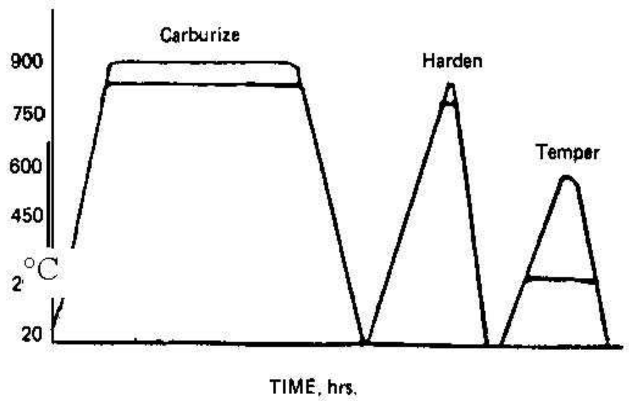


FIG. 1.65. Typical heat treatment cycle for carburizing.

1.3.13.4. 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 the entire 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.

1.3.13.5. 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 treatment 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 is 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.

1.3.13.6. 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.

1.3.13.7. Metallizing

Metal spraying or metallizing is a process in which metal wire or powder is fed into anoxy-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 mm 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.

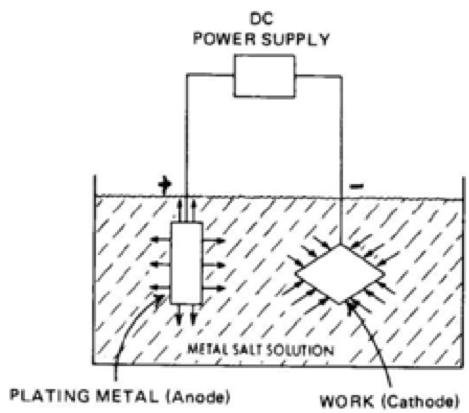


FIG. 1.66. Electroplating.

1.3.13.8. 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 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. Behavior 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. Service 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.

1.4.2.1. 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 anything 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.

1.4.2.2. 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.

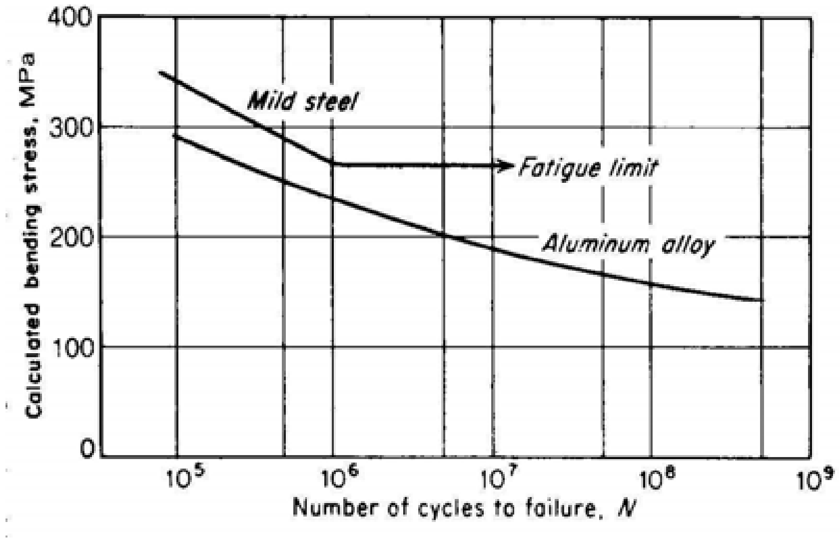


FIG. 1.67. Typical fatigue curves for ferrous and non-ferrous metals.

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.

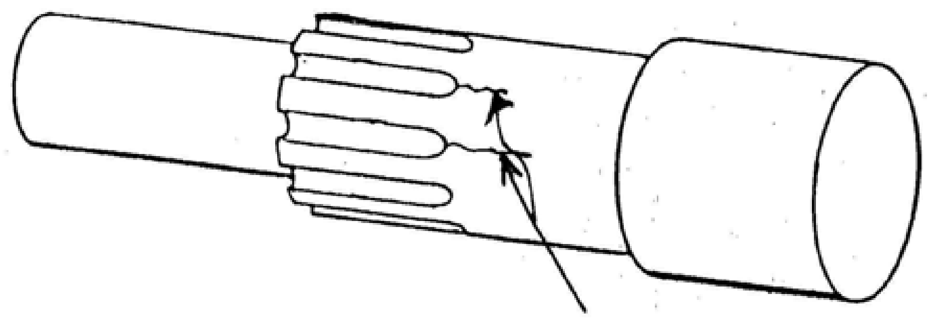


FIG. 1.68. Fatigue cracks.

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).

1.4.2.3. 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_o, 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.

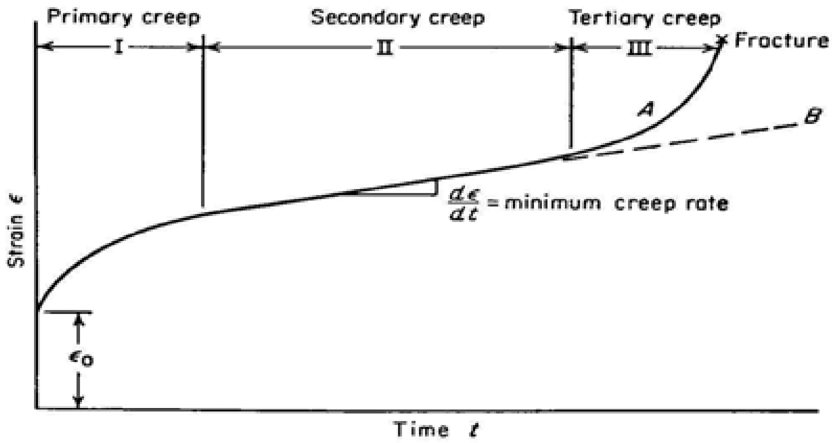


FIG. 1.69. Typical creep curve showing the three steps of creep curve A, constant-load test; curve B, constant-stress test.

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.

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, re-crystallization, or diffusional changes in the phases that are present.

1.4.2.4. 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.

1.4.2.5. 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.

1.4.2.6. 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 trans-granular (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 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 classic example is provided by the internal notches due to graphite flakes in cast irons. The flakes embrittles 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. Definition of quality, quality control and standardization

1.5.1.1. 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.

1.5.1.2. 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.

1.5.1.3. 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.

1.5.2. Development of a quality system

As the name suggests quality system is a method for quality assurance which means 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. 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.

1.5.2.1. Independence of quality assurance department

Responsibility for the development, operation and monitoring of an effective quality assurance programme in a plan 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.

1.5.2.2. 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.

1.5.2.3. 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.

1.5.2.4. 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.

1.5.2.5. 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.

1.5.2.6. 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.

1.5.2.7. 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.

1.5.2.8. 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.

1.5.2.9. 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.

1.5.2.10. 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.

1.5.2.11. 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.

1.5.2.12. 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.

1.5.3. Examination, testing and inspection

1.5.3.1. 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.

1.5.3.2. 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.

1.5.4. Standards, codes, specifications and procedures

1.5.4.1. 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.

1.5.4.2. 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.

1.5.4.3. 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.

1.5.4.4. 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.

1.5.5. Protocols, records and reports

1.5.5.1. Protocols

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

1.5.5.2. 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.

1.5.5.3. 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.

2. PHYSICAL PRINCIPLES OF THE TEST

2.1. Fundamentals of visual and optical testing

2.1.1. Description of visual and optical testing

Visual Testing (VT) is the monitoring of specific parameters by visual and optical assessments of test objects and surfaces using the visible portion of the electromagnetic spectrum.

Although a visual test is a test in itself, it also forms an integral part of many of the other non-destructive testing methods. For example, magnetic particle and penetrant inspection requires visual observation and assessment of the detected indication; radiographs require visual inspection for the interpretation of results; ultrasonic inspection often requires the visual assessment of the trace on a monitor.

Luminous energy tests are used for two purposes a) Testing of exposed or accessible surface of opaque test objects and b) Testing of the interior of transparent objects.

For many types of components, Visual Testing is used to determine the quantity, size, surface finish, shape, colour, function, leakage, and surface discontinuities.

2.1.2. Image formation

Most optical instruments are designed to form images. The manner of image formation and proportion of image is determined by trigonometry and geometry. This practical technique is called geometrical optics and it includes formation of image by lenses and mirrors.

2.1.3. Light sources

Light sources for visual testing emit radiation of a continuous and non-continuous nature. Light sources emitting distinct spectral lines are low in cost and are effective for routine tests. These sources include mercury, sodium and other discharge lamps. Monochromatic light is produced by devices known as monochromator.

2.1.4. Stroboscopic sources

A device that uses synchronized pulses of high intensity light for viewing of objects moving with fast and periodic motion is called a stroboscope. It can be used for viewing of apparently still test objects or for exposure of photographs. This effect requires an accurately controlled, intermittent source of light.

2.1.5. Light detection and recording

Once light has interacted with an object, the resulting light waves are considered test signal that can be recorded visually or photo electrically. Such signals may be detected by photoelectric cells, bolometers or thermopiles, photomultipliers or closed circuit television systems.

2.1.6. Fluorescence detection

A material is said to fluoresce when exposure to radiation causes the material to produce a secondary emission of longer wavelength. This technique is used as means of quality control of chemical compounds, identifying counterfeit currency, tracing fluid flow and detecting discontinuities in materials.

2.1.7. *Optical and illumination equipment*

Inspection may be by the use of the eye alone or can be enhanced using optical systems such as magnifiers and microscopes. A variety of equipment is available to the visual inspector including mirrors and gauges which can be used for profile assessment. Borescopes and endoscopes are used on parts with limited access. Video and computer enhancement systems also exist.

It is not always feasible to use daylight, and the illumination required for visual testing can be provided by a number of auxiliary sources, which are chosen according to the application of the visual test. The light source is usually specified in a procedure.

Background lighting conditions can affect the test. A bright background with too much glare will interfere with the inspection, as will a background which is too dark or casts shadows over the test area. Daylight is the best light possible as it provides optimum wavelength distribution for the human eye, and an overcast day gives much better results than bright sunshine.

In any event, it is imperative that the level of illumination at the inspection area is sufficient for the test, and calibrated instruments are used to measure and record the prevailing light conditions.

2.2. Nature of light

2.2.1. *Generalities*

2.2.1.1. Wave Theory

The wave theory of light was proposed by Christian Huygens in 1679 and is based on the following postulates:

i) The luminous body is a source of disturbance in an hypothetical medium called the ether, which pervades all space.

ii) The disturbance from the source is propagated in the form of electromagnetic waves (comparable to ripples in water), and the energy is distributed equally in all directions.

iii) When these energy carrying waves are incident on the eye, the optic nerves are excited (stimulated) and the sensation of vision is produced.

In the Fig. 2.1 (i), S is a source of light sending out light in the form of waves in all directions. After the elapse of time t, all the particles of the medium are vibrating in phase on the surface of XY, which is called the primary wave front. The wave front can be defined as the locus of all points of the medium that are vibrating in phase.

In Fig. 2.1 (i), XY is a spherical wave front. In Fig. 2.1 (ii) XY is a plane wave front as the source of light is in the form of a parallel beam of light. All the points of primary wave front (1, 2, 3, etc.) in the Fig. 2.1 are sources of secondary disturbances.

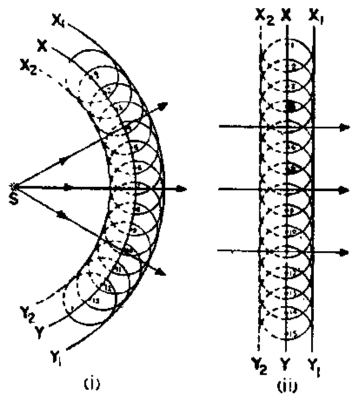


FIG. 2.1. Spherical and Plane Wave fronts.

These secondary waves travel through space with the same velocity as the original wave and after any given time give rise to secondary wave fronts.

Although Huygens could satisfactorily explain the phenomena of reflection, refraction and double refraction noticed in crystals like quartz and calcite, the phenomena of polarization and rectilinear propagation of light could not be explained on the basis of postulates put forward by him because of an incorrect assumption that light travels in the form of longitudinal waves rather than transverse waves - as was later correctly postulated by Fresnel and Young.

2.2.1.2. Quantum Theory

Planck's Quantum theory is an up-dated version of corpuscular theory, which was put forward in 1895 by Sir Isaac Newton. The Quantum theory strengthened the particle concept of the nature of light. Planck's theory is based on the following premises:

i) Energy is emitted and absorbed in discrete quanta (photons).

ii) One unit or quantum of energy was equal to hf, where f is the frequency of the particular radiation in Hertz and h is a constant called the Planck constant which is equal to 6.626 x 10^{-34} Joule/second.

It is very interesting to note that light is regarded as a wave motion at one time, and as a particle motion at another time. The light source continuously emits elastic particles called corpuscles in every direction. These particles are so small that they can pass through the interstices of the particles of the medium. When they fall on the retina of the eye, they produce the sensation of vision. Phenomena such as rectilinear propagation of light, reflection and refraction could be accounted for satisfactorily within Quantum theory.

2.2.1.3. Electromagnetic radiations

Visible light is defined as radiant energy (energy transmitted by electromagnetic waves) capable of exciting the human retina and creating a visual sensation. It is the portion of the electromagnetic spectrum with wavelengths between 380-730 nm. At these wavelengths radiant energy makes visible anything from which it is emitted or reflected in sufficient quantity to activate the receptors of the eye.

Infrared light, ultraviolet light, X-rays, and Gamma (γ) rays are electromagnetic radiations and are propagated through the free space with a velocity of light i.e. 3 x 10^8 m/s. All forms of this energy travel at the same velocity however each form of radiant energy differs in wavelength and therefore in frequency. The wavelength and velocity may be altered by the medium through which it passes but the frequency is fixed independently of the medium.

The relationship between radiant velocity (v) frequency (f) and wavelength (λ) is given by equation (2.1) given below:

$$V = \lambda f/n \text{ ---------------------------------- } \quad (2.1)$$

where n = refractive index of the medium.

(a) Light spectra

The light spectra is a visible spectrum which comprises only a small range of electromagnetic spectrum extending approximately from 380nm in the extreme violet region to 730nm in the extreme red. This visible spectrum in fact includes those wavelengths that can stimulate the sense of sight. The term electromagnetic spectrum is used for the range of wavelength from 10^4 metres to 10^{-12} metres. The electromagnetic spectrum of visible, ultraviolet and infrared is shown in Fig. 2.2.

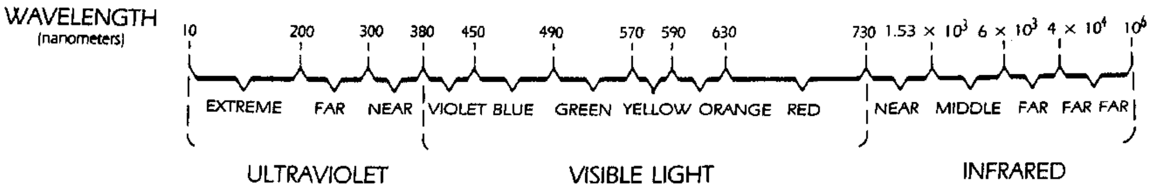


FIG. 2.2. The spectrum of visible, ultraviolet and infrared radiation.

A commonly used term to represent the electromagnetic spectrum is angstrom (Å), where 1Å = 10^{-10} metres

(b) Infrared radiations

The electromagnetic radiant energy of wavelengths longer than 730 nm is characterized as infrared radiations. On the electromagnetic spectrum, these radiations are recognized as lying in the region beyond the red end of the visible spectrum. Their wavelengths extend up to 4 x 10^6 nm.

(c) Ultraviolet radiations

The spectrum that covers the wavelengths from 10nm to 380nm is called the ultraviolet spectrum. The region of the ultraviolet radiation lies beyond the violet end of the visible spectrum. Sun is a natural source of ultraviolet radiations. An electric arc of carbon, mercury vapour lamps, discharges of electricity through hydrogen contained in quartz tubes and Light Emitting Diodes (LED's) are some of the artificial sources that produce ultraviolet radiations.

2.2.2. Characteristics of light

2.2.2.1. Intensity

The intensity of illumination is defined as flux per unit area incident on a given surface, the ray falling perpendicular to the surface. The word 'flux' here means luminous flux (∅v) that is a measure of the rate of flow of light i.e. the radiant flux in the wavelength range 380–760 nanometre (nm). It is measured by reference to emission from a standard source, usually in lumens (lm).

The intensity of illumination from a point source that falls on the surface is given by relationship known as Lambert's cosine law:

$$I = L.\cos\theta/r^2 \text{ ---------------------------} \quad (2.2)$$

Where L = illuminating power or luminous intensity of the point source

cos θ = cosine of the angle of incidence of light radiation on the given surface.

r = distance between the source and the surface.

The way the light distribution occurs over an area with distance i.e. the inverse square law and the Lambert cosine law are represented in Fig. 2.3 (a & b).

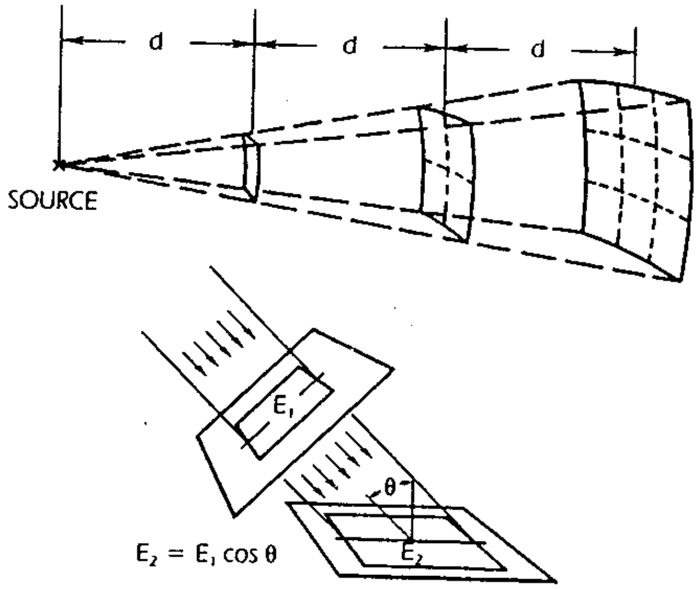


FIG. 2.3 (a & b). Inverse square law and Lambert law.

2.2.2.2. Colour

White light has a band of wavelengths of different colours. This is called the spectrum of white light. The longest wavelength is red light, which has a wavelength in air of about 700 nm (nanometres). The shortest wavelength is violet, which has a wavelength in air of about 450 nm. In a vacuum (and practically in air), all colours travel at the same velocity. In a medium such as glass, however the colours travel at different velocity, with red the fastest and violet the slowest. According to wave theory refraction is due to a change in the velocity of light when it enters a different medium. Thus when a ray of white light passes through a prism, it is refracted and split into its constituent colours, and this phenomena is called dispersion. The principal colours are given by the word VIBGYOR (Violet, Indigo, Green, Orange, Yellow, and Red). The deviation produced for the violet rays is maximum and for red rays it is minimum as shown in Fig. 2.4.

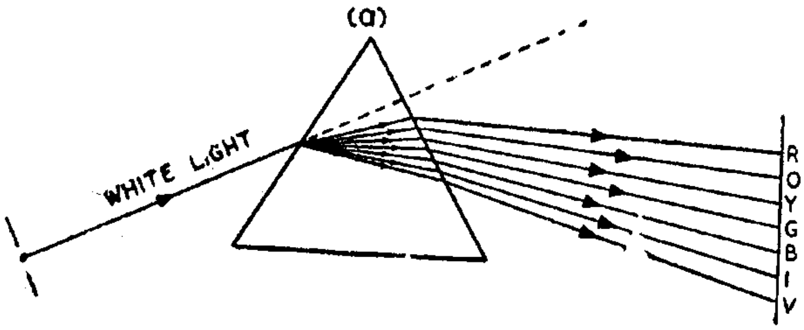


FIG. 2.4. Dispersion of light by a prism.

The prism has thus dispersed the white light into its various colours or wavelengths. The intensity is related to the amount of a particular colour. The different colours can have the same intensity. Every colour has the following three characteristics.

(a) Tone or Hue

Hue is associated with a range of wavelengths in the spectrum and is usually what an observer means when describing a colour e.g. red, blue or violet. An estimated seven million colours can be discriminated but, because the transition from one hue to the next is gradual, the demarcations are ill defined and only a few main colours are commonly distinguished. The normally distinguishable colours are:

Colour	Wavelength range (nanometre)
Violet	380 to 450
Blue	450 to 480
Blue-green	480 to 510
Green	510 to 550
Yellow – Green	550 to 570
Yellow	570 to 590
Orange	590 to 630
Red	630 to 730

(b) Brightness or Luminosity

A hue may also vary in brightness, according to the intensity of pre-dominant radiation. Excessive brightness (or brightness within the field of view varying by more than 10:1) causes the unpleasant sensation of glare. Glare interferes with the ability of clear vision, critical observation and judgement.

(c) Saturation

This is a relative or comparative characteristic and may be described as a hue's dilution with white light.

2.2.2.3. Magnitude & Units

(a) Candela (cd)

The candela is the SI base unit of luminous intensity; that is, power emitted by a light source in a particular direction. It is the luminous intensity in a given direction of a source that emits monochromatic radiation of frequency 540 x 10^{-12} Hz and that has radiant intensity in that direction of 1.4641 milliwatt per steradian. It is symbolized cd and was formerly known as candle.

(b) Lumen (lm)

Lumen is the SI unit of luminous flux and is the luminous flux emitted within a solid angle of1 steradian, by a point source having a uniform intensity of one 'candela'. As the lumen is a measure of energy per unit time it must also be related to the Watt. The energy of a light source depends on its wavelength, but as a rough guide 1 watt equals 621 lumens of green light (wavelength 5.54 x 10^{-10} m).

It follows that a point source having an intensity of 1 candela in every direction will be emitting a total flux of 4 lumens.

1 Lumen – Sec = 1Talbot
also, 1 Lumen = 0.0016 watt.

The angle 'steradian' is the unit of solid angle and is defined as the Steradian value of the solid angle is the angle substended at the center of a sphere by a part of its surface having an area equal to $(\text{radius})^2$.

(c) Foot -candle

It is the unit of intensity of illumination is defined as the amount of light falling on one square foot area of a spherical surface of radius 1 foot when a source of one candle power is kept at the centre of curvature.

1 foot–candle is also known as 1 lumen per square ft.

(d) Lux (lx)

A unit of illuminance, and is equal to the illumination produced by a luminous flux of 1 lumen distributed uniformly over an area of 1 square metre.

It can also be described as the illumination on a surface all points of which are at a distance of 1 metre (m) from a point source of 1 candela (cd).

(e) Phot

It is the unit of intensity of illumination and is equal to one lumen per square centimetre; it is therefore a larger unit and is equal to 10,000 lux.

TABLE 2.1. IMPORTANT VALUES OF ILLUMINANCE (INTENSITY OF ILLUMINATION)

Method of illumination	Lumens/m^2 (lux)
Star light	3×10^{-4}
Full moon light	0.2
Fluorescent tube light	100
Day light (inside near windows)	10^3
Overcast day	10^4
Sun light (maximum)	10^5

TABLE 2.2. MEASUREMENT CHARACTERISTICS OF SOURCES OF LIGHT

	Characteristics	Dimensional unit	Equipment
a)	Light		
	Wavelength	Metre (m)	Spectrometer
	Colour	None	Spectrophotometer or colorimeter
	Illuminance	Lux (lx)	Photometer
	Orientation of Polarization	Degree (angle)	Analyzing prism
	Degree of polarization	Percent (dimensionless)	Polarization photometer
b)	Light source		
	Energy radiated	Joules per square metre	Radiometer
	Colour temperature	Kelvin	Colorimeter or filtered photometer
	Luminous intensity	Candela	Photometer
	Luminance	Candela per square metre	Photometer or luminance meter
	Spectral power distribution	Watts per nanometre	Spectro-radiometer
	Power consumption	Watt	Wattmeter or voltmeter and ammeter
	Luminous flux (light output)	Lumen	Integrating sphere photometer
c)	Lighting material		
	Reflectance	Percent (dimensionless)	Reflecto-meter
	Transmittance	Percent (dimensionless)	Photometer
	Spectral reflectance & transmittance	Percent (at specific wavelengths)	Spectrophotometer
	Optical density	Dimensionless number	Densitometer

2.2.2.4. Measurement

The measurement characteristics of light, light source and lighting materials are summarized in Table 2.2.

(a) Measuring equipment

Although the human eye is the main detector for white light, instrument detectors such as photoconductive cells, photodiodes, phototransistors and photographic film etc. can measure the radiant properties of light and provide accurate data not available by human eye assessment. The measurement of light is called photometry with the measurement instruments being called photometers and radiometers and are either portable or laboratory based, the latter being the most accurate. A radiometer is an instrument used to detect and measure electromagnetic radiant energy. A photometer is a specific type of radiometer which measures only the visible part of the radiant energy.

(b) Measurement of visible light

Photometers are used to measure light energy within the visible spectrum and can measure luminous intensity, luminous flux, illuminance, luminance, light distribution, light reflection and light transmittance. A spectroscope measures the spectral distribution of colours or selective wavelengths. Apparent differences in the intensity of various light sources can be due to differences in the ability of the measuring instrument to detect different wavelengths (spectral response). This needs to be considered when any measurement of visible light is being made.

There are many types of photometers. For example, one type incorporates a photometer for visible light and radiometer for ultraviolet light. The choice of photometer will depend on the intensity of the light source, the wavelengths of the source, the accuracy required, whether testing is indoor or outdoor etc.

(c) Measurement of ultraviolet light

Ultraviolet light, known also as black light, is not visible to the human eye, but can be made visible by using fluorescent dyes. These dyes absorb the ultraviolet radiation and emit the absorbed energy as light of wavelengths usually in the yellow-green portion of the spectrum. Ultraviolet radiation is defined as the part of the electromagnetic spectrum having wavelengths from 100-400 nm i.e just beyond the violet end of the visible spectrum. It is divided into 3 types, UV-A, UV-B, and UV-C.

UV-A is the portion between 315-400 nm; UV-B is the portion between 280-315 nm; UV-C is the portion between 100-280 nm. Radiometers are used to measure radiant power over a wide range of wavelengths, including ultraviolet light. These instruments measure ultraviolet light in micro watts per cm^2.

2.3. Basic laws – characteristics of light

2.3.1. Reflection

The phenomenon of reflection is described as the return of all or part of a beam of light when it encounters the boundary between two media. As illustrated in the Fig. 2.5, AO is the ray of light incident at O on the plane surface of glass medium, some of the light is reflected from the surface along OC in accordance with the laws of reflection. The rest of the light travels along a new direction OB in the glass. The reflection of light ray AO at point O obeys, the following laws of reflection:

The incident ray, the reflected ray and the normal to the reflecting surface at the point of incidence are all in the same plane. The angle of incidence equals the angle of reflection.

2.3.2. Total internal reflection

If a ray AO in glass is incident on a small angle α on a glass-air plane boundary, part of the incident light is reflected along OE in the glass, while the rest of the light is refracted away from normal at an angle β into the air. The reflected light ray OE is weak, but the refracted ray OL is bright, Fig. 2.6(i). This means that most of the incident light is transmitted, and only a little is reflected.

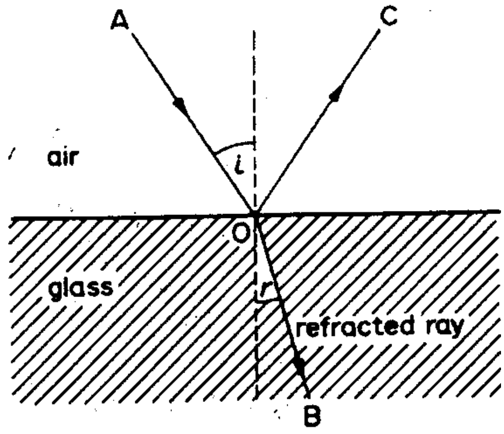


FIG. 2.5. Reflection at Plane surface.

We can observe in Fig. 2.6 that on increasing the angle of incidence α in the glass, the refracted angle β also increases up to a value of incident angle known as first critical angle such that the angle β becomes 90° i.e. the refracted ray travels along glass - air interface. As the angle of incidence is further increased, no refracted ray is seen and whole light is reflected back to the original medium, or we can say that the light is totally internally reflected. The angle of refraction in air is 90°, a critical stage at the point of incidence O is reached and the angle of incidence in the glass is known as the critical angle for glass and air as shown in Fig. 2.6 (ii). For crown glass the value of critical angle C is 41.5°, so for angle above the value say, 45° total internal reflection will take place and total light is reflected back into original medium of incidence.

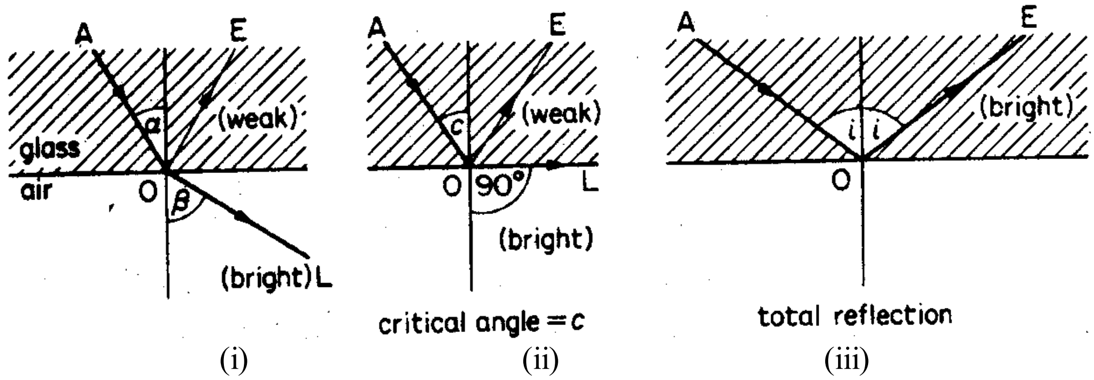


FIG. 2.6. Total internal reflection.

2.3.3. *Refraction*

The refraction phenomenon occurs where a change of direction of a wave front occurs as it passes from one medium to another, in which its velocity of propagation is altered. The phenomenon occurs with all types of waves, but is most familiar with light waves. In Fig. 2.5 we observe the incident ray of light AO travels along a new path OB, in the glass. The light is said to be ‘refracted’ on entering the glass. The angle of refraction, r, is the angle made by the refracted ray OB with the normal at O.

Snell, a Dutch professor, stated the following:

For a given boundary, the ratio of the sin of the incident angle to the sin of the refracted angle is a constant, and this constant is known as the refractive index (n). The incident and refracted rays, and the normal at the point of incidence, all lie in the same plane. Snells law can represented as:

$$\sin I / \sin R = V_I / V_R \qquad \text{.................} (2.3)$$

Where: I = incident angle

R = refracted angle

V_I = velocity incident

V_R = velocity refracted

2.3.4. Regular and diffuse reflection and refraction

Light falling on a surface may exhibit direct or diffuse reflection. Direct reflection is specular, as in a mirror. Diffuse reflection may be uniform or preferential. In the former the luminance is the same in all available directions, in the latter there are maxima in certain directions (Fig. 2.7).

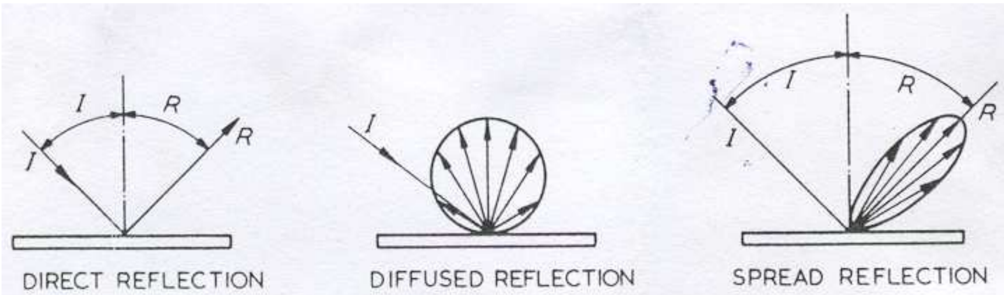


FIG. 2.7. Forms of reflections.

Direct and diffuse reflection may occur as mixed or spread reflection.

Reflecting Surfaces are:

Direct	mirror glass, chrome plate
Uniform	chromium plate
Diffuse	blotting paper
Preferential diffuse	anodized aluminium, metallic paint

2.3.5. Transmission

Light falling on a translucent surface undergoes partial transmission.

The transmission may be direct as through clear plate glass, diffuse as through flashed opal glass, or preferential as through frosted glass (refer to Fig. 2.8).

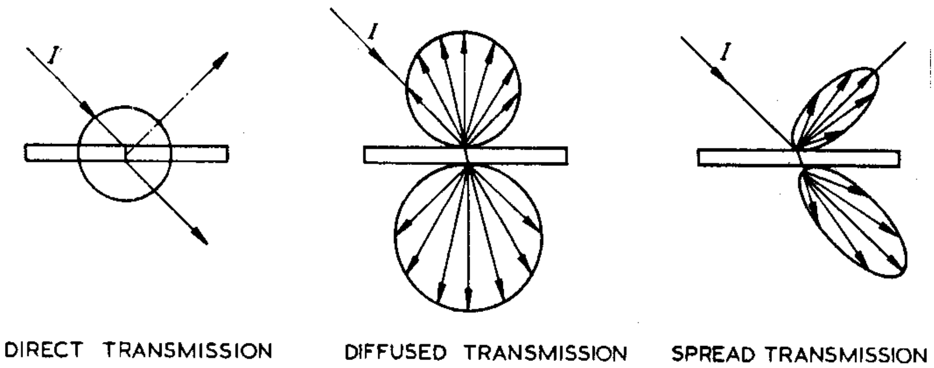


FIG. 2.8. Forms of transmission.

2.3.6. Dispersion

The splitting up of a ray of white light by refraction into its components is known as dispersion. Dispersion occurs because the deviation of each wavelength is different on account of the different velocities at which they travel through the refractive medium. If a ray of white light strikes one face of a prism and passes out of another face, the white light is split into its components and the full visible spectrum will be formed as shown in Fig. 2.4. Dispersive power of a prism (or other medium) for white light is defined by the given relation:

$$\text{Dispersive Power} = (n_b - n_r) / (n_y - 1)$$

where n_b, n_r, and n_y are the refractive indexes for blue, red and yellow light respectively.

2.3.7. Diffraction

Diffraction phenomenon is the spreading of waves after they pass through small openings (or around small obstacles). The diffraction is appreciable when the width of the opening is comparable to the wavelength of the waves and very small when the width is large compared to the wavelengths. Light has a very short wavelength such as 6×10^{-7} m and so light waves are diffracted appreciably only through small openings. Diffraction phenomena are part of our common experience. The luminous border that surrounds the profile of mountain just before sun rises behind it and the coloured pattern (in the form a cross) that one sees while viewing a distant source of light through a piece of cloth are all examples of diffraction effects.

Diffraction phenomena are divided in to two groups, namely: Fresnel diffraction and Fraunhofer diffraction phenomena.

In the Fresnel class of diffraction the source or the screen or both are at finite distances from the aperture or obstacle causing diffraction. In this case, the effect at a specific point on the screen due to the exposed incident wave front is considered and lenses and mirrors make no modification. In this case, the phenomenon observed on the screen is called the Fresnel diffraction pattern.

In the Fraunhofer class of diffraction phenomena, the source and the screen on which the pattern is observed are at infinite distances from the aperture or the obstacle causing diffraction. The Fraunhofer diffraction pattern is easily observed in practice. The incoming light is rendered parallel with a lens and the diffracted patterns do not require any lenses.

Fresnel class of diffraction pattern for a circular aperture AB of the size in actual of a pin hole for a point source S of monochromatic light on the screen XY will be concentric bright and dark rings Fig. 2.9 (i & ii) at the centre P bright or dark depending on the distance b (distance of P from the aperture O). The width of the rings continuously decreases.

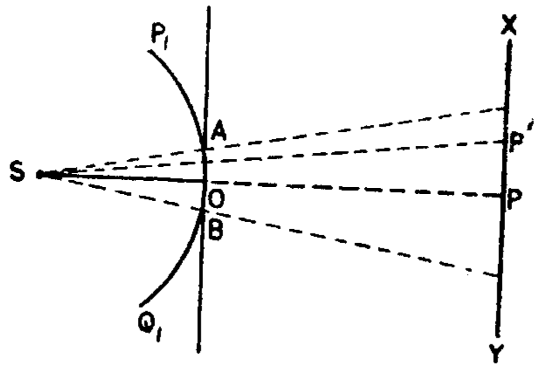


FIG. 2.9 (i). Fresnel class of diffraction for circular aperture.

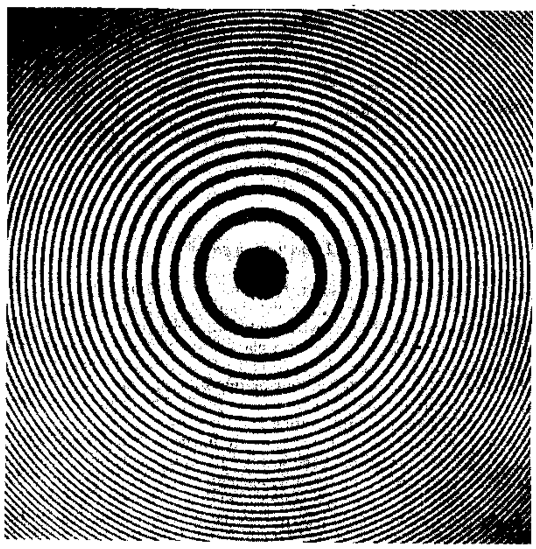


FIG. 2.9 (ii). Diffraction pattern of circular aperture.

In case of Fraunhofer diffraction at a single slit opening, the diffracted pattern on the screen consists of a central bright maximum at P followed by secondary maxima and minima on both the sides as shown in Fig. 2.10. The principal maxima diffraction images become sharper as the number of slits is increased.

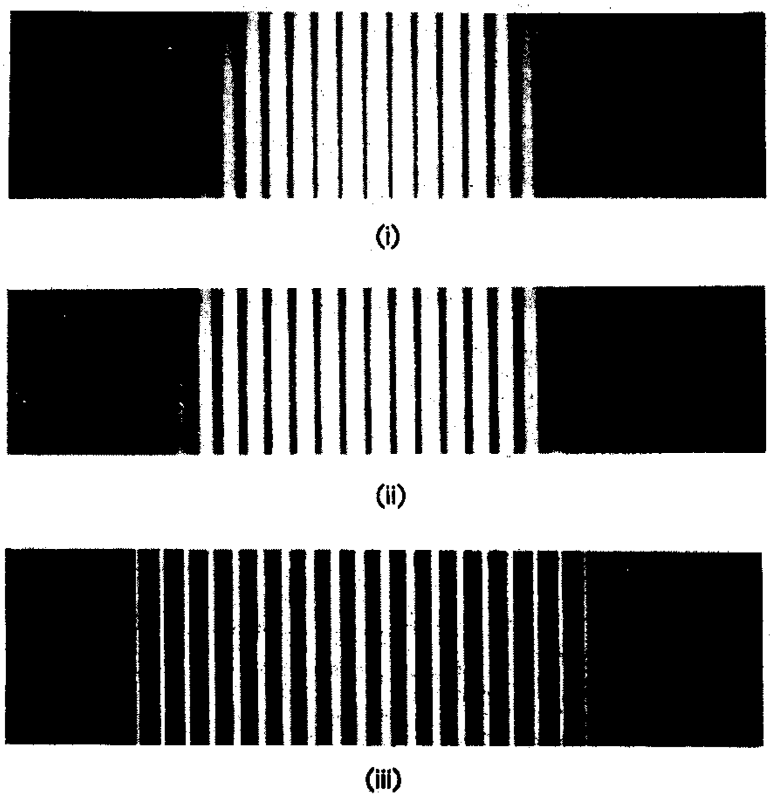


FIG. 2.10. *Diffraction by gratings (i) 3 slits; (ii) 5 slits & (iii) 20 slits.*

2.3.8. Absorption and transmission of light

When passing through a medium a beam of light may lose intensity because of two effects: scattering of light out of the beam, and absorption of photons by atoms or molecules in the medium. When a photon is absorbed there is a transition to the excited state.

The illuminance of a surface illuminated by light falling on it perpendicularly from a point source is inversely proportional to the square of the distance between the surface and source. If the rays make an angle with the normal to the surface, the illuminance varies as the cosine of the angle of incidence.

The luminous intensity (I) of light (or other electromagnetic radiation) decreases exponentially with the distance d when it enters an absorbing medium i.e.

$$I = I_o e^{-\alpha d} \qquad (2.4)$$

Where I_o = Intensity of the radiation that enters the medium (i.e. Incident intensity)

α = Linear absorption coefficient of the medium

These laws for light were first stated by Johann H. Lambert (1728 – 77).

Materials, with respect to light, are transparent, translucent or opaque. The transparent material permits the transmission of light without significant deviation or absorption. However, a substance may be transparent to radiation of one wavelength but not to radiation of another. Some forms of glass are transparent to light but not to ultraviolet radiation, while other forms of glass may be transparent to all visible radiations except red light.

Translucent materials permit the passage of radiations but not without some scattering or diffusion. Frosted glass allows light to pass through it but an object cannot be seen clearly because the light rays are scattered by it.

The extent to which a medium is opaque to electromagnetic radiations, especially to light, is the opacity of the medium and this is the reciprocal of the transmittance. A medium which is opaque to X-rays and gamma rays is said to be radio-opaque.

2.4. Emissivity and reflectance

2.4.1. Emissivity

It is well known that hot bodies emit radiations in the form of heat. These thermal radiations consist of electromagnetic waves with longer wavelengths than visible light and X-rays. The emitted energy in the form of thermal radiations is distributed over a continuous wave, and this spectral distribution changes with temperature. At low temperature, the radiation emission rate is small and is chiefly of relatively longer wavelengths (infrared radiations). At temperatures between 500 and 550°C, bodies begin to radiate visible light, which means that the distribution of energy among the various wavelengths has shifted so that large portion of the radiant energy has wavelengths within visible spectrum. At still higher temperatures, the fraction of visible light increases until at 3000°C, when the body appears white hot and the emitted radiations contain the shorter wavelengths.

In 1879 Stephen suggested an empirical formula which was based on the measurements made by Tyndall on the radiations from hot platinum wire. The relation is given by the equation 2.5:

$$W = e\sigma T^4 \qquad (2.5)$$

Where:

W = rate of emission of radiant energy per unit area, expressed in ergs/cm^2.

T = absolute temperature in Kelvin (K°)

σ = Stephen-Boltzman constant having values of 5.67 X10^{-8} Joules/Sec.m^{-2} K^{-4}

e = emissivity of the surface and has a value between zero and unity.

W is called the total emissive power, or total emittance. The value of e i.e. the emissivity for a black body is unity, and the total emissive power of a black body depends only on the temperature and not on the nature of the body. The emissivity is defined as the ratio of the power per unit area radiated by a surface to that radiated by a black body at the same temperature. A black body is the one which absorbs all of the energy incident on it. A black body does not exist in nature, but some substances such as lamp black, flat black lacquer, rough steel plate, or asbestos board reflect only a few % of the incident radiations and approximate a black body. Fig. 2.11 represents the distribution of energy in the spectrum of a black body at different temperature.

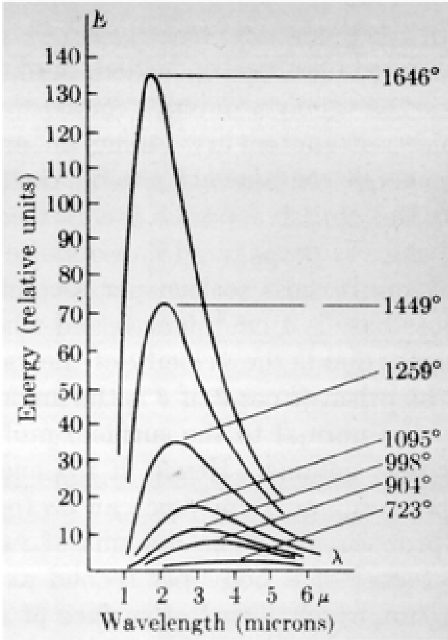


FIG. 2.11. Distribution of energy in the spectrum of a black body at different temperatures.

2.4.2. Reflectance

Reflectance is defined as ratio of radiant flux reflected by the surface to that falling on it. This quantity is also known as radiant reflectance. The radiant reflectance measured for a specified wavelength of the incident radiant flux is called the spectral reflectance.

3. VISION

3.1. The eye

Various components of the human eye are illustrated in Fig 3.1. The eye operates in a similar way to a camera.

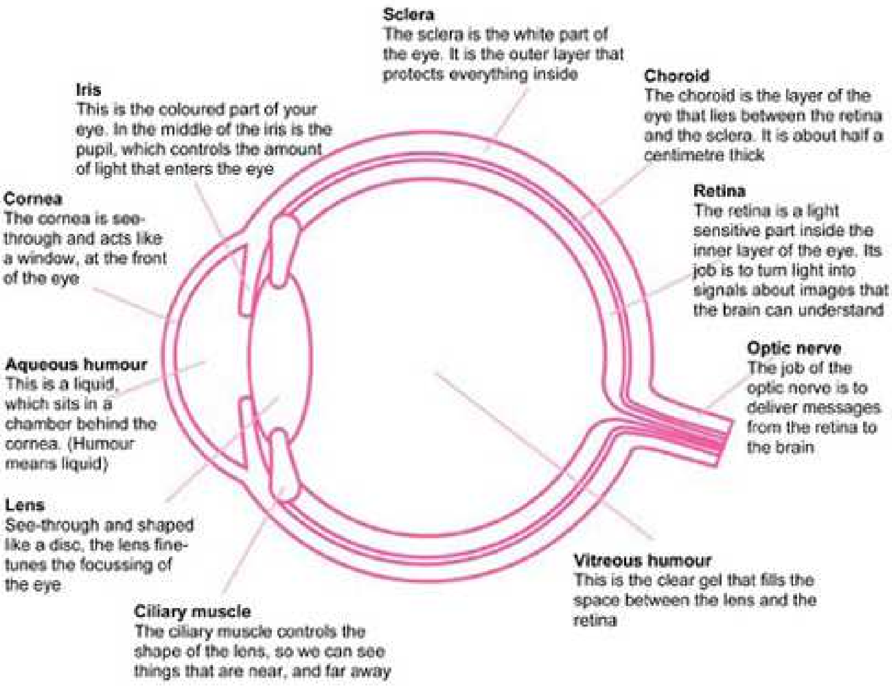


FIG. 3.1. Components of the human eye in cross section.

3.1.1. Formation of an image in the eye

Light passes through the transparent cornea and enters the inner part of the eye through the pupil. The size of the pupil and thus the amount of light entering the eye is controlled by the iris. The lens focuses light rays from an object onto the retina, at the rear of the eyeball. The retina is a complex part of the eye, and only the very back of it (an area of approximately 380 mm^2) is light sensitive. It is packed with photosensitive cells called rods and cones and, by converting light to electrical signals, these allow us to see images in colour and detail, and to see at night.

Rods are not colour sensitive but detect the intensity of the light and can respond at very low levels, whereas cones are sensitive to different colours, responding according to the colour's specific wavelength, but need a much higher intensity of light to respond. These signals are passed along the optic nerve to the brain which then processes the information and forms the picture we see. The brain requires process data to enable the picture to be formed and identified, which is gained by training and experience.

3.1.2. Perception of intensity and colour

There are four different sensations felt as a result of stimulation of the retina with light. These are: light sense, form sense, sense of contrast and colour sense. The light sense is the faculty which permits us to perceive light, not only as such, but in all its gradations of intensity. If the light which is falling upon the retina is gradually reduced in intensity there comes a point when it is no longer perceived: this is called the 'light minimum'. It varies greatly according to the amount of light which has been falling upon the retina before the observation has been made (adaptation). The rods are much more sensitive to low light than the cones, so that in the dusk we see with our rods; in bright illumination the cones come into play.

The quantity of light admitted to the lens is controlled by the contraction of the iris (the eye's aperture, or pupil). At night the opening of the pupil automatically becomes wider to allow more light to enter the eye.

The colour sense is the faculty whereby we are enabled to distinguish between different colours as excited by light of different wavelengths. The retina, where the image for clear vision is focused by the lens, consists of rods and cones over nerve endings that lie be beneath the surface. They are in groups that represent specific colour sensitivities and pattern recognition sections. These areas are further subdivided into areas that collect data from lines, edges, spots, positions and orientations.

The light energy is received and converted to electrical signals that are transmitted by way of the optic nerve system to the brain, where the data is processed. Each wavelength of the constituent colours of the light reaching the retina is focussed at different depths within the retina, stimulating specific groups of rods and cones.Fig. 3.2 represents the spectral response of human eye, with the colours at each end of the spectrum (red, blue and violet) appearing much dimmer than those in the centre (orange, yellow and green).

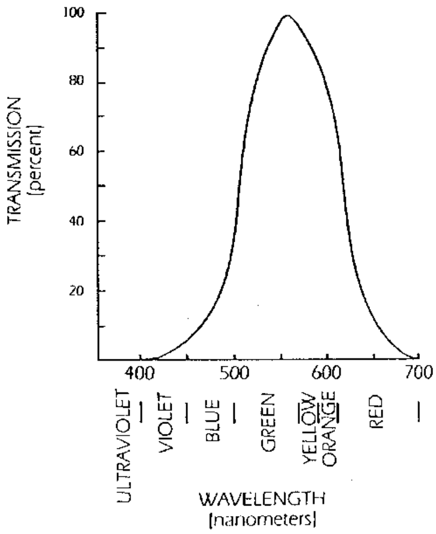


FIG. 3.2. Human eye response at 1070 lx.

3.1.3. Separation ability (resolution)

The normal human eye has the ability to resolve or separate the images formed of two objects lying side by side. For objects to be situated at the least distance of distinct vision from the eye (25 cm), the linear separation between two nearby object points should be of the order of 0.1 mm. If the object points are separated by a distance larger than 0.1 mm, they are clearly visible and are well resolved.

Similarly two point objects appear just resolved if the angle subtended by them at the eye is 1 minute of an arc. If the diameter of the pupil of the eye is smaller than the normal 2 mm, the numerical aperture decreases and hence the value of h increases i.e. two points will appear to be just resolved if the distance between the two is larger.

In Fig. 3.3, MN is the eye lens, A and B are two object points separated by a distance h and $A^{/}$ and $B^{/}$ are the corresponding image points separated by a distance $h^{/}$ on the retina. If the object is placed in air, μ =1 and the image medium is vitreous humour whose refractive index is 1.33 and under the conditions when the object is placed at the least distance of vision, u = 25 cm for a normal eye and for a eye with eye ball diameter of about 25mm from the geometry of the image formation, it can be calculated that the two point object of size h to be resolved , h should be equal to 0.1 mm .This implies that the two objects are clearly visible when placed at the near distance of vision if their size is equal or greater than 0.1 mm.

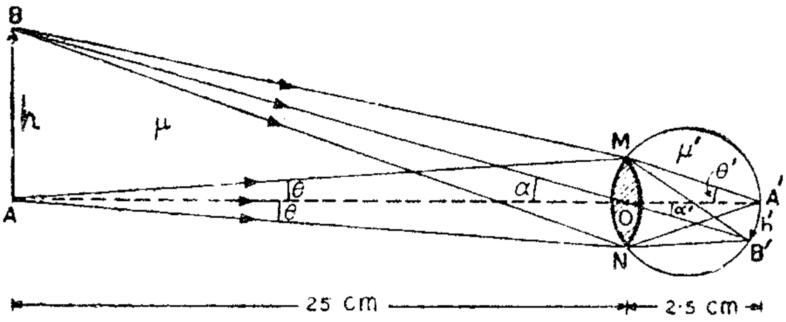


FIG. 3.3. Limits of resolution of the eye.

3.1.4. Perception

Perception is the difference between physical reality and the view that we think we see. It is how an observer's brain interprets the data it is being given. The Müller-Lyer illusion demonstrates one of the problems (Fig 3.4).

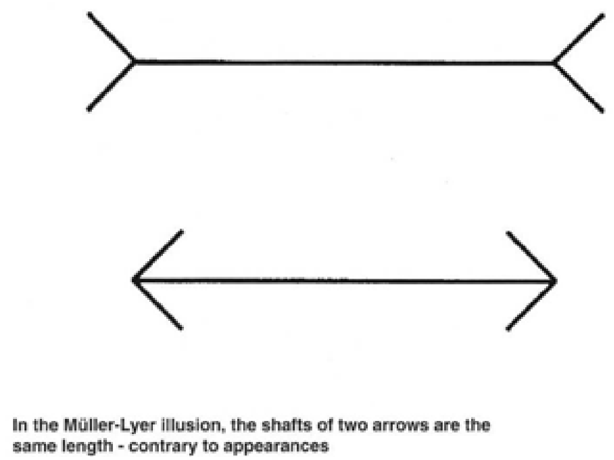


FIG. 3.4. Müller-Lyer illusion.

Different individuals perceive the same view in different ways and it is important to know why and how these differences occur. The difference between observers depends upon pre-programming of the brain by training and experience and the mental and physical state at the time of observation.

3.1.5. Vision acuity

Vision acuity is the term used to express the spatial resolving power of the eye. It involves near vision and far vision to cover and identify what is seen and will be dependent on physical, medical and physiological conditions and differs from person to person, as depicted in Fig 3.5.

FIG. 3.5. Focussing on near (left) and far objects.

The limitation of unaided normal vision with average viewing conditions is a disc approximately 0.25 mm diameter and a line 0.025 mm wide at a distance of about 150 mm, the nearest the eye can focus.

All the rays of light must focus on the retina for perfect vision. Some people have eye defects in which the rays of light cannot focus on the retina creating an out of focus image.

Near sightedness is when the eye lens focuses the light rays in front of the retina. Far sightedness is when the lens of the eye focuses light rays beyond the retina. Both of these conditions can be corrected by placing a suitable eye glass lens 17-21 mm from the retina.

The majority of visual tests require near vision acuity within 400 mm. Far vision examination is carried out at 6 m. The charts used for the vision examination should be white with letters printed clearly in black. The lighting conditions should be as specified, e.g. the room lighting should be 800 lx and the background luminance of the chart should be 85 ± 5 cd.m^{-2}.

3.1.6. Near vision acuity tests

ISO 9712 [2] and EN 473 [3] stipulate the minimum acceptable near vision acuity for NDT operators as follows:

- The candidate [and certificate holder] shall provide documentary evidence of satisfactory vision in accordance with the following requirements:near vision acuity shall permit reading a minimum of Jaeger number 1 or Times Roman N 4.5 or equivalent letters (having a height of 1.6 mm) at not less than 30 cm with one or both eyes, either corrected or uncorrected, the documented tests of visual acuity shall be carried out at least annually,Vision can also be checked with certain machines. These produce patterns of all shapes and sizes and are used to perform a quick check or screen the eyesight. If someone fails an eye test using this type of machine, their vision is then checked more accurately using one of the standard reading charts.

3.1.7. Far vision

As for near vision examination standard test charts or machines can be used. If using a chart, the test is carried out at 6 m with the charts containing varying sizes of letters. There are no far vision requirements in either ISO 9712 [2] or EN 473 [3] for NDT candidates or operators.

3.1.8. Colour vision

There are applications where colour vision is a major factor in the correct assessment of an object. A person's ability to correctly identify all the colours is therefore important. If there are colour deficiencies (colour blindness), then important details can be missed or misinterpreted.

Colour deficiencies and true colour blindness can be either inherited or acquired from specific medical problems. Ten per cent of the male population have some sort of colour deficiency. The most common hereditary defect is an inability to distinguish clearly between red and green, and occurs in approximately 2% of males but very rarely in females. Acquired colour deficiencies can be due to many illnesses and varies in severity depending on cause. Ageing can also affect colour vision.

Colour vision testing can be carried out with:

a) an anomaloscope, which allows mixing of colours.

b) charts with different coloured spots. A commonly used test is one devised by S Ishihara, which is a set of charts using coloured dot patterns.

c) caps with 15 changes in colour hue to check for red blindness and green blindness.

ISO 9712 [2] and EN 473 [3] stipulate the minimum acceptable colour vision perception for NDT operators as follows:

> The candidate [and certificate holder] shall provide documentary evidence of satisfactory colour vision in accordance with the following requirements:
>
> colour vision shall be sufficient that the candidate can distinguish and differentiate contrast between the colours or shades of grey used in the NDT method concerned as specified by the employer.

3.2. Reaction of the eye to excitation

The eye is a complex receptor organ, the mechanism of which is only partly understood. When the eye views a scene it views it in two stages:

a) Entire field vision called pre-attentive processing.

b) Localised focus on a specific object in the field.

Both of the above are processed by the brain to produce the pictures we see.

It is thought that the eye and brain simplify the various light patterns into spots, lines, shadows, edges, colours, orientation and position within the entire field. This data is then compared with data previously collected and stored in the brain's long-term memory. This enables images to be identified and compared and allows differentiation between pattern changes and colour changes. Different objects can be easily identified but problems arise when attempting to identify objects of similar shapes, characters and colours.

When an unspecified object is being sought, the full field of vision requires careful examination but when a specified object is of a known characteristic, it can be shown that only half the field requires inspection and so is identified more quickly.

Weber’s Law is used by psychophysicists and states that:

a) single points and lines are more important than their relationship to each other.

b) closed forms or objects appear to stand out more than open forms.

These laws mean that the brain picks out certain items in preference to others, e.g. the brain will pay more attention to a closed, solid object than to open shapes. Each item within a field of view is coded and stored in a specific part of the brain and withdrawn when required to produce a complete picture. Sometimes the incorrect item is withdrawn and positioned in the wrong place thus creating an optical illusion and causing the real picture to be misunderstood. This also accounts in part for the differences between what people see and the true picture.

Adaption, reaction to glare

3.2.1. Phototopic vision

Phototopic vision (foveal vision) is when the eye is adapted to bright conditions - after a few minutes of exposure to more than 3.0 cdm^{-2}. As the cones work effectively at higher light intensities, phototopic vision is mediated mainly by the colour sensitive cones and so colour vision is clear.

3.2.2. Scotopic vision

Scotopic vision (parafoveal vision) is when the eye becomes dark adapted to low levels of illumination of below 3.0 x $10^{-5}cdm^{-2}$. This requires a considerable time of 30-45 minutes, depending upon the initial light exposure values. Only the rods are sensitive to low light intensities, therefore differences in intensity can be detected but colour vision is poor or absent.

3.2.3. Distance and relief perception (stereoscopic perception)

When a person views an image or scene, each eye records the view from a slightly different angle producing two views of the same object or scene. This enables the brain to produce three dimensional images of objects and produces a perception of depth and distance when viewing a scene.

In the normal eye, the depth of the eyeball and the refractive power of the cornea and lens are such that images of objects at 6 metre or more are sharply focused on the retina when the muscles of accommodation are relaxed. To resolve near objects the ciliary muscle bulges, relaxing tension in the lens, which becomes more convex to focus on objects at close distances.

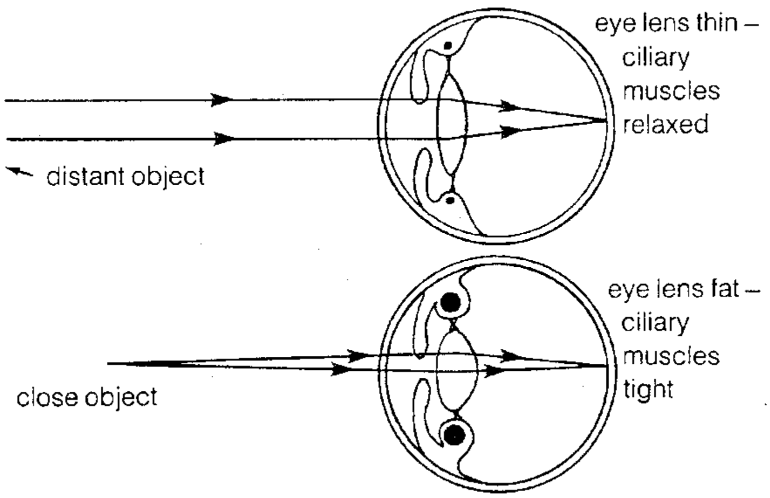


FIG. 3.6. Adaptation for near and distant objects.

Binocular vision is an important aid in accurate judgement of distance. Distance Judgement is the basis for depth perception. Human and other animals able to focus both eyes on a single object are capable of stereoscopic vision. The principle of stereoscopic vision can be described in terms of a vision process involving stereoscopy, which presents an image from two slightly different angles so that the eyes can merge them into single image in three dimensions. Stereoscopic vision partially depends on the fact that each eye gets a slightly different view of the object. The right eye sees a little more of the right hand surface of the object. The left eye on the other hand sees a little less of this surface but more of the left hand surface. When the images on the retina differ in this way, the object is perceived as a three dimensional image.

An important consideration for Visual Testing is the expectation factor, or the pre-programmed condition of what is expected in the inspection, and this is influenced by either a negative or positive pre-emption, i.e. if a person is told to look for defects in an object, defects may be found even if none are present.

3.2.4. Perception of contrast and colour

Details of perception of contrast and colour are already discussed in section 3.1.2

3.2.5. Threshold levels of intensity

The sensitivity of eye for visual testing depends on suitable lighting thresholds. There is an optimum lighting condition at which eye responses well to detection of minute indications such as cracks. Lighting for visual testing has two functions:

a) Illuminating the object.

b) Providing luminance contrast for discontinuity detection.

3.3. Vision defects

3.3.1. Types of blindness

3.3.1.1. Day blindness

A lack of photopic vision is known as day blindness (Hemeralopia)

3.3.1.2. Night blindness

A lack of scotopic vision is known as night blindness (Nyctalopia)

3.3.1.3. Colour blindness

Colour blindness is the deficiency in ability to perceive or distinguish hues. This can be inherited or acquired. The most common colour deficiencies are hereditary and occur in the red – green range.

Most such deficiencies occur in both eyes and in rare instances in only one eye. The acquired colour deficiency may affect only one eye and a change from acceptable colour vision to a recognizable problem may be very gradual. Various medical conditions can cause such a change to occur e.g., in blue – yellow deficiency, glaucoma, pigmentary degeneration of the retina, diabetic retinopathy, methyl alcohol poisoning etc.

3.3.1.4. Symptomatic disturbance

Refer to section 3.3

3.3.1.5. Injuries

Physical or chemical injuries of the eye can be a serious threat to vision if not treated appropriately and in a timely fashion. The most obvious presentation of ocular (eye) injuries is redness and pain of the affected eyes. Some of the common causes are as follows:

3.3.1.6. Thermal injuries

The blink reflex usually causes the eye to close in response to a thermal stimulus. Thus, thermal burns tend to affect the eyelid rather than the cornea. Eyelid burns should be cleansed thoroughly with sterile isotonic saline solution followed by application of an antimicrobial ointment. Most thermal burns affecting the cornea are mild and heal without significant sequellae.

3.3.1.7. Injuries due to ultraviolet radiation

The most common light-induced trauma to the eye is due to ultraviolet light, which can be thought of as sunburn to the cornea. Sources of damaging ultraviolet light are arc welders, tanning booths, and the sun.

3.3.1.8. The effects of health on vision

A person's health affects his sight ability, a variable that may be difficult to detect but which produces inconsistent or incorrect visual assessments.

Diseases, for example diabetes, impair normal vision years after it first appears and may produce a gradual loss of vision due to cataracts, which is a loss of transparency in the lens of the eye.

Glaucoma is the build-up of pressure within the eye starting with slight vision impairment and, when severe, results in total blindness and destruction of the eye. This is genetic and capable of appearing in persons whose parents are afflicted with the disease. Detection is by frequent eye pressure checks, at least once per year, by an optician and, if present, can be controlled with drugs.

Standard eye testing only detects certain physical abnormalities, such as long sightedness or short sightedness, colour blindness etc., but there are many other eye related factors which are not assessed and which may influence visual ability.

3.3.1.9. Lighting

The eye is capable of adaptation to variable lighting conditions. Time is required and it can take up to 30 minutes to achieve full sensitivity with changes from high to low levels of lighting and vice versa. The adaptation time is also influenced by disease, fatigue, chemical emissions and drugs and generally becomes more sluggish with age. These, together with environmental factors of heat, noise, dust and posture, can produce images far removed from the actual physical object being inspected.

3.3.1.10. Eye defects

Non-defective eyes are termed ‘emmetropic’. In emmetropic eyes the refractive power of the cornea and lens is exactly matched to the length of the eye. Light rays are deflected in the eye in such a way that they fall exactly on the retina, producing a sharp image. With the aid of its crystalline lens, the eye can adapt to all distances in much the same way as a zoom camera lens. This process is known as accommodation.

3.3.1.11. Myopia (otherwise termed presbyopia or short sightedness)

The near vision defect called "presbyopia" results in loss of accommodation that normally develops in human eyes over the age of 45–50 years. Vision of distant objects remains unchanged but accommodation of the eye to the near objects is reduced as a result of loss of elasticity in the lens of the eye.

A person with short sight cannot focus distant objects. In this case the lens of the eye forms the image in front of retina. To enable such a person to see distant objects, a concave lens of suitable strength is placed in front of the eye. This lens forms an image of the distant object or scene close enough to be focussed clearly. The image is up right and reduced in size. (Fig. 3.7 (a)).

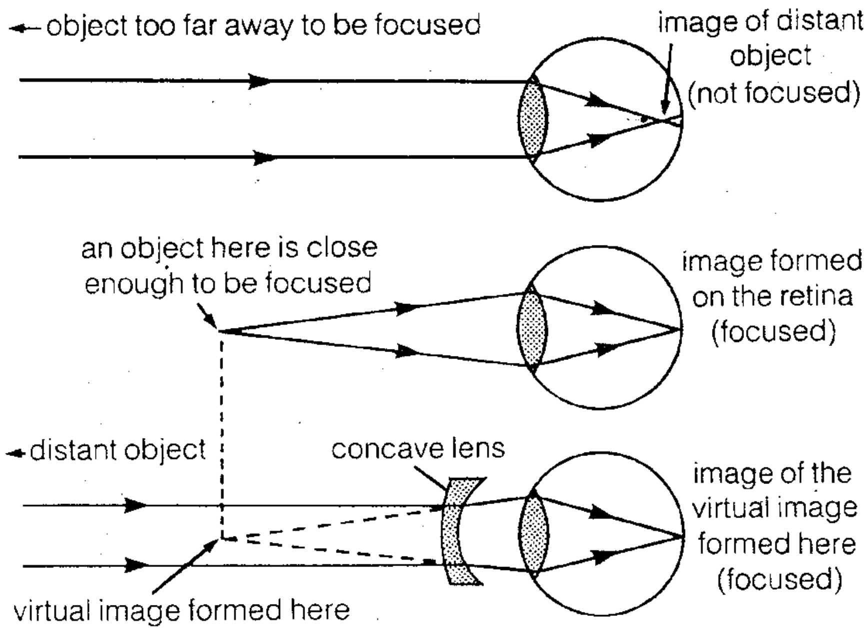


FIG. 3.7 (a). The use of a concave lens to correct for short sightedness.

3.3.1.12. Hyperopic or long sightedness

In case of long sightedness the lens of the eye is too weak and focuses the rays towards an image behind the retina. To enable the person to see close things, a convex lens of suitable strength is used to form an image far enough away for it to be focussed by the eye. The image formed is upright and slightly enlarged. Fig. 3.7 (b) illustrates the use of convex lens to correct for long sightedness.

3.3.1.13. Effects of fatigue and health on perception

Seeing is an active process, where changing images are constantly being processed and interpreted by the brain. Fatigue reduces an observer's efficiency and visual ability. There are many diseases which will impair the sight and general ill health will reduce the brain's processing ability. These problems will all lead to inaccurate interpretation of physical data. For visual inspection to have the highest degree of detectability we require a set of conditions which, whilst desirable, are often not achievable and will generally be a compromise, except under laboratory or test room conditions.

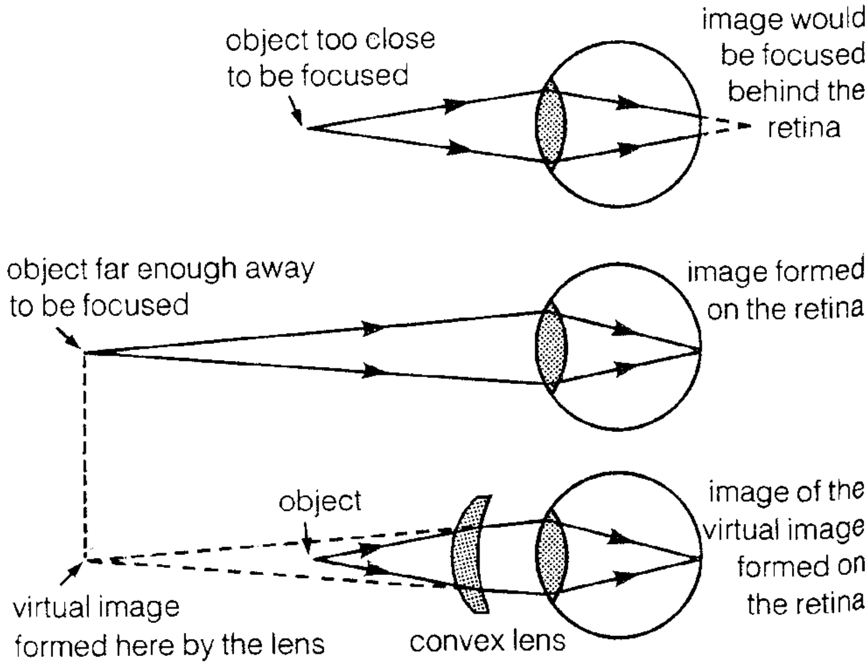


FIG. 3.7 (b). The use of a convex lens to correct for long sightedness.

Probably the major factors which are controllable are training, experience, lighting, environmental conditions and equipment. As outlined above, accurate observation of physical data needs ideal environmental conditions and training/experience to overcome the problems associated with perception.

4. EQUIPMENT AND ACCESSORIES

4.1. Instruments for illumination

4.1.1. Source of visible radiation

An important factor affecting visual tests is lighting, an improper lighting condition existing during a visual examination is that can't be rectified by improving upon the magnification. The amount of light required for visual test is dependent on several factors such as type of test, the importance of speed or accuracy, reflections from backgrounds and inspection variables.

4.1.2. Spectral quality

Daylight is the best light possible, as it produces optimum wavelength distribution for the human eye. Among indoor areas the available light is normally insufficient. Sunlit areas may be satisfactory for general examination, but may not be sufficient for examining internal areas such as bores and deep crevices. Both general lighting devices and specific lighting devices are available and are required for use depending on the situations.

4.1.3. Luminous efficiency of light sources

The luminous efficiency of a light source is defined as the ratio of the total luminous flux (lumens) to the total power input (Watts or equivalent). The maximum luminous efficiency of an ideal white source is about 200 lumen/watt. A white source is defined as a radiator with constant output over the visible spectrum and no radiation in other parts of the spectrum.

FIG. 4.1. General lighting devices.

4.1.4. Classification of light sources

For various reasons it is not always possible to inspect under daylight conditions and the following light sources are most frequently used for visual inspection.

4.1.4.1. Continuous

(a) Flash lamp

This is a tungsten filament bulb, with a battery supply up to 12 V. It is portable robust and easy to use.

(b) Incandescent

These devices are most commonly sold as microscopic lights. Their useful life is not long as they burn out and overheat easily. They do not have sufficient intensity and tend to produce an image of light-bulb filament on the subject being illuminated.

(c) Discharge

These are gas discharge lamps. They emit only certain (selective) wavelengths, so are usually only used where there is no other source available.

Examples include: sodium and mercury vapour lamps.

(d) Fluorescent

This is a gas discharge tube, which can be battery operated or use mains voltages. Their usefulness is limited, but they give a soft uniform light over a large area.

4.1.4.2. Non-continuous - Electronic flash (stroboscopic)

This method is using a synchronised pulse of light to inspect rapid moving machinery. This makes rotary/moving components appear still, so that they can be inspected more accurately.

4.1.4.3. Ancillary equipment for light source

(a) Tripod supports

Tripods are three-legged support used for holding cameras and light sources. The light sources for specific overall general lighting are mounted on fixed stands, stands with expandable base and adjustable head for light source to be moved up and down and the head swivels in all directions. The tripod stands are used for holding cameras both for still and video photography and recording purposes.

Rigid and flexible bore scopes with their inbuilt light guides are also at times mounted on tripod stands for viewing the test surface and photographing purposes.

(b) Transformers

Transformers are an integral part of the equipment supplying the input power to the light source. They can be step down in situations where light source requires 110 volts instead of 220 volts A.C. as is the case for high-pressure mercury bulbs. In case of mercury vapour arc lamp/bulbs, these transformers with current control circuitary known as current regulating or ballast transformers are used.

(c) Filters

The optical filters attenuate the radiation of various wavelengths either uniformly or selectively at different wavelengths. These filters may be made of coloured glass, plastic, gelatin, or sometimes a coloured liquid in a glass cell. They are most often placed over the camera lens but can in some cases be placed over the light source with the same effect. The filters are normally used, are recognized as neutral density and coloured respectively. Coloured filters are used in colour photography to alter the colour quality of the light to match the colour sensitivity of the film. Neutral density filters decreases the intensity of the light without affecting its colour and are used when the light intensity is too great for correct exposure. When incident light $\varnothing_o$ passes through a coloured filter, a fraction $\varnothing_R$ of the energy is reflected at both the glass/air boundaries. Another fraction $\varnothing_A$ is absorbed and the remaining $\varnothing_T$ is passed through it.

$$\varnothing_o = \varnothing_A + \varnothing_R + \varnothing_T \qquad (4.1)$$

Ultraviolet filters (UV) used in front of the light sources are meant to allow the light of the desired wavelength to pass. Black light source equipped with deep red coloured glass filter, hard UV radiations are stopped and those of 365 nm are allowed to have maximum fluorescence during visual inspection of fluorescent penetrant and magnetic particle testing.

(d) Collimator

A collimator is a device for restricting beam divergence to an acceptable level. A common arrangement used for the collimation of light consists of convex achromatic lens flitted to one end of a tube with an adjustable slit being at the principal focus of the lens. Light rays entering the slit leave the lens as an almost parallel beam. The purpose of using achromatic lens combination (known as achromatic lens) is to make the light of different wavelengths to focus at the same point.

4.1.5. Types of illumination

4.1.5.1. Directional

Lighting from a preferred direction or angle.

4.1.5.2. Diffused

In optics, a diffuser is any device that diffuses or spreads out or scatters light in some manner, to give soft light. Optical diffusers use different methods to diffuse light and can include ground glass diffusers, Teflon diffusers, holographic diffusers, opal glass diffusers, and greyed glass diffusers.

4.1.5.3. Secondary

A light source which is not self-luminous but receives light and redirects it as by reflection or transmission.

4.1.6. Sources of non-visible radiations

4.1.6.1. Ultraviolet

The electromagnetic spectrum that covers the wavelengths from 10 nm to 380 nm is called ultraviolet radiation. Human eye response is insensitive to these radiations i.e. they are not visible to human eye. Sun is a natural source of light rich in ultraviolet radiations. An electric arc of carbon, iron or other materials, mercury vapour lamps, discharge of electricity through hydrogen contained in quartz tubes are some of the artificial ultraviolet producing light sources.

4.1.6.2. Mercury vapour arc lamp

Mercury vapour lamp is a source of ultraviolet light. This type of lamp emits light whose spectrum has several intensity peaks within a wide band of wavelengths. Radiation emitted is confined to four visible wavelengths in the visible spectrum and several strong ultraviolet lines. The spectral quality of the emitted light of a mercury lamp is represented in Fig. 4.2.

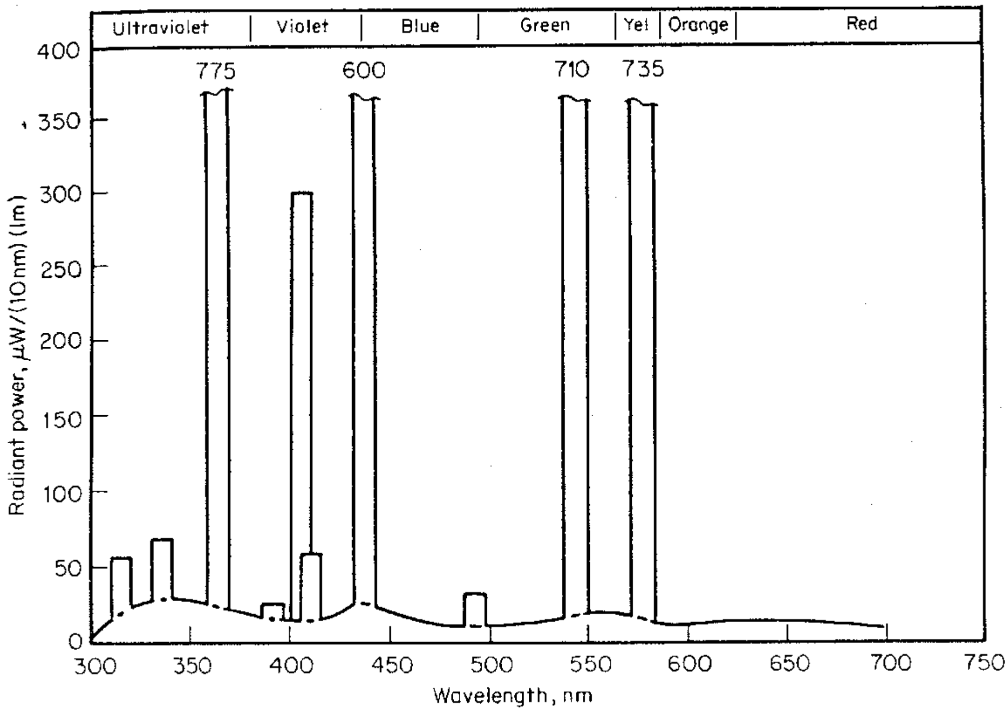


FIG. 4.2. Spectral quality of typical mercury lamp.

When used for a specific purpose such as examination of test part by liquid fluorescent penetrant and magnetic testing methods, the use of glass filter is made to filter out un-wanted radiations of these sources and permit UV peaking around 365 nm.

A clear mercury lamp of 1000 watt input power has a typical initial luminous efficiency of 56 lm/watt. Luminous efficiency is the measure of light–producing efficiency of the source. It is the ratio of the total luminous flux output to the total input power of the source. Mercury vapour lamp of 100 to 1000 watt input power has mean life times in excess of 24000 hours based on 5 hour burning time per start and operation from correct ballast transformer.

4.1.6.3. Carbon arcs

Carbon arcs are of three basic types, the low intensity arc, the flame arc and the high intensity arc. The low intensity arc has its source of light the incandescent tip of the positive carbon that is maintained near the sublimation point of carbon (3700°C). The heat supplied to positive carbon is from high current density electron bombardment originating from the negative carbon.

The flame arc is obtained by enlarging the core of the electrode of a low intensity arc and replacing the removed material with compounds of rare–earth elements such as cerium.

The high intensity arc is obtained by increasing the core size and the current density so that the anode spot spreads over the entire tip of carbon. A crater is formed and this becomes the primary source of light.

The initiation of the arc is made by, bringing in contact the two electrodes and then separating them to a distance of 1.2 mm to 6.25 mm. The carbon rods are connected to DC potential of about 40 to 45 volts and the current of about 12 amperes is adjusted with the help of rheostat.

A brilliant arc passes between the rods and the arc itself provides conducting path between the rods. For DC voltage, crater is formed on +ve electrode and cone on negative electrode. The maximum illumination is for positive electrode (85%). The temperature of +ve and –ve electrodes is about 4000°C and 2500°C respectively. Carbon arcs can be run on AC potentials and in this case both the rods are of same thickness and both become pointed. They work on about 30 volts and efficiency is about 1.12 candles/watt (Fig. 4.3).

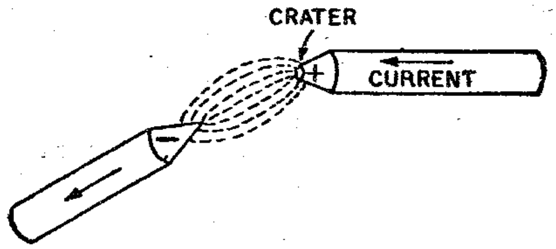


FIG. 4.3. Carbon arc.

4.1.6.4. Infrared

Electromagnetic radiations with wavelengths longer than that of red light but shorter than radio waves i.e. radiations in the wavelength range 700 nm to 10^6 nm are described as infrared. Scientist William Herschel first discovered these radiations in the spectrum of the sun.

Among artificial infrared sources incandescent lamps such as of tungsten filament operated at low temperatures produce in large quantities the infrared radiations. Similarly infrared emitting diode (IRED) is a diode capable of converting electrical energy directly into infrared energy. It is fabricated as PN junction diode from gallium arsenide. Fig. 4.4 represents the spectral distribution of tungsten incandescent lamp compared with black body at the same temperature.

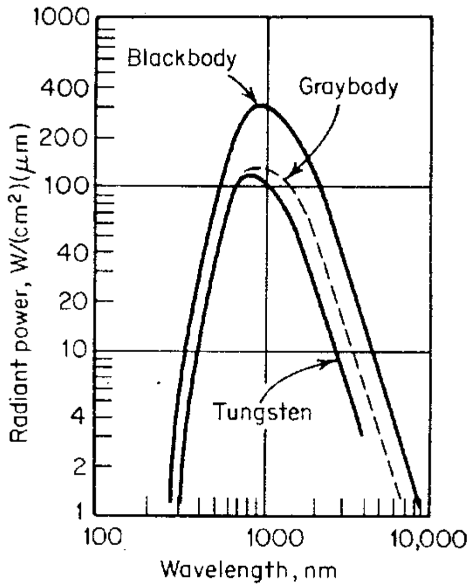


FIG. 4.4. Spectral distribution of tungsten lamp.

4.1.6.5. Filters - ultra violet and infrared

Many light sources provide a range of wavelengths that result is the emission of ultra violet, visible and infrared from a given source. A filter is a device used to restrict the transmission to specific wavelengths, resulting is the emission, for example of infra-red or ultra violet radiation, which is useful for NDT.

The glass filter almost universally used for Black Light is a dense red-purple colour. It functions in two ways.

i) Absorbing of all radiations in the visible range.

ii) Absorbing of all radiation below 300 nm. This helps in removing the harmful short wavelength ultraviolet (UV-A). The filter passes radiations which peak at 365nm, the optimum for energizing the most of the fluorescent dyes used for liquid penetrant testing and magnetic particle testing. Fig. 4.5 represent the transmission curve of the black light filter.

A glass filter is opaque to infrared radiation of wavelength greater than 2000 nm.

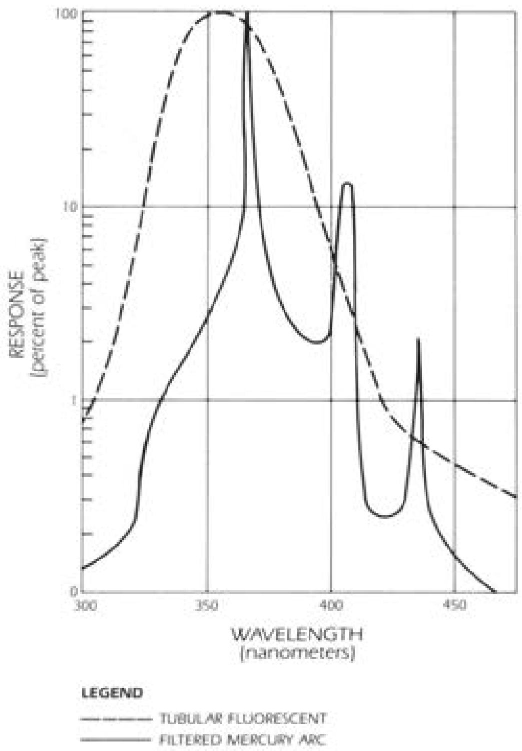


FIG. 4.5. Light transmission curve of black light filter glass (Kopp 41).

4.2. Machine vision technology

Machine vision acquires processes and analyzes an image to reach a conclusion automatically. A machine vision system consists of a light source, a video camera, a video digitizer a computer and an image display. The light source illuminates the test object for the camera to form image. The video digitizer converts the image into digital form and the digital image is then stored in a two dimensional memory. The computer first enhances the contrast of the image with a procedure known as image enhancement. The image is then simplified by the process image segmentation. The next step is feature extraction and finally the computer identifies and groups objects in the image.

4.2.1. Lighting techniques

The result of the machine vision is largely dependent on the quality of the image acquired by the system. Proper lighting techniques are important for high quality images. The following lighting techniques are commonly used in machine vision systems.

4.2.2. Front lighting

The light source and image sensor are on the same side of the component. It is the most convenient mode for machine vision systems.

4.2.3. Back lighting

The light source and image sensor are placed on opposite side of the component.

4.2.4. Structured lighting

It is a combination of light source and optical element to form a line of light. The line of light can be formed in two ways,

(a) By placing a semi cylindrical lens in front of light source.

(b) By using a scanning mirror to deflect a laser beam.

4.2.5. Strobe lighting

Strobe lighting is used to image moving objects or still objects with potential movement. In this technique a pulse of light illuminates the object momentarily.

4.2.6. Ultraviolet lighting

Ultraviolet light causes fluorescent material to glow and is used in liquid penetrant and magnetic particle testing for detecting discontinuities.

4.2.7. Optical filtering

Image sensors used in machine vision systems detect the intensity of the electromagnetic waves in the visible range. If only a portion of visible spectrum is of interest, a filter in front of sensor is used to produce a high quality image.

Band pass filters transmit a band of electromagnetic waves and reject the remaining. Short pass filters transmit the waves below a cut off wavelength. Long pass filter transmit the waves above a cut off wavelength. Neutral density filters attenuate the light level incident on the image sensor.

4.2.8. Image sensors

The two main types of image sensors are image tube and solid state imaging devices.

4.2.9. Image tubes

These are used to generate a train of electrical pulses that represent light intensities present in an optical image focused on the tube.

4.2.10. Solid state imaging devices

The principal is based on the photoelectric effect and the fact that free electrons are generated in a region of silicon illuminated by photons. The number of free electrons is linearly proportional to the incident photons. If the pattern of incident intensity is an optical image of an object, the charge packets generated form an electric image of the object.

4.2.11. Image processing

A digital image is a two dimensional array of pixels that represent the grey levels of an image. Image processing is a method of analyzing these pixels to reach conclusion about the image. It consists of four steps:

i) image enhancement
ii) image segmentation: It is a process that divides an image into overlapping regions called blobs. The most common technique is thresholding. It reduces a grey level image into a binary image.
iii) feature extraction
iv) classification

4.3. Visual aids

4.3.1. Lenses, prisms and mirrors

4.3.2. Characteristics of construction Lenses

A lens is a portion of transparent refracting medium bounded by two spherical surfaces or by one spherical surface and a plane surface. Lenses usually are made of glass or other transparent material. The centres of curvature of all lens surfaces lie on a single straight line called the principal axis of the lens. The converging types of lens in common use include: double convex or bi-convex lens, plano-convex and concavo-convex. These bring parallel beam of light to a real principal focus. The lenses such as double concave or bi-concave, plano-concave and convexo-concave are diverging type of lenses. These lenses diverge the beam of incident parallel rays, after refraction. Fig. 4.6 is an illustration on types of lenses.

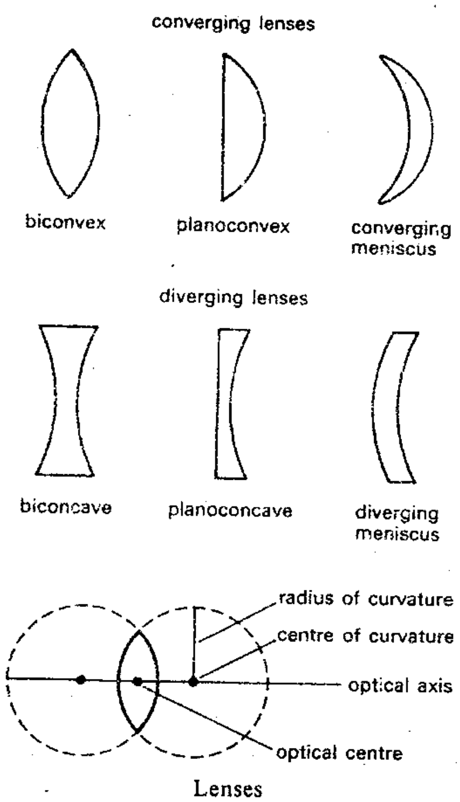


FIG. 4.6. Types of lenses.

4.3.3. Formation of image

4.3.3.1. Convex lens

The position, size and nature of the image formed by a convex lens can be found by knowing the position of the object and focal length of the lens. The construction of a ray diagram as described below will illustrate the image formation for a particular case as shown in Fig. 4.7

The image formed by a convex lens is real, inverted for object to lie beyond lens and its principal focus, whereas the image formed is virtual and erect if object lies between focus and lens.

4.3.3.2. Concave lens

The image formed by a concave lens can be constructed by the ray diagram as shown in Fig. 4.8.

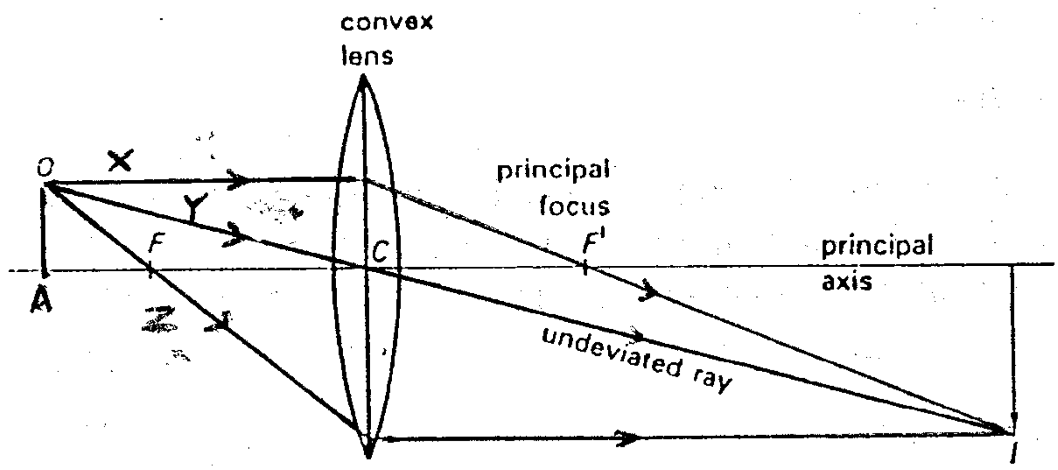


FIG. 4.7. Formation of image by convex lens.

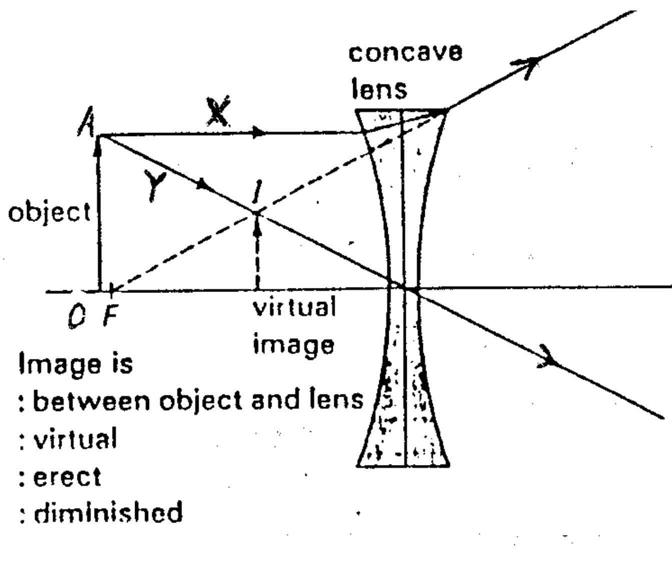


FIG. 4.8. Formation of image by concave lens.

The images formed by the concave lens are always virtual, erect and diminished for any position of the real object. The images formed are on the same side as the object and always lie in between lens and object.

4.3.4. Magnification (linear magnification) of lenses

Magnification is defined as the ratio of the size of an image to the size of the object.

Mathematically, it is given by

M = Size of Image/Size of object

The magnification is positive when the image is real and inverted and is negative when the image is virtual and erect.

4.3.5. Lens aberrations (defects)

4.3.5.1. Chromatic aberrations

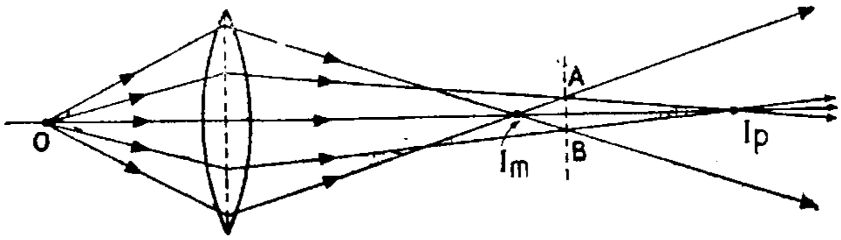
The refractive index of the material of a lens is different for different wavelengths of light. Hence the focal length of a lens is different for different wavelengths. Since the magnification of the image is dependent on the focal length of a lens, the size of the image is different for different wavelengths (colours). Elimination of this defect is called 'achromatism'. For a convex lens, two lenses, one of which a convex and the other concave make an achromatic combination. In magnifiers used for visual inspection chromatic aberration is removed.

4.3.5.2. Spherical aberrations

This arises due to fact that light rays passing through the centre of lens and at the outer edges come to a focus at different points. Using 'Stops' to reduce the effective lens aperture reduces this defect. The image produced thus, is however also less bright. Fig. 4.9 (a & b) represents an illustration of this defect in case of single convex lens and concave respectively.

4.3.6. Prism

A prism is a transparent refracting body that is bounded by three rectangular and two triangular surfaces. The angle between two refracting rectangular surfaces opposite to the base is called the angle of the prism. Prisms have many uses in the optical systems. They can be used to deviate a ray of light to disperse white light into visible spectrum or to erect an inverted image as is in Binoculars and Projectors. In periscope prism is an important optical component used to guide the path of light to see an object over the surface for which the observer is within the sea as in submarines.



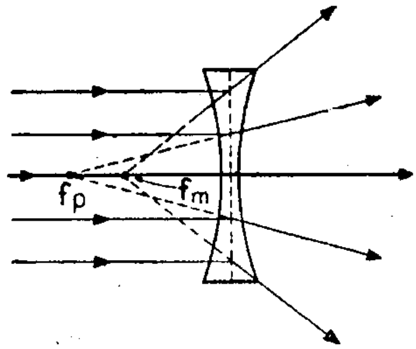


FIG. 4.9 (a & b). Spherical aberration.

4.3.7. Mirrors

A surface that reflects most of the light falling on it is called a mirror. A plane mirror is a flat and shining surface.

4.3.7.1. Image formed by a plane mirror

The formation of the image by a mirror is due to the fact that the rays travelling from an object to our eyes change their direction after reflection so that they appear to come from points other than those from which they really started. We observe the image of an object in the direction in which the light rays enter our eyes. Please refer to Fig. 4.10.

The characteristics of the images formed by the plane mirror are:

(a) The images are found to be laterally inverted i.e. the right side of the object appears as the left side of the image.

(b) The images formed are of the same size as of the object.

(c) The images are found to be virtual i.e. they can't be obtained on the screen.

(d) The image is as far behind the mirror as the object is in front of the mirror

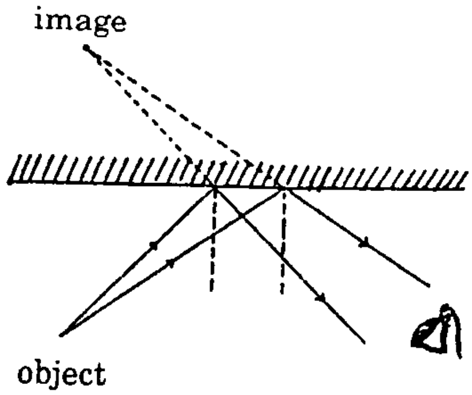


FIG. 4.10. Formation of image by plane mirror.

4.3.7.2. Spherical mirrors

Concave or converging mirror is a spherical surface whose inner surface is polished. On the other hand a spherical surface with outer surface polished is a convex mirror and has the ability to diverge the parallel beam of light incident on it. As images formed in case of spherical mirror are real as well as virtual and diminished and enlarged so to distinguish between the various situations, following are the sign conventions used:

(a) All distances are measured from the pole of the mirror.

(b) Distances of the real objects and images are taken to be positive.

(c) Distances of virtual objects and images are taken as negative.

(d) The focal length of concave mirror is positive and that of convex mirror is negative.

4.3.7.3. Image formation by concave and convex mirror

Normally we consider any two (or more) of the following four rays to locate the image formed by concave and convex mirrors.

4.3.7.4. Concave mirror

The rules of image formation are based on the following facts:

(a) The ray of light parallel to principal axis passes through focus after reflection from concave mirror (Fig. 4.11 (a)).

(b) The ray of light passing through focus becomes parallel to principal axis after reflection from mirror (Fig. 4.11 (b)).

(c) The ray of light through the centre of the curvature of a concave mirror is reflected back along the same path (Fig. 4.11 (c)).

(d) The ray of light incident at the pole of a concave mirror is reflected back making the same angle of reflection with principal axis as the incident ray makes with it (Fig. 4.11 (d)).

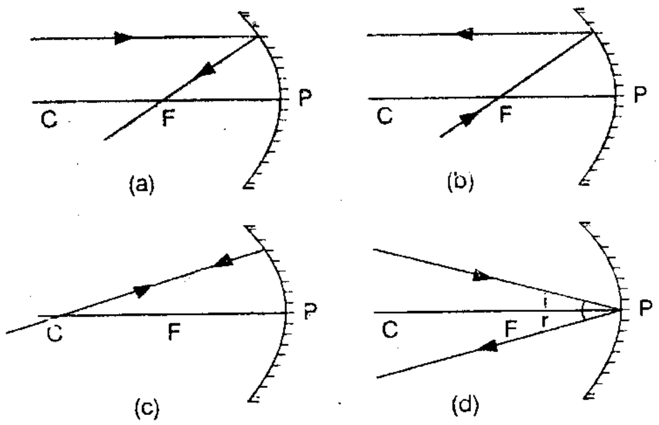


FIG. 4.11 (a to d). Reflection by a concave mirror.

4.3.7.5. Convex mirror

(a) The ray of light parallel to principal axis appears to come from the focus of a convex mirror after reflection from it. (Fig. 4.12 (a)).

(b) The ray of light going towards the focus of a convex mirror becomes parallel to principal axis after reflection from it. (Fig. 4.12 (b)).

(c) The ray of light going towards the centre of curvature of a convex mirror, is reflected back along the same path. (Fig. 4.12 (c)).

(d) The ray of light incident at the pole is reflected in such a way that it makes the same angle with principal axis before and after reflection. (Fig. 4.12 (d)).

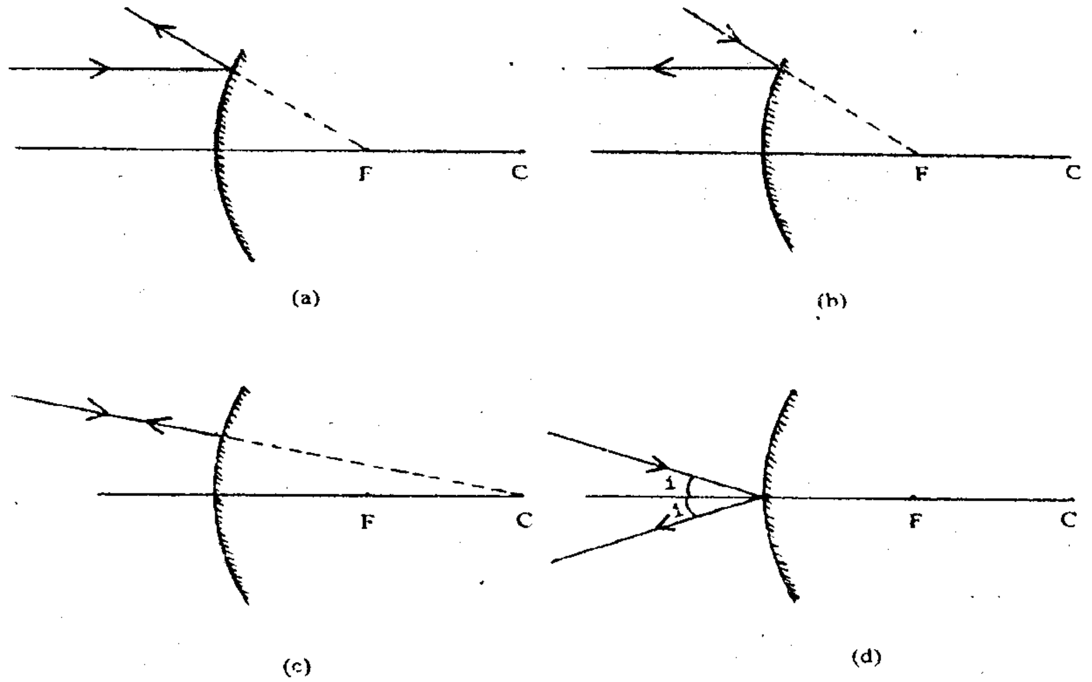


FIG. 4.12 (a to d). Reflection by convex mirror.

4.3.7.6. Mirrors as optical tools

An essential tool for visual examination is a mirror. Mirrors are available in all sizes and shapes, with and without lights. They are available with long extensions, swivel heads, and remotely actuated heads. Fig. 4.13 shows some forms of inspection-mirrors.

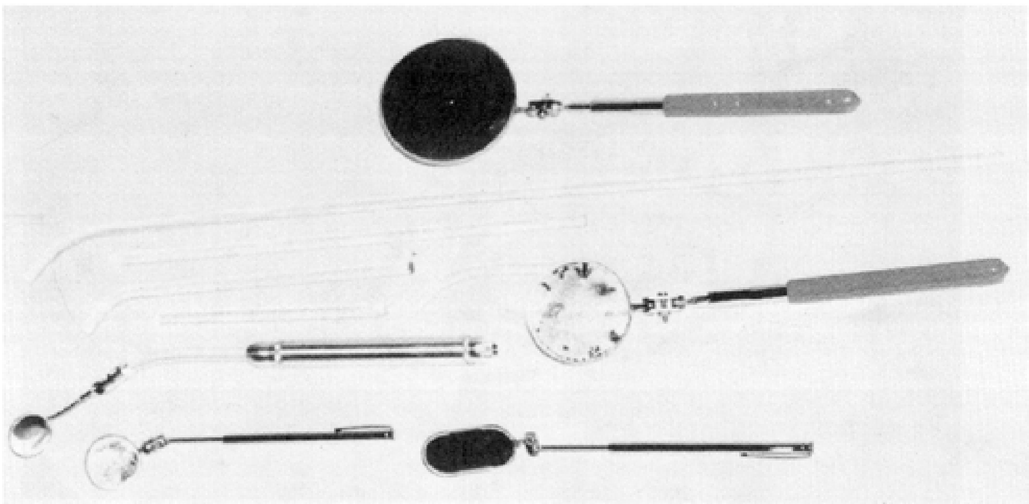


FIG. 4.13. Inspection mirrors.

4.3.8. Optical systems

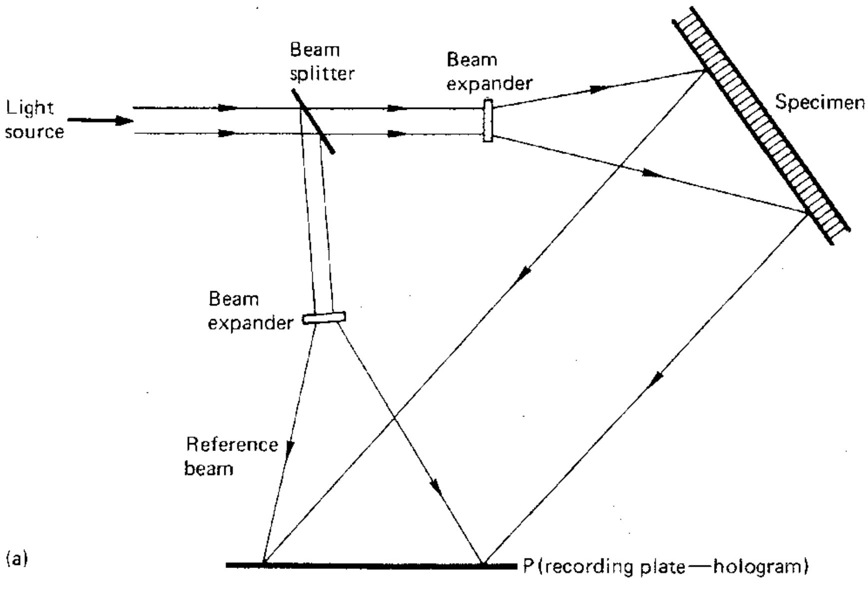
4.3.8.1. Optical holographic methods

Holography is a process of creating a three dimensional image of a diffusely reflecting object having some arbitrary shape. It is a means of recording and subsequently reconstructing wave fronts that have been reflected from or transmitted through an object of interest. The image obtained can be viewed with full depth of field, location and parallax.

4.3.8.2. Principle of holography

The light incident on an object is scattered by its different parts producing light waves having a certain amplitude and relative phase. In normal image recording process such as by a radiographic film, the sensitivity and response of film is only to intensity i.e. to $(\text{amplitude})^2$ but in fact the scattered light waves contain more information of phase angle and intensity. The holographic process extracts and allows use of phase information by producing interference between the waves from the object and a simple reference wave. Fig. 4.14 (a & b) illustrates the experimental set up on optical holography.

The two waves, one having a complex distribution of phase and amplitude due to scatter on the specimen and the other a uniform distribution, interfere to produce a pattern of dark and light fringes, which are recorded on a photographic plate (P) as a hologram. After photographic processing the image can be reconstructed from the hologram by illuminating it, as shown in Fig. 4.14(b). Pattern on the hologram now acts like a complex grating, and an observer looking through the hologram plate sees the original object in place, even though it has been removed. The image is virtual one but is three dimensional, and if the observer moves his head sideways, there is a full effect of perspective and depth. If this image is reconstructed with the object in its original position, the three-dimensional image superimposes exactly on the object. But on the contrary if the object has moved slightly, or has been deformed locally, the observer sees bands of fringes on the surface, the number and spacing depending on the amount of object movement.



(a)

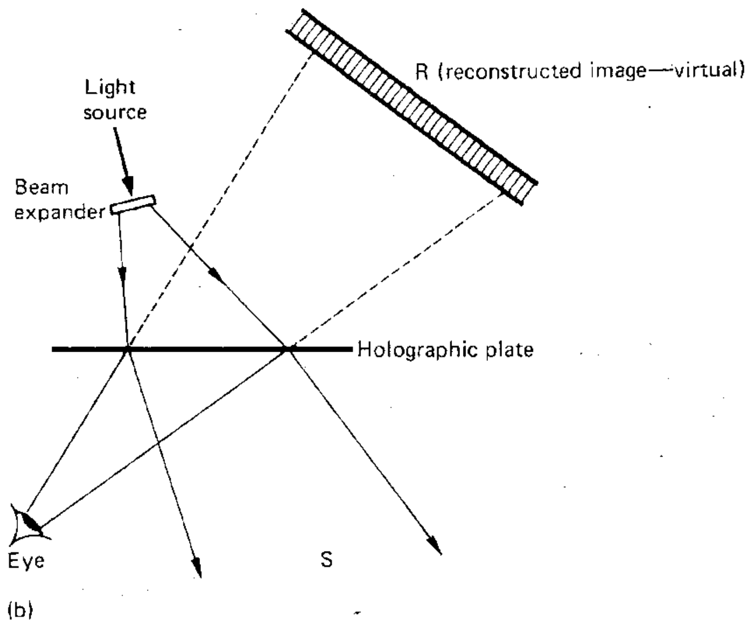


FIG. 4.14(a & b). Optical holography: (a) hologram formation and (b) image reconstruction.

4.3.8.3. Applications of optical holography

Optical holographic interferometry has been successfully used both in research and testing applications as a non-contacting tool for displacement, strain and vibration studies, depth contour mapping, and transient / dynamic phenomena analysis. Specific applications of optical holography in non-destructive evaluation include:

a) Detection of de-bonds within honey-comb core sandwich structures

b) Detection of un-bonded regions within pneumatic tyres and other laminates

c) Detection of bonds and lack of bonding in adhesively - bonded structures

d) Detection of cracks in hydraulic fittings

e) Qualitative evaluation of turbine blades

In general, the specimen is given a slight stress either mechanically or thermally, and non-uniform effects due to defects are shown by fringe anomalies. Holographic NDT is particularly useful on complex shapes where other NDT methods, such as ultrasonic testing, are difficult to apply or time consuming. For defect detection in solid specimens, by deformation a useful rule-of-thumb for holographic testing is that the defect should be at least twice as large in diameter as it is deep, or that a crack should be longer than the material thickness.

4.3.9. Automated visual inspection (AVI)

Rapid advances in the automation of production methods have increased inspection requirements for two main reasons. Firstly, high production speeds require higher inspection speeds. Secondly, the implicit inspection involved in manual production and assembly is no longer present and must be accommodated else- where. The techniques in industrial inspection using automated image analysis are called automated visual inspection. The basic components of a typical AVI system are shown in Fig. 4.15.

The basic principle involves storing an image of the test part in the digital image memory. This image may be considered as two-dimensional array of numbers stored in the computer's memory, where the magnitude of a particular number represents the relative intensity of the corresponding point in the plane of the object. The image computer is used to analyse the image, in order to extract information about the part being inspected, and then to take appropriate actions e.g. reject if faulty.

The prime intentions or motives for carrying out AVI are for the following features of the system:

4.3.9.1. Reliability

An AVI system unlike human inspector is not prone to fatigue or boredom and in a carefully controlled environment can be far more consistent than a human inspector. As in AVI there are no parts in contact with the item being inspected and no gauges to wear, the reliability is enhanced and greater consistency assured. An AVI system however is not immune from making mistakes. It is thus possible for the system to err when it encounters a situation not thought of by the designer, or a component may be presented to the camera upside down, leading to an incorrect operation by the AVI system.

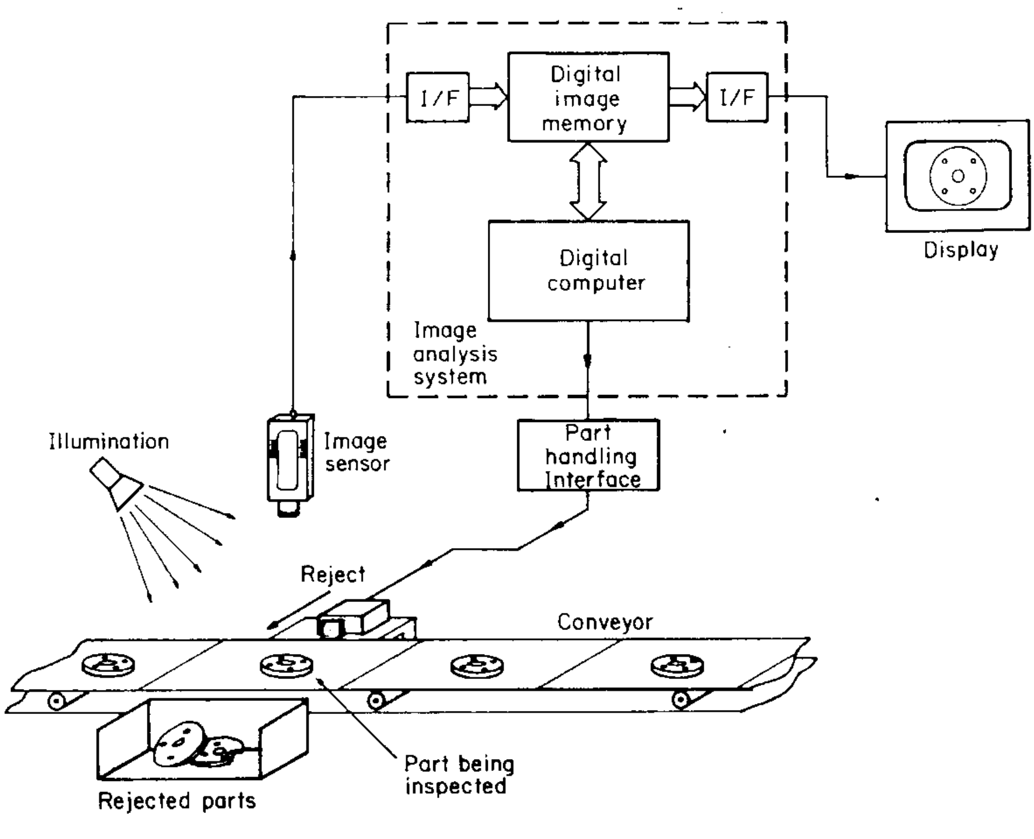


FIG. 4.15. Automated visual inspection system.

4.3.9.2. Versatility

In comparison to other forms of quality assurance (QA) techniques, visual inspection is very versatile. Automated visual inspection has potential to solve many inspection problems that are difficult to solve in any other way e.g., the examination of surface scratches or cracks, or the measurement of non-linear features such as area, perimeter and angles. AVI being a non-contact process has important implication in the inspection of delicate or hygienic products, e.g., food products, toiletries and pharmaceuticals. Similarly it is possible to use in harsh environment where manual inspection is not possible.

4.3.9.3. Speed

In a number of existing AVI applications sufficient speed has been only achieved by using dedicated hardware. For products those are produced at very high rate of production, their inspection is not possible by the existing techniques. Advances in powerful high-speed, low-cost micro-processor, along with the development of special image processing computer architecture, are greatly improving the speed of general-purpose AVI systems.

4.3.9.4. Cost saving

Cost saving can be obtained by eliminating expensive manual inspection, especially repetitive high - volume production. The cost saving benefits is becoming more attractive as the cost of microcomputers, memory and solid state imaging devices falls.

4.3.10. Magnifier

Optical aids to vision such as mirrors, lenses, microscopes, borescopes, fiber optics and magnifiers, compensate for some of the limits of the human eye by enlarging small discontinuities. The optical device recognized as magnifier helps in enhancing the size of surface discontinuities and other anomalies through the process of magnification. In regard to selection and use of simple magnifiers, the following features and facts should be kept in mind.

4.3.10.1. Magnification and depth of field

The letter X is normally used to designate the magnifying power of a lens, e.g., 10X. Magnification is defined as the ratio of the apparent size of an object seen through a magnifier (known as the virtual image) to the size of the object as it appears to the unaided eye at 250 mm. The main limiting factor for magnifying device is depth of field. As magnification increases the distance between peak and valleys (of an irregular surface that is simultaneously in focus) lessens. At 100X magnification the surface examined must be flat and polished.

At this level of magnification, variation of only 0.025 mm between lens and object can render the image out of sharp focus. A quality magnifier gives the view of the object without any distortion. Fig. 4.16 shows lens evaluation charts.

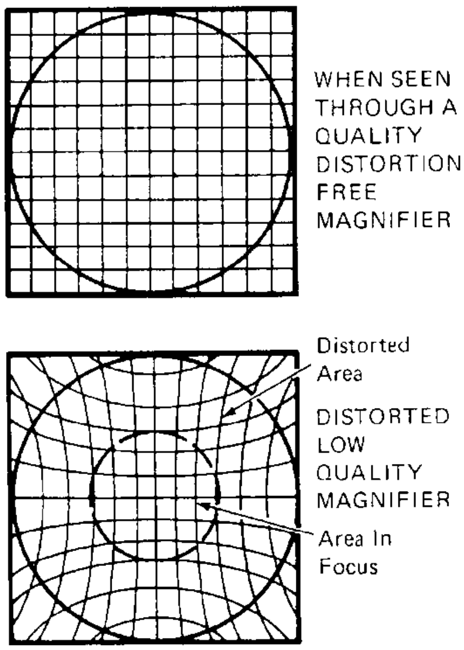


FIG. 4.16. Lens evaluation chart.

4.3.10.2. Focal length

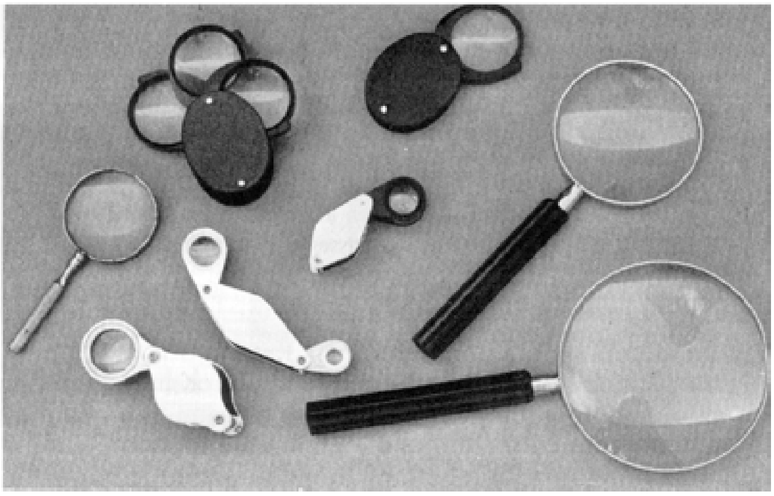
Magnification power of a lens =10/focal length (mm)

A lens with 25 mm focal length will have a magnification power of 10X.This is true if the lens is held 25 mm from the object and the eye is placed 25 mm from the lens.

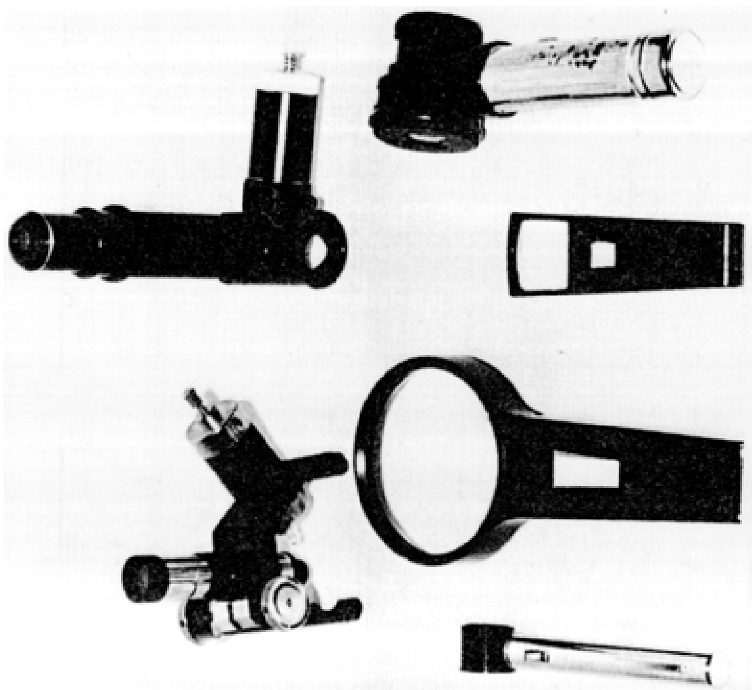
4.3.10.3. Types of magnifiers for visual inspection

These can be categorized into i) Hand –held lenses, single and multiple, ii) Pocket microscopes, iii) Self-supporting magnifiers, iv) Magnifiers that can be worn attached to the head or in some manner be used like eyeglasses or in conjunction with eyeglasses and Magnifying devices with built –in light sources.

In Figs. 4.17 (a & b) are shown some hand held magnifiers an illuminated magnifiers.



(a)



(b)

FIG. 4.17 (a). Hand held magnifiers (b) Illuminated magnifiers.

(a) Microscope

Microscope is a device for forming a magnified image of small object. The simple microscope consists of a bio-convex magnifying glass or an equivalent system of lenses, either hand held or in a simple frame. The object is placed between lens and focal length of the lens, such that an erect, virtual and magnified image is formed. The eye is placed at or nearly the least distance of distinct vision (25 cm or so). The image formed by simple microscope is illustrated in the Fig. 4.18. The size of the image of an object depends upon the angle subtended at the eye by the object. This is called the visual angle, which can be increased by using a convex lens of small focal length.

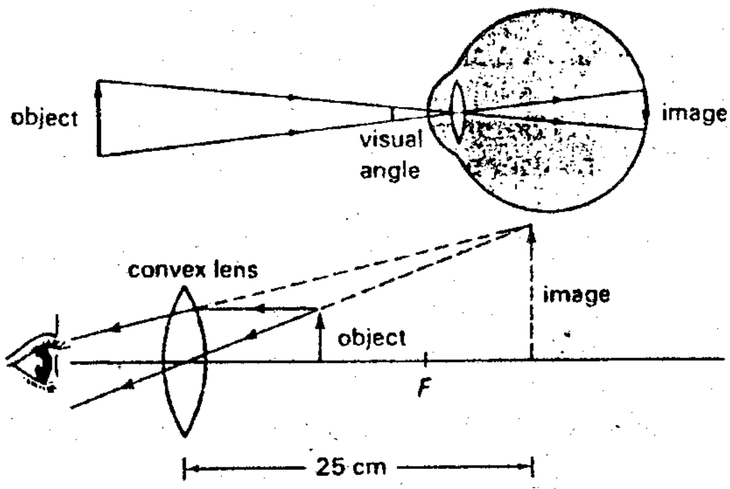


FIG. 4.18. Image formed by simple microscope.

Pocket microscope of about 12 mm in diameter and 150 mm in tube length are available for viewing the surfaces with magnification in the range of 25X to 60X. These microscopes are not with in-built light source and so an auxiliary light is often required during visual inspection.

The limited magnification obtainable in simple microscope because of difficulty in making lenses of very short focal length is overcome in compound microscope in which a combination of lenses is used fixed at the ends of the two tubes. One of the tubes can slide over the other so that the distance between them can be changed for focusing adjustment. The lens near the eye is called eyepiece ‘E’ and the one nearer the object is called Objective ‘O’. The objective has a focal length shorter the eyepiece. The combination of two lenses gives rise to a highly magnified and inverted virtual image.

The stereoscopic microscope is another form of the microscopes most important and widely used of all visual tools. It allows three-dimensional viewing, clearly and sharply, to magnifications as high as 180X. The equipment in actual consists of two separate instruments fastened together so that both eyes look through respective instruments. This gives a stereoscopic vision. There are several variations to be considered with equipment. These are lens combinations, stand and zoom option for varying the magnification. Fig. 4.19 shows a stereoscopic microscope with an extension arm for more flexibility during the used.

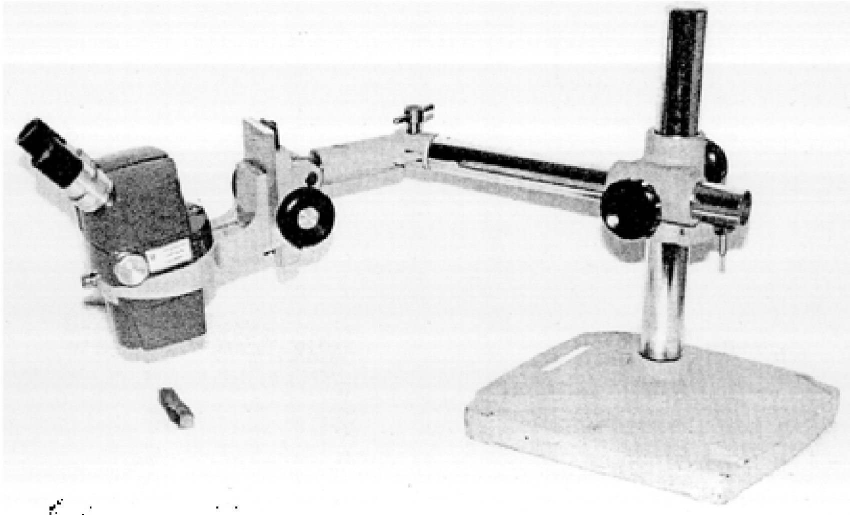


FIG. 4.19. Stereoscopic microscope with extension arm.

(b) Telescopes

Telescope is an instrument that collects radiation from a distant object in order to produce an image of it. An optical telescope uses visible radiations. Various types of telescopes are discussed in brief below:

Astronomical telescope

Optical astronomical telescopes fall into two main classes, refracting telescopes and reflecting telescopes. Refracting telescopes use a converging lens to collect light and the resulting image is magnified by eyepiece, a lens of short focal length. Galileo used a diverging lens as eyepiece but later it was further developed by Kepler who substituted diverging lens with a converging lens that is still in use for small astronomical telescopes.

Terrestrial telescope

The image obtained in an astronomical telescope is inverted and hence is suitable for astronomy, as it makes little difference while viewing stars. For terrestrial telescope an additional lens is inserted in order to provide an upright image. This feature is of value for seeing an object on the surface of the earth where an erect image is a necessity.

Reflecting telescope

The first reflecting telescope was produced by Newton in 1668. The telescope has a concave mirror to collect and focus the light and a small mirror to collect at an angle of 45° degree to the main beam to reflect the light into the magnifying eyepiece. The early telescope used objective of speculum, an alloy of copper and tin. Later objectives of glass silvered on its surface were used. At present objective made from Pyrex coated with aluminium are used. The Fig. 4.20 illustrates the geometrical constructional characteristics of the Newtonian telescope.

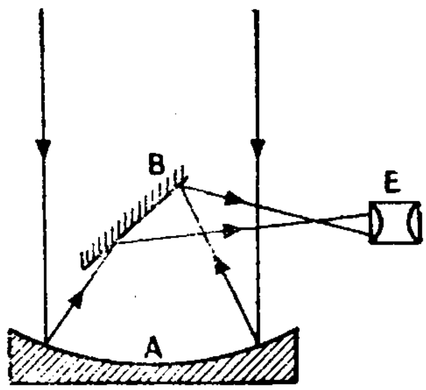


FIG. 4.20. Newtonian telescope.

Reflecting telescopes have the following salient features:

- There is no absorption of light as in thick lenses.
- The mirrors are free from chromatic aberrations.
- Mirrors can be constructed with considerable larger diameters than lenses.
- Mirrors can be easily mounted whereas lenses can be mounted only on the edge or rim.

4.3.11. Optical comparators

Optical comparators are the magnifying devices for visual examination and measurement. A comparator produces two - dimensional enlarged image of an object on a large ground-glass screen. It can be used with reflected light or background lighting (or combination of both). Optical comparators project the silhouette of small parts onto a large projection screen .The magnified silhouette is then compared against an optical comparator chart, which is a magnified outline drawing of the work piece being gauged. Optical comparators with magnifications ranging from 5X to 500X are available. Results can also be photographed. Fig. 4.21 represents an optical comparator.

4.3.11.1. Industrial uses of optical comparator

The main advantage of using optical comparators is the ability to view outline or surfaces at definite known magnifications.

Dimensional testing of test parts such as cutting tools is done well with comparators having built in measuring attachments.

Surface impressions or replicas of faint surface pattern are made for permanent record by using softened or resilient surface into which impressions are made. Such impressions are then viewed with shadow projection or surface illumination. Permanent photographic records can also be made of screen viewing showing surface pattern or conditions.

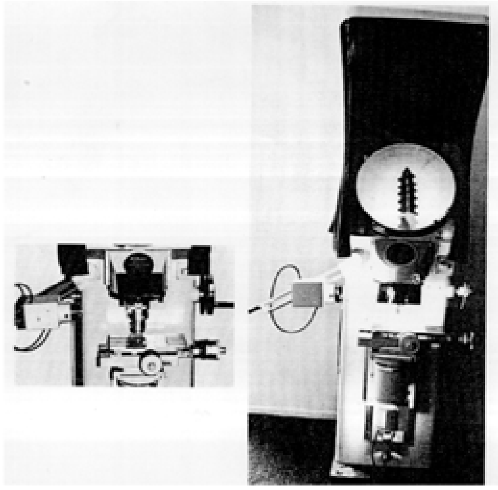


FIG. 4.21. Optical comparator.

4.3.11.2. Micro-alignment telescope

Micro-alignment telescope is a form of telescope as shown in Fig. 4.22, used for a number of applications in industry. Typically custom-made telescope is used for checking and setting for the following applications: alignment (series of bores or bearings), squareness (column to a base), parallelism (series of rollers), level/flatness (machine bed foundation and straightness rails or guide-ways). A typical instrument has the following features:

Micrometer range	+/- 1.2 mm with 0.02 mm graduations
Barrel material	Chromium plated hardened steel precision ground after plating
Barrel diameter	57.137-57.147 mm
Optical axis	Parallel to mechanical axis within 3 arc second and concentric
Field of view	From 50 mm at 2 m to 600 mm at 30 m
Magnification	X34
Focussing range	25 mm to infinity
Image	Erect

4.3.11.3. Typical applications in machine tool industry

(a) Steel rolling mills

Steel rolling mills all have a common problem of setting a series of Rollers, such that they are at the same height and parallel to one another, i.e. in plane. The configuration of this particular customers-machine was suited to the use of the Micro Alignment Telescope with sweep optical square, combined with some special target mounts (Fig. 4.22).

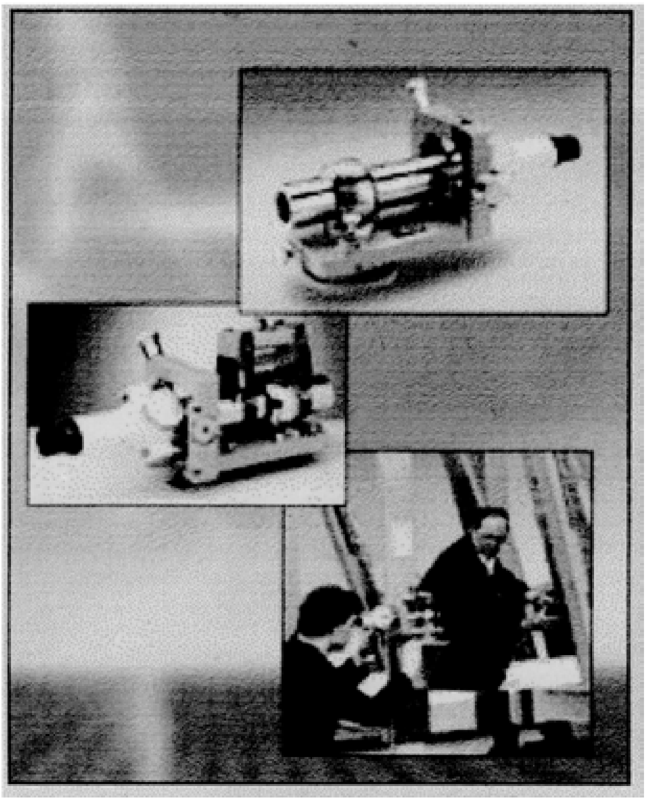


FIG. 4.22. Micro alignment telescope.

(b) Machine tool rebuild and refurbishing

Buying, refurbishing and selling used machine tools is a very profitable business, for those companies with the expertise required to do the work involved. In the past, purchasers of these machines have accepted the equipment without any guarantee of accuracy and accordingly have paid a reduced price. Prospective purchasers are now being pressed to obtain certificate of accuracy of all machines, including refurbished items.

(c) Horizontal forging press

Manufacture of seamless stainless-steel tubes is carried out on high-powered horizontal forging presses. It is important that all the relevant tooling components are accurately set co-axial to one another, in order to achieve a high quality, even thickness of tube. The micro alignment telescope gives a quick, accurate method of alignment, reducing down time and improving quality. The equipment is also used for annual maintenance check- ups and machine refurbishment.

(d) Specialist machine tool alignment

Manufacturers of specialist machine tools have found it necessary to update quality control methods and introduce a formalized machine alignment procedure during machine assembly and test. Measurements of datum bar straightness, motion straightness, squareness of axes, flatness, level and twist checks can be carried out using the micro alignment telescope with a full range of accessories.

(e) Portable machining systems

Manufacturers of portable machining systems are often faced with the problem of aligning the machining centre to the original datum of the component being machined on site. The application of the micro alignment telescope to this alignment problem was proposed to a company involved in the refurbishment of steel mill roller frames.

(f) Aluminium sheet manufacture

Aluminium sheets are not flat when they are produced from the rolling mill. To flatten the sheet, it is stretched between heavy-duty hydraulically-operated grips. After stretching, the plates must be checked for flatness within specified tolerances. The micro alignment telescope with sweep optical square provides a quick and easy solution to this problem with the additional benefit of checking the alignment of the stretching machine itself.

(g) Transfer manufacturing machine

The relocation of a transfer manufacturing machine from one motor vehicle plant to another necessitates the development of a simple but accurate method of alignment during installation. The micro alignment telescope can be used to align the machine through the actual working areas and the use of closed circuit television (CCTV) is recommended due to lack of space in the area of working.

(h) Plotting machine manufacture

Large X, Y plotting machines have similar squareness and straightness problems to machine tools. The accuracy required is of a lower order, but even so it has to be checked. By mounting an alignment target on the moving head of the plotter, the straightness of motion of X-axis can be observed with the micro alignment telescope. The engineer then introduces an optical square into the system and checks and Y-axis for both straightness and squareness.

(i) Printed circuit board drilling machine

Printed circuit board drilling machines must have an accurate X, Y motion for maintaining tolerances of hole positions on the end product. To measure out-of-straightness of the motion on this machine, the micro alignment telescope was offered with suitable accessories.

4.3.12. Gauges and measuring devices

Weld integrity is often verified with visual testing techniques. Visual testing plays its role at all stages viz. before, during and after welding of an assembly. The objective is to confirm the welding procedure and welded structure meeting the applicable standard’s requirements.

Dimensional conformance of finished weldment is usually determined by conventional measuring methods. The conformity of weld size and contour is normally determined by using a weld gauge. In case of a fillet weld, the weld gauge is used to determine whether the weld size is within allowable limits and whether there is an excessive concavity or convexity when necessary, special gauges may be made for use where surfaces are at acute or obtuse angles.

Some of the measuring devices include: Linear measuring devices (ruled straight edge), magnifiers with built-in reticules, micrometers, (inside & outside micrometers), Vernier callipers, gap measuring gauge, radius gauge, depth gauge, inside and outside callipers, centre gauge, thread profile gauge etc.

4.4. Image transmitting instruments

4.4.1. Instruments for optical transmission of images

4.4.1.1. Rigid borescopes

A rigid borescope is used as visual inspection aid and equipment to inspect internal surfaces such as bores of rifles, cannons, in- service defects in a variety of equipment such as turbines, automotive components and process piping etc. Similarly the borescopes are of immense use in aircraft and aerospace industry. Rigid borescopes are generally limited to applications with a straight - line path between the observer and area to be observed. Fig. 4.23 represents a rigid borescope. Rigid borescopes in length in sizes ranging from 0.15 m to 30 m and in diameters from 0.9 mm to 70 mm are available. The magnification is usually 3X to 4X, but powers up to 50X are available.

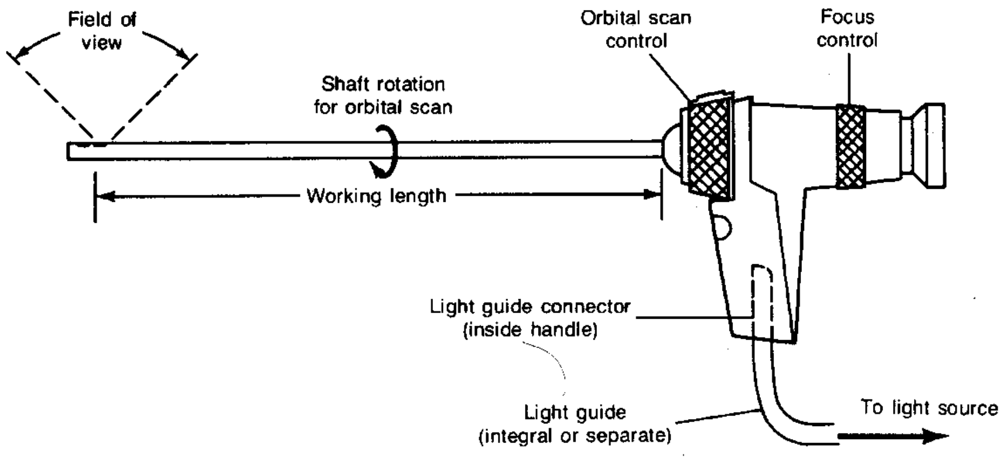


FIG. 4.23. Rigid borescope.

The illumination system is either an incandescent bulb located at the distal end or a light guide bundle made from optic fibres that conduct light from an external lighter source. For the illuminated surface the image is brought to the eyepiece by an optical train consisting of an objective lens, sometimes a prism, relay lenses and an eyepiece lens. A brief description of essential components of rigid borescope is follows:

(a) Light guide

The optical fibre bundle that carries light from an external high intensity source to illuminate the test part is called the light guide bundle. These fibres are normally of about 30 µm in diameter; the size of the bundle is determined by the diameter of the scope.

(b) Image guide

The image is brought to the eyepiece by an optical train consisting of objective lens, sometimes a prism, relay lenses and an eyepieces lens. The image is not a real image but in the air between the lenses. This implies that it is possible to provide both diopter corrections for the observer and to control the objective focus with a single adjustment of the focusing ring at the eyepiece. The transmission of light in single optical fibre is limited and thus thousands of fibres are bundled for transmission of light and images. To prevent light from diffusing, each fibre consists of a central core of light quality optical glass coated with a thin layer of another glass with a different refractive index. This cladding acts as a mirror and all light entering the end of fibre is reflected internally and travels that cannot escape by passing through the sides to an adjacent fibre in the bundle. Some light is absorbed within the optical fibre depending on its length.

(c) Focusing control

The rigid borescopes are of fixed focus type and focusing type. The focus control in rigid borescope expands the depth of field over non-focusing or fixed focus design.

(d) Distal end (objective lens)

The choice of viewing heads vary according to their application, rigid borescopes generally have a 55 degree field of view although field of view can range from 10° to 90°. Typically the distal tips are not changeable, but some models (extendable borescopes) may have interchangeable view heads.

(e) Accessories

Many accessories such as still camera and video camera can be added to provide a permanent record of a visual test. Closed circuit television displays, with or without recording capabilities are common as well. Attachments at the eyepiece permitting dual viewing for increased accessibility are also available.

4.4.1.2. Flexible fibrescopes

Flexible fibrescopes are generally used in situations that do not have a direct line of sight to the observer such as around bends and corners. A typical flexible fibrescope is shown in the Fig. 4.24.The flexible fibrescopes are available in diameters ranging from 1.4 mm to 13 mm and lengths up to12 m. Special quartz fibrescopes are available in lengths up to 30 m.

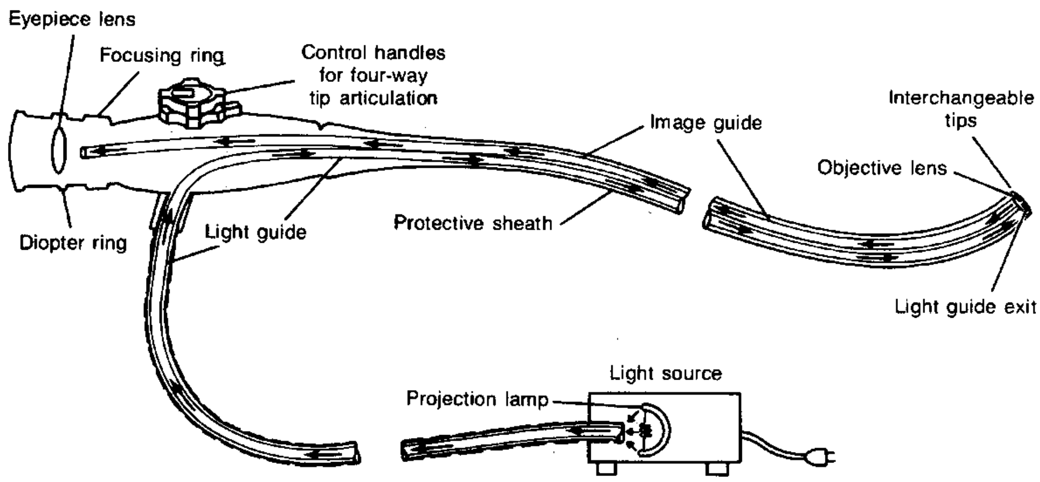


FIG. 4.24. Flexible fibrescope.

The fibres used in the light guide bundle are generally 30 µm in diameter. The fibre diameter in the image guide range from 6.5 µm to 17 µm for better image resolution. For enhancing image resolution further, an objective lens with a wider field of view and also to magnify the image at the eyepiece is used. The features of construction of a flexible fiberscope are discussed below:

(a) Eyepiece lens

The eyepiece is a lens through which observer views the test area and image formed for visual inspection. The observer can attach a photographic or video camera to it using the appropriate adapters.

(b) Diopter adjustment ring

It enables the inspector to adjust eyepiece to his vision by turning the ring till the image is in clear focus.

(c) Focusing ring

For flexible fibrescopes with focusing type, the ring on the eyepiece adjusts the position of the objective lens in the distal tip through a connecting control wire. As the objective lens is moved back and forth, the instrument is focused.

(d) Articulation control

Articulation knob controls two-way or four-way movement up, down, right and left of the distal tip. The distal tip contains the objective lens and the illumination window.

(e) Light guide bundle

The function is similar to that in case of rigid borescope i.e. of transmitting light from the light source to the test area to be illuminated.

(f) Insertion tube

It is also recognized as the working length or probe, contains the image guide and light guide bundles, and control wires. To one end of the light guide is light guide plug that is connected to light source to conduct the light to the test area. These bundles are encased in a special protective sheath consisting of flexible metallic spiral clad with plastic. The insertion tube is designed to be flexible and engineered to give a right balance between flexibility and stiffness.

4.4.1.3. Periscope

Periscope is an instrument used for remote observation of otherwise inaccessible areas. In simple periscope, two right angle prisms are utilised (as totally reflecting prisms) in combination with a series of lenses. Light entering and leaving each prism does not suffer refraction because the angle of incidence is zero. The periscope are of major use for remote visual inspection in hazardous situations such as radiation areas, toxic environment and for overhead viewing of areas involving obstacles like walls and other opaque objects.

4.4.1.4. Combination equipment for transmission of images

(a) Video image borescope components

A video borescope has following four main components

- A probe with a charge-coupled device embedded in the distal tip.
- Video processor to communicate signals to the monitor.
- A monitor, black and white or colour.
- An alphanumeric keyboard for entering identification references into the display or into a permanent record.

These components are discussed below:

- Video probe

Video probes are available in a variety of sizes, lengths and articulation options. Similar to simple borescopes, video scopes test area is illuminated by fibreoptic light guide or by light from light-emitting diodes (LED). The lighting can be used for black and white or colour imaging. The illumination of the test surface is picked first by the fixed focus lens in the tip of the distal end and directs it to the surface of the charge-coupled device CCD.

- Charge coupled device (CCD)

The distal end of electronic video scopes contains a CCD chip, which consists of thousands of light-sensitive elements arranged in a pattern of rows and columns. The objective lens focuses the image of an object on the surface of the CCD chip, where the light is converted into electric signals. This is in proportion to the light falling on it. The signals travel down the length of the probe through a series of amplifiers and filters up to the video processor, of the Video image scope.

- Video processor or camera control unit

The image information of electric signals from pixels is digitized. The image can now be displayed on the monitor, recorded and if desired sent to a computer for enhancement and analysis.

- Advantages of video borescopes

- As the image is viewed through a monitor, the fatigue & discomfort due to eyestrain and the operators' positioning to see through the eyepiece in non-video borescopic are eliminated in video scopes.

- The video borescopes allow multiple views of the same image making evaluation more reliable and facilitating training. The image can be transmitted simultaneously to any number of monitors at the site or to remote stations.

- A video borescope has a large depth of field that is generally controlled by the CCU. This saves time-consuming task of re-focussing as is in the non-video borescopes.

- Magnification and resolution can be higher than non-video borescopes.

(b) Digital cameras

- Basic principle

Digital images are made up of individual dots of colour and each dot is called a pixel; the greater the number of pixels the greater the resolution.

- Digital camera features

Note: The following sections are of necessity brief since technology in this area is so fast moving. Some of the essential features are described below:

- Zoom

Cameras can zoom from a level of 2X to in excess of 24X. A 4X zoom would most likely be enough for the average user. One should understand the difference between "digital" zoom and an "optical" zoom. Digital zooms enlarge your image by adding extra pixels so that it looks like it has zoomed in, but it really just gives you less accurate pixel information. A "digital" zoom is also called a "fake" zoom.

- Image storage - Digital cameras store data on internal or removable storage devices.

- Data transfer - Data transfer is by direct physical or wireless connection.

- Flash

Similar to the normal camera that comes with some kind of built-in flash, digital cameras also are available with options which include: red-eye reduction, fill flash (a gentle flash used to soften Shadows), and Auto flash and "forced" flash. Some of the high-end models have a "hot-shoe" for attaching an external flash.

- Liquid-crystal display (LCD) screen

LCD screens are used to view and frame the pictures.

- Batteries

Digital cameras can use AAA, AA or even lithium batteries. Some cameras provide rechargeable batteries that come with a charger.

- Movies

Many digital cameras record video and sound.

4.5. Optical equipment for monitoring vibration

Refer to stroboscopic systems 4.1.2.

4.6. In-situ metallography

Metallography is the science and practice of microscopic testing, inspection and analysis of surface of metal, typically at a magnification of 50X to 2500X. In-situ metallography is the metallographic examination of equipment in operation (in power plants, oil drilling rigs etc.), on large objects (e.g. boilers, aircraft engines) and also in places where it is not possible to cut a specimen for preparation and microscopic examination in the laboratory. The procedure of examination is simple and comprises of initiating coarse grinding with flapper wheels, grinding and fine grinding with silicon carbide (SiC) paper discs, and polishing with diamond paste on cloth etc. The last procedural step is that of etching the surface. Electrochemical etching is easily done, in-situ, even on a vertical surface, using a glass tube and a sealant to the surface. A portable microscope with a camera attachment is then used on the prepared surface. The other approach of examination is through use of replication method. Cellulose acetate replicating material is used for surface cleaning, removal and evaluation of surface debris fracture surface microanalysis and micro structural evaluation.

The one side of acetate tape is moistened with acetone, a short time is allowed for softening and applying the wet side of the tape to the etched surface under examination. Following a short period, the tape hardens and is removed by peeling them off and held between glass strips; they are examined with a reflecting aluminium foil background.

Another method of producing replica is to use a varnish having a nitrocellulose or plastic base, spread on with a spatula, and allowed to dry. Great care is needed in lifting the replica off the surface. Instead of aluminium background for viewing, the surface of the replica not containing the impression can be made reflecting by vacuum deposition of an aluminium coating.

4.7. Temperature indicating materials

4.7.1. Radiation pyrometers

The measurement of high temperatures often requires an instrument which is not in contact with the hot body. These instruments measure the radiation emitted by the hot body.

Radiation pyrometers, the instruments used to measure the emitted radiation under black body conditions, follow the Stefan Boltzmann Law which may be stated as an increase of 1% in the absolute temperature of a radiating body results in an increase of 4% in the energy emitted. Since this only applies to black body conditions similar to energy emitted from a chamber at uniform temperature, corrections are required for hot bodies in the open.

Radiation pyrometers use lenses or mirrors to concentrate the emitted energy onto a thermocouple which then generates an electro-motive force (EMF) and is measured on a calibrated milli voltmeter. The bottom end of the temperature measurement is about 500°C with no upper limit.

4.7.2. Optical pyrometers

Optical pyrometers compare the intensity of light from the hot source with a bulb filament. The current is applied to the bulb filament until a match is achieved or the filament disappears.

The comparison is carried out in the red light part of the spectrum and temperature can be read off direct. The method is only effective at temperatures above 500°C.

4.7.3. Temperature indicating sticks

Temperature sticks are crayon or chalk material with a calibrated specified temperature at which they will melt and are available over a range of +38°C to +1370°C with an accuracy of +/- 1%.

The stick is placed in contact with the surface of the component and will melt at the temperature marked on the stick. A typical application is in welding to check preheat and post heating temperatures. Some sticks do not melt, but change colour at the indicated temperature instead.

4.7.4. Temperature indicating pellets

Pellets have an advantage over sticks in that they have a longer indication period and are used in prolonged heating applications in which a temperature stick could fade with time or are not accessible. One of the uses is to check oven and muffle furnace chambers.

The pellets are placed within the oven at selected positions to check temperature distribution. When the temperature is reached the pellets begin to melt. After cooling down, the different positions are checked to see which pellets melted and which pellets failed to reach temperature.

4.7.5. Liquid temperature indicators

Liquid indicators, which change colour at specific temperatures, are available for component surface temperature checks where temperature sticks may be unsatisfactory.

The liquid is brushed on before the operation and used on highly polished surfaces or for marking large areas which require viewing from a distance.

4.8. Chemical aids

In visual testing, chemical techniques are used to clean and enhance the surface of the component to be tested. Cleaning process removes dirt, grease, rust and mill scale. Contrast is enhanced by chemical etching.

Macro etching is the use of chemicals to attack material surfaces to improve the visibility of discontinuities for visual inspection at normal and low power magnifications.

5. WORK PARAMETERS AND CONDITIONS

5.1. Surface preparation

An important factor affecting visual test is lighting. In visual tests, the amount of light may be affected by distance, reflectance, brightness, contrast or the cleanliness, texture, shape and size of the test object. Cleanliness of the surface under test however is a basic requirement for a good visual test. It is impossible to obtain visual data through layers of opaque dirt unless cleanliness itself is being examined. In addition to hindering vision, dirt on the weld surface can hide the actual discontinuities.

In visual non-destructive testing, for surface preparation, chemical techniques are used to clean and enhance test object surfaces. Cleaning processes remove dirt, grease, oil, rust and mill scale. Contrast is improved by means of chemical etching. Macro-etching helps in improving the visibility of discontinuities for visual inspection at normal and low magnifications.

The significance of surface preparation for visual examination by the un-aided eye in case of welds is also high. The test surface should be free of slag, dirt, weld spatter or other contaminants that might make it obscure to the un-aided eye.

Surface preparation may also include those steps needed for valid interpretation of subsequent non-destructive tests. The test area normally consists of 100% of the readily accessible exposed surfaces of the test object, including the entire weld crown at a specified distance such as 25 mm of the adjacent base metal.

Rust and mill scale are normally removed by mechanical methods such as wire brushing or grinding. Rust can also be removed by chemical means. Strong etchants can be used to remove lose rust and mill scale. Fine grinding and polishing are needed for visual tests of small structural details, welds and the effects of heat treatment. During grinding it is critical that all marks from the previous step be completely removed.

5.2. Observation techniques

5.2.1. Direct visual examination

Direct visual examination is the type of examination made in situations where there is an access to the area of interest without any possibility of injury to the inspectors. Mirrors or lenses may be used to improve angle of vision or magnification.

5.2.1.1. Visual angle and distance

It is general recommendation for operator to be placed at a distance for his eye to be within 600 mm of the test surface at an angle not less than 30 degrees. The criterion set above is based on the fact that the angle of vision and the distance of the eye from the test surface determine the minimum angular separation of the two points resolvable by the eye as shown in Fig. 5.1. This is known as eye's resolving power.

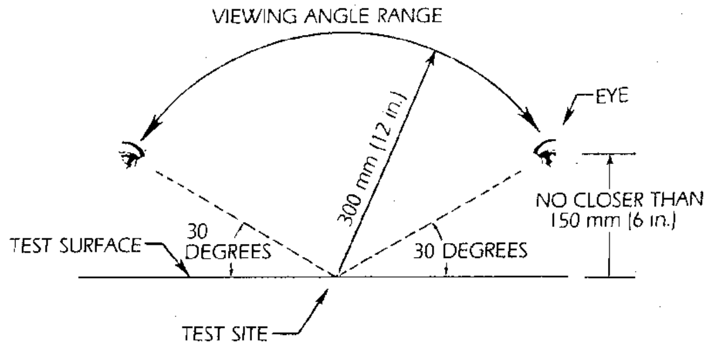


FIG. 5.1. Minimum angle for typical visual testing.

For the average eye, the maximum resolvable angular separation of two points on an object is about one minute of arc (0.0167 degrees). This implies that at a distance of 300 mm from a test surface, the best resolution to be expected is about 0.09 mm. At 500 mm, the best anticipated resolution is about 0.18 mm.

To complete a test, the eye is brought close to the test object to obtain a large visual angle. However, the eye cannot sharply focus on an object if it is nearer than 250 mm. Therefore, a direct visual test should be performed at a distance of 250 to 500 mm. The angle that the eye makes with the test surface should not be less than 30 degrees.

Natural or artificial lighting of sufficient intensity and placement is needed to illuminate the test areas and to allow proper reading of weld gauges and other equipment. The visual test resolution is considered adequate when the examiner, by combination of lenses, access, lighting and angle of vision, can resolve a 0.8 mm wide black line or an artificial flaw located on the surface to be examined. On the test surface the lines or the artificial flaw should be in the least discernible location.

5.2.1.2. Illumination

The specific part, component or vessel should be illuminated if light available is insufficient and it should be a minimum of 800 lx for general examination.

5.2.1.3. Objective of direct visual inspection

- To confirm that a material or product meets design or manufacturing specifications;
- To determine that once in-service a material or product is free from defects that may render it unfit for service.
- To facilitate the analysis of the cause of fracture/failure of products and structures.

5.2.1.4. Translucent visual testing

Translucent visual testing is a supplement of direct visual testing. The method is based upon back lighting of a translucent material to aid examination of such material for internal and surface flaws. Light sources used shall be sufficiently diffused as to prevent glare obscuring fine detail. Light sources should have adjustable intensity for adaptation to changing sessions or material structures.

5.2.2. Remote visual examination

For surface inaccessible to the naked eye, direct visual inspection method is substituted by remote visual examination. Remote visual examination may use visual aids such as mirrors, telescopes, borescopes, fibre optics (flexible borescopes), cameras or other suitable instruments. The resolution expected for remote visual examination has to be at least equal to that of direct visual inspection.

5.2.3. Comparison between direct visual inspection & remote visual inspection

Remote visual inspection is used in hostile environments unsafe for human being or in areas of inaccessibility. All of the variables that apply to direct visual inspection can also be applied to remote visual testing.

The main difficulties associated with remote visual examination are:

a) scanning the test site with full coverage without line of sight;

b) inability to easily implement supplemental non-destructive tests.

The inability to use supplemental tests is the most severe constraint. This is critical, because a percentage of visual targets that appear as crack like discontinuities can not be separated into non-relevant or relevant indications without additional non-destructive testing. The inability to provide evaluation with a high confidence level is a significant limitation of the remote visual testing method.

5.3. Illumination conditions dependent on type of surface to be examined & expected defects

For a successful visual test, lighting the surface by a source of adequate intensity and spectral distribution is of foremost importance. Brightness is an important factor in visual test environments. Excessive or insufficient brightness interferes with ability to see clearly and so obstructs critical observation and judgement. The brightness of light depends on the reflectivity of the test surface and the intensity of the incident light. For these reasons, the level of illumination must be tightly controlled.

A minimum intensity of 160 lx of illumination should be used for general lighting and a minimum 500 lx should be used for finely detailed tests. Dependant on the applicable standard higher illumination levels may be required.

To check and ensure the availability of required light, a light meter should be used to determine if the working environment meets this standard.

Perception by eye sight (vision) is dependent on the reflected light reaching the eye. Reflectance and surface texture are related characteristics. It is the objective of lighting to enhance a target area, but not to the extent causing it to glare to mask the test surface. A highly reflective surface or on the other hand a roughly textured surface may require special lighting technique to illuminate without masking. Supplementary, lighting should be shielded to prevent glare from interfering with inspector’s view.

Glare, reflected or direct can be a major problem that is not easily corrected. One possible solution of minimizing the glare is by decreasing the amount of light reaching the eye. This can be achieved by enhancing the angle between the glare source and line of vision by increasing the background light in the area surrounding glare source or by dimming the light source.

5.4. Evaluation of visual acuity, calibration of the examination using reference samples

Vision Acuity is the ability of the eye to distinguish fine details visually. Quantitatively, it is reciprocal of the minimum angular separation in minutes (1/60th of a degree) of two lines of width subtending one minute of arc when the lines are just resolved as separate. Two forms of vision Acuity are recognized and are considered to qualify one’s visual ability. These are known as near vision and far vision. A normal eye views a sharp image when the object subtends an arc of five minutes, regardless of the distance the object is from the eye. When vision cannot be normally varied to create sharp clear images, then corrective lenses are required to make the adjustment.

Visual testing of critical products requires qualified and certified personnel. For certain inspections, it may be required for the eyes of the inspector to be examined as often as twice per year. However, the frequency of such examination is determined by code, standard, specification, recommended practice or company's policy.

5.4.1. Chart types

5.4.1.1. Jaeger eye chart

Use of Jaeger Chart is made for the near vision examination. The examination distance should be 400 mm for the eyeglasses or from the eye plane, for tests without glasses. The reading chart such as 'Jaeger Chart' should be in the vertical plane at a height where the eye is on the horizontal plane of the centre of the chart. Each eye should be tested independently while the un-examined eye is shielded from reaching the chart but not shut off from the ambient light. The visual inspectors performing visual examination may be required to read the smallest letters at a distance of 300 mm of the Jaeger Chart. The Jaeger Chart widely used in USA and other parts of the world is a 125 x 200 mm off-white or greyish background with an English language text arranged into groups of gradually increasing size. Each group is a few lines long and the lettering is black.

The exact requirements for near vision acuity examination are specified by the employer. If the employer allows visual inspector with corrected lenses, then the inspector must wear them during the visual examinations. Photo-greying lenses can create some problems under some fluorescent lights, in such cases, the inspector may wear the normal power lenses for near vision correction and inspection purposes.

5.4.1.2. Use of tumbling E eye chart

In 1976 Taylor created a chart using a single optotype, a stylized letter E, in various orientations to test visual acuity of Australian Aborigines. This has become standard for testing of illiterates and populations not familiar with the Roman alphabet. The problems associated with variability of the tests defined in ISO 9712 have long been recognised. A solution using the tumbling E eye chart is presently being discussed.

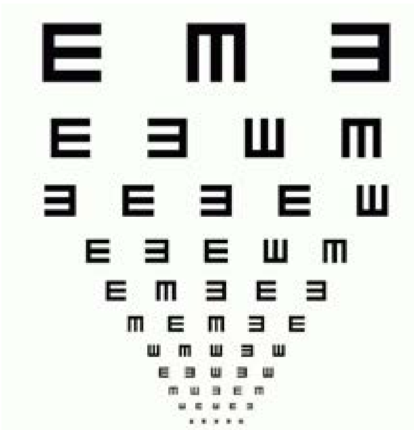


FIG. 5.2. Tumbling E eye chart.

(a) Advantages of the tumbling E eye chart:

- Standardised test – removes variability;
- Test conditions defined (illumination, distance, acceptance etc.);
- Verifies visual acuity not reading ability;
- Ensures a defined minimum level is achieved;
- Easily controlled and administered locally;
- The test is conducted using actual corrective lenses, where applicable;
- Fails safe as far as possible;

- Removes reliance on equivalences.

(b) Calibration of the examination using reference samples - Target detection (resolution test)

A critical performance standard for some visual examination is the detection of a line to verify system's sensitivity. This process is called as resolution test. Single line detection for a direct visual examination is usually performed using a 750 µm width black line on an 18 % neutral grey flat uniform line. Some performance criteria require detection of 25 µm black line for remote visual tests in critical applications. The requirement set by these standards is relatively gross as a 750 µm black line can be reliably indicated by individuals classified blind (20/200 corrected both eyes). In such a situation even the 25 µm widths should not be used as the performance standards because they do not determine image sharpness.

Image sharpness is critical to discontinuity recognition and is an important feature for recognition of welding discontinuities. Fig. 5.3 shows a photograph of a 0.75 mm line on 18 % grey card with an equivalent 20/200 near vision.

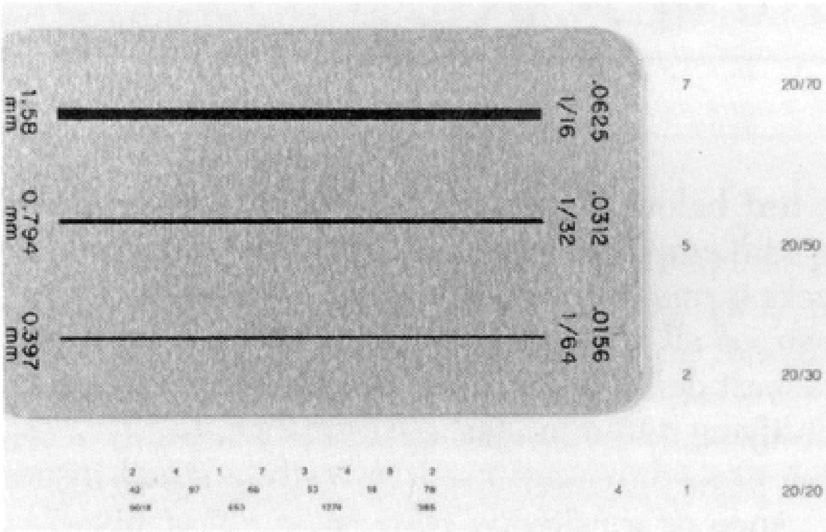


FIG. 5.3. Photograph of a 0.75 mm line on 18 % neutral grey card with an equivalent 20/20 near vision acuity.

(c) Reference sample for calibration of examination

In addition to specific calibration or verification standards, most of the non-destructive testing specifications include the use of test objects with known discontinuities as performance standards for visual testing. The use of discontinuity reference standard has two distinct advantages:

- They represent actual conditions that cannot be accurately simulated by vision acuity eye tests or line detection.
- Reference standards are critical for training inspectors in pattern recognition as well as proper detection and evaluation methodology.

5.5. Presentation of results to be used in analysis, documentation and filing

After performing the visual inspection test as per the written procedure or instruction sheet, the test results are submitted in the written form as 'Test Result' report on the form developed for this purpose. If no form is developed, the inspector may develop one that provides the following essential data:

i) Date of performing test;

ii) Instrument used, type and identification;

iii) Procedure used, identification (check list);

iv) Lighting conditions;

v) Record of test results;

vi) Job description i.e. whether a weld, surface or in-service along with the applicable application area (items examined) for the visual testing;

vii) Applicable documents such standards & specifications relevant to procedure & acceptance standards;

viii) Person's identification performing the test, qualification etc.

The recording of test results to be reported as test results in the form of test result report has to be proper and adequate mean should be adopted to do so. Recording of indications & other anomalies is desirable for report or during technique evaluation and development of permanent visual record which is often required for engineering purposes, personnel training, failure analysis and crack growth monitoring. Some record keeping methods are:

a) Use of sketches

The sketches provide the simplest method of recording indications. The sketch should include a recognizable landmark on the inspection area so that the indication can be properly located and oriented. A description of the type of indication, length and other characteristics should also be mentioned in the sketch.

b) Photography and digital imaging

Photography is the best approach of recording the indications of discontinuities & other anomalies for preserving them for later studies. Using photographs or digital images as a permanent record of a test makes it possible to subsequently review, scrutinize and evaluate a discontinuity. Photographs can be used as a reference documents. (Fig. 5.4)

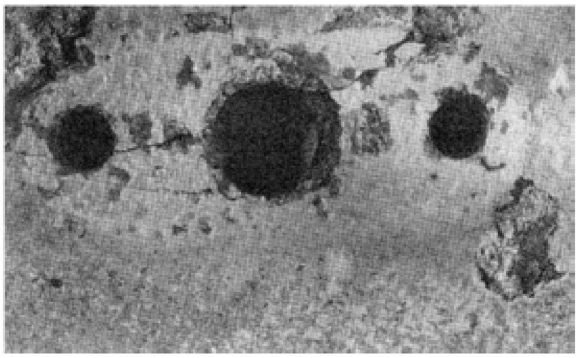


FIG. 5.4. A macro lens view revealing cracks and corrosion pitting on a casting.

Filing and retrieval should be made through a file management system. When the need arises, to review a document, finding it should not be a problem. For the extent of time for which records should be kept, the recent government legislation or code's requirement should be followed.

5.6. Visual and optical testing procedures

To ensure reliability and reproducibility of the visual inspection it is critical that the inspector carry out the inspection in accordance with approved procedures. As a minimum a procedure should contain the following elements:

- Qualification requirements of inspection personnel
- Stage of testing
- Type of surface condition
- Cleaning instructions
- How the test is to be performed
- Illumination technique and measurement of illumination
- Sequence of performing the test
- Data to be tabulated
- Check list for testing
- Report forms
- Permanent records - if any
- Specialised equipment if required for hazardous areas

The written procedure shall define scope of coverage and may be limited to specific tasks. The procedure shall contain a reference report form and a check list to prompt inspectors during surveillance of the test area. The checklist shall include all facets related to the specific surface examination and may be used to verify that the required observations were performed.

6. IMAGE RECORDING

6.1. Photographic recording

Photographic recording can be described as the process of forming a permanent record of an image. Methods of recording the image include film and digital cameras.

6.1.1. Main characteristics and fundamentals of photographic cameras

Photographic camera is an optical device for obtaining still photographs or film. It consists of a light proof box with a lens at one end and a plate of light-sensitive medium at the other. The lens of the photographic camera is a converging type (double convex) which focuses the light from an object onto a light - sensitive medium. To make an exposure the shutter is opened to allow the light of the focussed object to pass through the lens to form an image of it on the medium. The length of exposure is determined by intensity of the light available, the ISO number and aperture of the lens. In simpler cameras the shutter speed and aperture of the lens are controlled manually, but in automatic cameras the iris of the lens or the shutter is adjusted on the basis of information provided by a built-in exposure meter. Fig. 6.1 illustrates the basic principle of the lens camera.

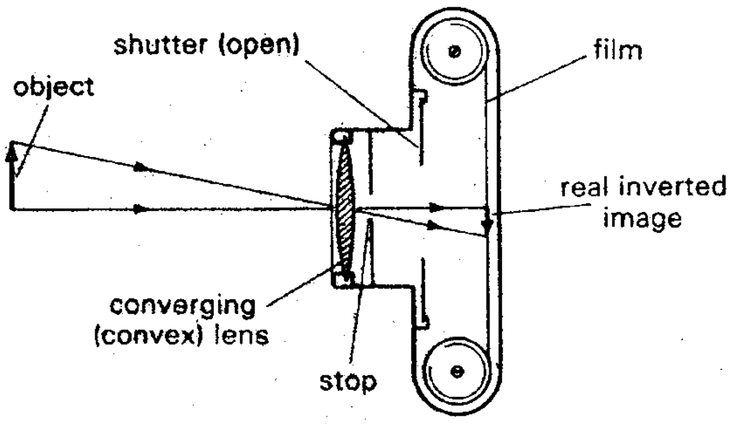


FIG. 6.1. Principle of lens camera (film).

For greater sharpness of images, the light is restricted to the central part of the lens by the iris or aperture.

6.1.1.1. Focal ratio and f-number

The effective diameter of a lens or mirror is its aperture (or stop). The ratio of effective diameter to the focal length is called the relative aperture, which is commonly known as the aperture, especially in photographic usage. The reciprocal of the relative aperture is called focal ratio. The numerical value of the focal ratio is known as f-number. A camera lens with a 40 mm focal length and a 10 mm aperture has a relative aperture of 0.25 and a focal ratio of 4. Its f-number would be f/4, often written as f4.

The diameters of the stop (aperture) of a camera are doubled between each position e.g. f/5.6, f/8, f/11, f/16, f/22. Therefore, f-ratios are 5.6, 8, 11, 16 and 22 etc. and their squares are in the ratios of 1:2:4:8:16. This implies that if correct exposure for f/5.6 is one second, the correct exposure for f/11 would be 4 seconds.

6.1.1.2. Depth of field

When a lens focuses on a subject at a distance, all subjects at that distance are sharply focused. Subjects that are not at the same distance are out of focus and theoretically are not sharp. However, since human eyes cannot distinguish very small degree of un-sharpness, some subjects that are in front of and behind the sharply focused subjects can still appear sharp. The zone of acceptable sharpness is referred to as the 'depth of field'. Thus, increasing the depth of field increases the sharpness of an image. We can use smaller apertures for increasing the depth of field.

Depth of field determines the overall sharpness of focus throughout a photograph. When a photograph is made, a single plane through the subject is actually in focus and this is called principal plane of the focus. In a typical camera, the lens aperture (f-stop) controls the extent of the principal plane of focus or what is known as the image depth of field (Fig. 6.2). For obtaining best quality visual image, the lens diaphragm is fully closed (high f-number).

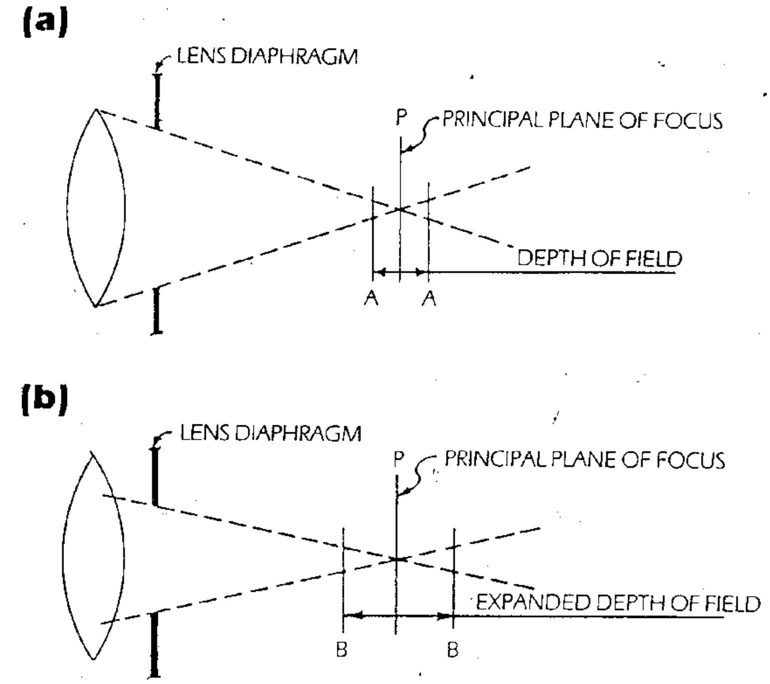


FIG. 6.2. Effect of aperture on depth of field in still photography: (a) large aperture and (b) small aperture.

6.1.1.3. Borescopic photography - some basics

Borescopic photography is a highly specialised methodology. It requires a camera system that meets the following needs:

- The camera should allow the operator to view the scene through the 'taking' lens immediately before making the exposure.
- The camera must have the facility to accept a suitable focusing screen designed for scopes.
- The camera system should have means to easily attach and optically couple the borescope or fiberscope to it, with the least loss of light.
- The camera body should have both automatic & manual exposure systems.
- The view finder image should be magnified with accuracy.
- The camera should be rugged and reliable for industrial use.

Fig. 6.3 illustrates such a camera on an articulating support arm adapted for Borescopic photography.

FIG. 6.3. Borescopic photographic and video system.

6.1.1.4. Different types of films

Where film photography is required, the inspection procedure should specify the specific type of film required.

6.2. Replication

This is a permanent record of the surface of a part. Replication is used to copy surface conditions such as impact damage, wear, corrosion, and cracking. The material used to form the replica determines the fine quality resolvable, with nitrocellulose and cellulose acetate having the best replication ability. These materials are used when a microscopic examination is anticipated. Other materials used to produce replicas are plaster, plastic materials, Plasticine, varnishes, clays, silicone rubber, tapes, etc.. Silicone rubber has the ability to flow into cracks, crevices and pits. Examination of the replica allows detailed inspection and measurement of specific features or profiles, e.g. depths of pits could be measured using gauges, micrometers or a low power magnifier with graticules.

Replication is a method of copying the topography of surface that cannot be moved from one that would be damaged in transfer. These replicas produce a negative topographic image of the subject known as a single stage replica. A positive replica made from the first cast to produce a duplicate of the original surface is called a second stage replica.

6.2.1. Different replicating techniques

Replication techniques can be classified as either surface replication or extraction replication. Surface replicas provide an image of the surface topography of a specimen, while extraction replicas lift particles from a specimen. The discussion of methods is restricted to surface replication techniques.

6.2.2. Replicating medium

The most extensively used direct methods involve plastic, carbon or oxide replica material.

6.2.3. Plastic replicas

All direct methods except plastic methods are destructive and therefore require further preparation of the specimen before making additional replicas. Plastic replicas lend themselves to in-plant non-destructive examination because of their relative simplicity and short preparation time. Plastic replicas can be examined with light optical microscope, the scanning electron microscope, and the transmission microscope, depending on the resolution required. As illustrated in Fig. 6.4, the plastic replica technique involves softening a plastic film, applying it to surface, and then allowing it to harden as solvent evaporates from the surface. The plastic film contains a negative image, or replica, of the micro-structure that can be directly examined in the light microscope or, after some preparation in the electron microscope. Double-face tape is used to bond the replica to the glass slide, in order to obtain large, flat, undistorted replica surfaces.

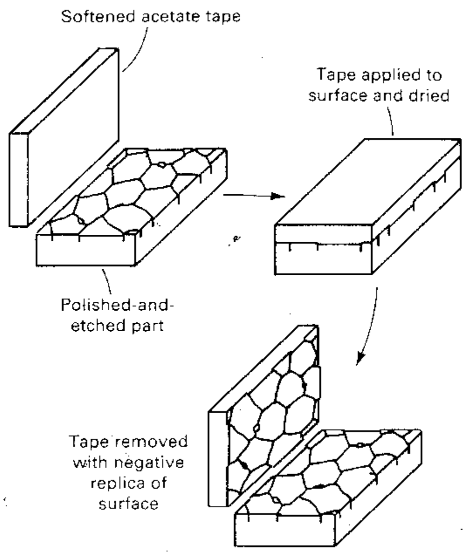


FIG. 6.4. Schematic of the plastic replica technique.

6.2.4. Cellulose acetate replication

Acetate replicating material is used for surface cleaning, removal and evaluation of surface debris, fracture surface microanalysis and for micro structural evaluation. Fig. 6.5 illustrates the schematic diagram of micro structural replication.

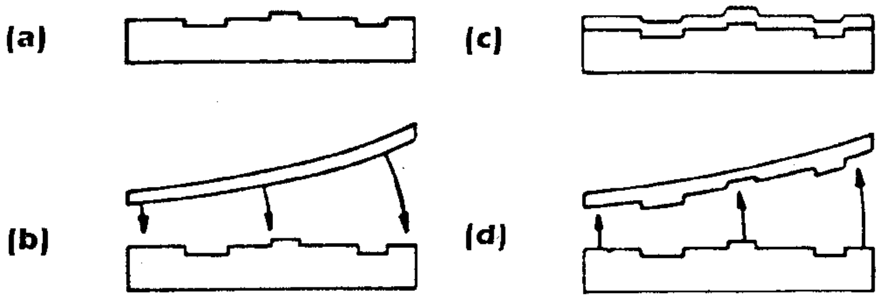


FIG. 6.5. Principles of acetate tape replication producing a negative image of the surface: (a) microstructure cross section, (b) softened acetate tape applied, (c) replica curing and (d) replica removal.

For surface preparation, cleaning is required when the test surface holds loose debris that could hinder analysis and that cannot be removed with a dry air blast.

Removal of loose surface particles is usually done by wetting a piece of acetate tape on one side with acetone, allowing a short period for softening and applying the wet side of the tape to the area of interest. Thicker tapes of 0.013 mm work best for such cleaning applications. Thin tapes tend to tear. Following a short period, the tape hardens and is removed. This procedure is repeated several times until a final tape removes no debris from the surface.

The use of acetate replica for non-destructive testing has come from their use in micro structural testing and interpretation. Micro structural replication is done in two steps: surface preparation followed by the replication procedure. Surface preparation involves progressive grinding and polishing until the test surface is relatively free of scratches. Depending on the material type and hardness, this can be obtained by using a 1 μm to 0.05 μm polishing compound as the final step. Electro polishing can increase efficiency if many areas are tested.

Next, the electro-polished surface is etched to provide micro structural topographic contrast that may be necessary for evaluation.

To replicate the surface microstructure, an area is wetted with acetone and a piece of acetate tape is laid on the surface. The tape is drawn by capillary action to the surface, producing an accurate negative image of the surface micro structure. Before removal of the tape from the surface, the back is coated with paint to provide a reflective surface that enhances microscopic viewing. The replica is removed and stored for future analysis.

6.2.5. Silicon rubber replicas

Silicon impression materials have been used extensively in medicines, dentistry and in the science of anthropology. In non-destructive testing, silicone materials are used as tools for documenting macroscopic and microscopic material details. Quantitative measurements can be obtained for depth of pitting, wear, surface finish and fracture surface evaluation.

Silicon replicating materials are supplied in two parts:

- A base material

- An accelerator

The two parts are mixed in recommended ratios thoroughly and spread over the surface area. Additional material can be added to thicken the replica. Moulding clay can also be used to build a dam around a replicated area. The dam supports the replica as it sets and allows thicker replica to be made.

To evaluate pit depth and surface finish, the replica is cut and the cross - section is examined with a microscope or macroscopic measuring device (a micrometer or an optical comparator).

Wear can be determined in a similar manner by replicating a worn surface to an unworn surface.

6.2.6. Acrylic casting resin method

A powder is mixed with a liquid on the surface to be replicated. After hardening, the replica can be examined directly in an optical microscope without further processing. If adhesion is a problem, a composite replica can be made of an initial layer of Parlodin lacquer before the acrylic layer is applied.

6.3. Film digitization and image processing

Image processing (also called picture processing) are the actions applied singly or in combination to an image, in particular the measurement and alterations of image features by computer.

Visual images are valuable tool in non-destructive testing of many kinds. The primary advantage of a visual record is that, it can be reviewed and evaluated more than once. Digital image processing can be a powerful tool in the interpretation of many types of visual images. The information contained in such images is more that what our eye can see because of its limited ability to detect edges and gray levels. The gray level is an integer number representing the brightness or darkness of a pixel or, as a composite value of an image comprised of pixels. The human eye can only resolve gray levels that differ by at least 2% (between 32 to 64 gray levels). A boundary or edge condition can be discriminated by the eye when two adjoining areas of an image differ in density by 12% or more. So the need of digitization image through image enhancement system arises for better interpretation and evaluation of the recorded visual images.

6.3.1. Image capture and film digitizing

An important part of image enhancement for subsequent image processing is the system that captures or acquires the data. In many cases, an image will be recorded on film to be digitized, or the data will come directly from a digital system. The quality and dynamic range of image will influence subsequent processing. A digital image as illustrated in Fig. 6.6 is a two dimensional arrays of pixels that represent the gray levels of an image, and if the pixel is composed of 8 bits, 256 gray shades or colours can be displayed.

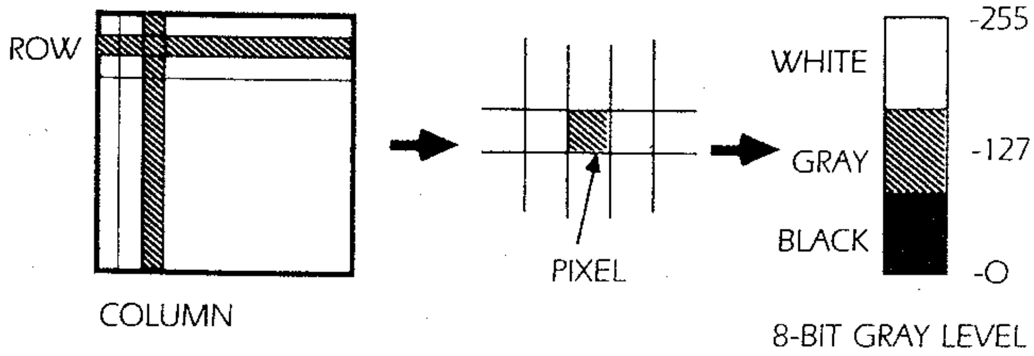


FIG. 6.6. A digital image is made from combinations of pixels with varying gray levels.

Because the eye has an approximate dynamic range of 150, a 256 level display is adequate for gray level viewing. For computational purposes, for the display of colour and for the ability to fully digitize the film, it is sometimes desirable to have a 12 (or more) bit pixel, which can be compressed into 8 bit for display. The display size indicated in Fig. 6.7 is N×N; for most systems, N should be at least 512, with 1024 preferred.

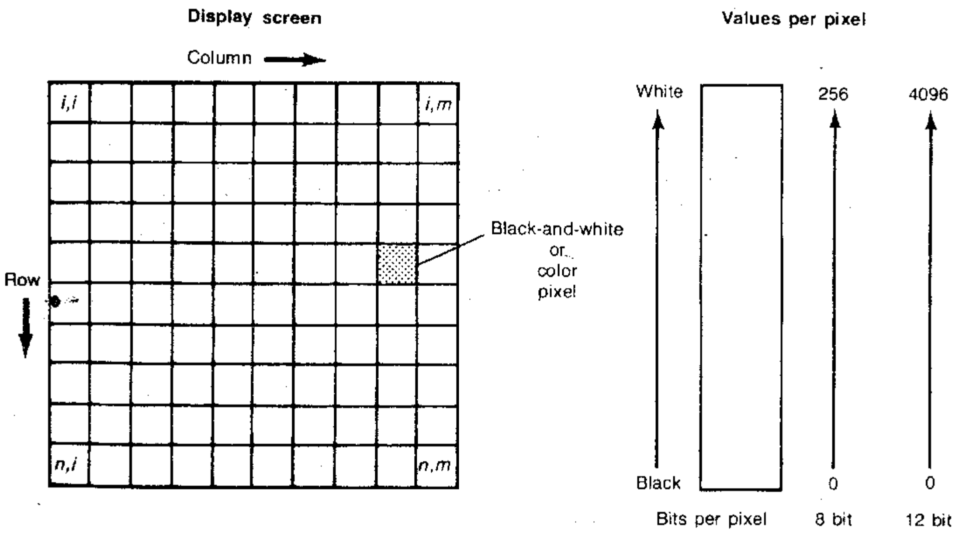


FIG. 6.7. Concept of image display (a) and representation (b) in computer memory.

6.3.1.1. Digital imaging

The use of digital images has numerous advantages, these include:

a) Ease of storage and recall;

b) Sharing and file transfer capabilities;

c) Low cost

d) Post processing and image enhancement;

e) Environmental factors.

6.3.1.2. Film digitisation

Film digitisation is the process of converting a film image to a digital image. The conversion process can be carried out in a number of ways using a variety of equipment types. The quality of the collected/scanned image is dependant of the equipment type and process.

6.3.1.3. Image processing

As digital equipment manufactures record data in different formats, it is often necessary to convert the file into a specific file type prior to image processing.

Image processing in general involves four steps, image enhancement, image segmentation, feature extraction and classification. Image enhancement involves the use of a variety of steps for image processing employed, singly or in combination, to improve the detectability of an image.

Typical benefits and applications of image processing include:

- Contrast enhancement;
- Measuring;
- Annotating;
- Pattern recognition;
- Enlargement.

7. CODES, STANDARDS, SPECIFICATIONS & PROCEDURES

7.1. General knowledge & overview of codes & standards

7.1.1. General knowledge of specifications and procedures

Many phases of design, fabrication, construction, service and maintenance are governed by documents known as codes, standards and specifications. These are used as guides, practices, regulations or rules. A technical standard or code is an established norm or requirement. It is usually a formal document that establishes uniform engineering or technical criteria, methods, processes and practices. Codes and standards are sometimes confused with one another. It is always best to check with the local jurisdiction to find out what applies, and not just use the titles of standards to make your choice of what documents to follow. The use of specification or code becomes mandatory only when referenced by codes or contractual documents.

Many purchasing organizations develop and issue specifications designed to meet their requirements. Once such specifications are referenced in purchasing documents, they influence the product quality and the work of the visual inspectors. Such specifications reflect the needs of a specific situation. Public interest in safety and reliability started the development of nationwide or industry-wide codes and standards.

Codes and standards are periodically revised by the issuing organisations. When contracts for services are signed, it is typically assumed that the current reference document is in effect unless a particular revision is specified. Also when a new revision is published, it is customary for it to stipulate a grace period (for example six months) during which the contractor may adjust practices to meet new requirement.

A prime example of codes is the American Society of Mechanical Engineer (ASME) Boiler & Pressure Vessel Code (B & PV) which is a set of standards that assure the safe design, construction and testing of boilers and pressure vessels.

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

Standardisation of a process can be defined as the setting up of process parameters so that it constantly produces a product of uniform characteristics.

7.1.2. Objectives of standardization

7.1.2.1. Clear communication

Written standards make it easy for the customer or user to communicate with the producer.

7.1.2.2. Economy of effort

The purchaser or designer may have a general idea of what is required (and what is available) for a desired level of inspection. If all the possible parameters and variables are detailed in a document, already prepared by the experts in the field and published as a standard, then one is saved the effort of preparing everything themselves.

7.1.2.3. Minimum performance

Published codes and standards accepted by the industry in general, provide the regulator or purchaser with confidence that the product or service will at least perform to the level detailed in the standard.

7.1.2.4. Historical record

After the product has gone into service (sometimes years after), a life record of the standard used for production or inspection will likely be sufficient documentation of the process used to produce it.

7.1.2.5. Collective wisdom

A standard developed by the consensus process involves the technical experts from the producers, users and general public. It helps the protection of the consumer's interests through adequate and consistent quality of goods and services. The whole process of development of a standard which involves technical discussions and debates, results in a document, based on the collective wisdom of the participants.

7.1.2.6. Improvement in quality

Standards are helpful in the repetitive production of 'good quality' products.

7.1.2.7. International organizations producing standards on visual testing

The following organizations publish standards applicable to visual testing:

- Aerospace Industries Association (AIA)
- American Bureau of Shipping (ABS)
- American National Standards Institute (ANSI)
- American Society for Non-destructive Testing (ASNT)
- American Society for Testing and Materials (ASTM)
- American Society for Mechanical Engineers (ASME)
- American Welding Society (AWS)
- Department of Defence (DOD)
- Ship Structure Committee (SSC)
- Society of Automotive Engineers (SAE)
- American Petroleum Institute (API)
- French Association of Standardization (AFNOR)
- British Standards Institute (BSI)
- The European Committee for Standardization (CEN)
- German Institute for Standardization (DIN)
- International Organization for Standardization (ISO)
- Japanese Industrial Standards Committee (JISC)

7.1.2.8. Standards widely used in visual testing

Visual testing is cited in a number of major national standards. In addition, ISO or EN standards are frequently used in the industry. The importance of each is described in the following paragraphs:

(a) ASME Boiler and Pressure Vessel (B & PV) code

i) According to section III (Rules for Construction of Nuclear Power Plant Components) of the ASME (B&PV) Code, the results of the section III visual testing shall be evaluated in accordance with the requirements and acceptance standards of the referencing code sub-section. The general requirements of section III, subsections NB and NF, specify that the visual testing shall be performed in accordance with section V (Non-destructive Examination), Article 9. Article 9 (Visual Examination) of section V (Non-destructive Examination) of the ASME Code gives details for the needed level of quality for inspection circumstances such as access and illumination.

ii) ANSI B 31.1 (Power Piping) - developed to parallel section 1 (Power Boiler) of the ASME Boiler & Pressure Vessel Code - is generally used for fossil plant applications and for piping systems in nuclear power plants not under the scope of other codes. Visual testing in these documents includes dimensional checks of welds.

iii) IWA-2200 of section XI (Rules for In-service Inspection of Nuclear Power Plant Components) of the ASME Code describes three kinds of visual testing and calls them VT-1, VT-2 and VT-3. VT-1 is for general service inspection, conducted to detect discontinuities and imperfections on the wear, corrosion and erosion. VT-2 is conducted to detect evidence of leakage from pressure retaining components. VT-3 is conducted to detect discontinuities and imperfections such as loss of integrity at bolted or welded connections, loose or missing parts, debris, corrosion, wear or erosion.

iv) IWA-2300 of section XI of ASME Code, has been addressing visual testing since its 1977 edition. The 1989 edition of ASME section XI requires visual testing to be conducted in accordance with Article 9 of section V. Section XI lists the requirements for near vision test charts, remote visual testing and illumination level requirements.

(b) American Petroleum Institute (API) standard for welding pipelines and related facilities

Section 6 (Standards of Acceptability – Non-destructive Testing) of API 1104 (Standard for Welding Pipelines and Related Facilities) explicitly addresses radiographic and visual testing. The section describes a number of weld defects that can be detected or measured through visual testing.

(c) American Welding Society (AWS) structural welding code

Many buildings with structural steels have been designed and built according to the requirements of AWS D 1.1 (Structural Welding Code - Steel). AWS D 1.1 contains references to visual testing both in workmanship requirements and in specific visual testing acceptance standards. AWS D1.1 uses the term "inspection" where the ASME document would use "examination" and ASNT document would use "testing".

(d) American Society for Non-destructive Testing (ASNT)

ASNT Recommended Practice No. SNT-TC-1A is not a specification or standard. It is a set of guidelines or recommendations for employers to establish and conduct a non-destructive testing personnel qualification and certification programme. Recommendations included in SNT-TC-1A are:

i) Establish three levels of non-destructive testing personnel qualification Level-I, II and III, Level-III being for the method specialist and administrator).

ii) Specify the activities or functions that personnel should perform at each level non-destructive testing qualification.

iii) Specify the training education and experience that personnel should have at each level of qualification.

iv) Specify the subjects that the training should cover.

v) Specify the degree of acceptability for each level.

SNT-TC-1A provides guidelines intended to assist employers developing their own practices or procedures for qualifying and certifying their own NDT personnel. SNT-TC-1A requires modification of the recommendations as needed to make them properly fit particular needs.

(e) ISO or EN standards related to visual testing

The followings are the standards issued by ISO or EN.

i) ISO 3057 2nd edition (1998) : Non-destructive testing – Metallographic replica techniques of surface examination
ii) EN 13927 (2003) : Non-destructive testing Visual testing Equipment
iii) EN 13445-5 (2002) : Unfired pressure vessels
iv) ISO 3058 2nd edition (1998) : Non-destructive testing-aids to visual inspection-Selection of low-power magnifiers
v) EN 12454 (1998) : Founding- Visual examination of surface discontinuities- Steel sand castings general terms)
vi) EN 1330-2 (1998) : Non-destructive testing – Terminology, (Part 2: Terms common to the non-destructive testing method)
vii) EN 1330-10 (1998) : Non-destructive testing Visual Examination -Terminology,
viii) EN 1330-1 (1998) : Non-destructive testing – Terminology, (Part 1: List of Terminology)
ix) EN 13018 (2001) : Non-destructive testing- Visual testing-General principles
x) EN 970 (1997) : Non-destructive examination of fusion welds- Visual examination
xi) EN 12454 (198) : Founding- Visual examination of surface discontinuities- Steel sand castings
xii) EN 1370 (1997) : Founding- Surface roughness inspection by visual tectile by visual tactile comparators
xiii) ISO 5817 (1992) / BS EN 25817 (1992) : Arc-welded joints in steel- Guidance on quality levels for imperfections
xiv) EN 10163-1 (2004) : Delivery requirements for surface condition of hot-rolled steel plates, wide flats and sections (Part 1: General requirements)
xv) BS EN 10163-2 (2004) : Delivery requirements for surface condition of hot-rolled steel plates, wide flats and sections (Part 2: Plate and wide flats)
xvi) EN 10163-3 (2004) : Delivery requirements for surface condition of hot-rolled steel plates, wide flats and sections (Part 3: Sections)
xvii) EN 13445-5 (2002) : Unfired pressure vessels (Part 5: Inspection and testing)
xviii) EN 473 (2008) : Non-destructive testing – Qualification and certification of NDT personnel-General principles
xix) ISO 9712 (2005) : Non-destructive testing- Qualification and Certification of Personnel

The procedure writing of any NDT method is the responsibility of the NDT personnel qualified and certified to Level 3. An individual certified to Level 2 in NDT is qualified to perform and direct non-destructive testing in accordance with established or recognized procedures. This includes interpreting and evaluating results according to applicable codes, standards and specifications.

The person qualified to Level 2 or Level 3 prepares a NDT instruction for implementation by a person qualified to Level 1 or Level 2. The NDT instruction is a document that, in accordance with a general procedure contains only requirements and instructions that apply to a particular examination. This document is issued for internal use to a subordinate and serves as further explanation of the existing procedures.

7.2. Performance of test in accordance with written instructions

7.2.1. Records of operating conditions on test forms

As described above, the basic objective of preparing a document containing a set of NDT instructions is to assist the NDT operator to perform the particular test. The instruction sheet contains all the details essential for the operator to follow and perform the test. The instruction sheet is derived from the main detailed procedure of a particular method.

The data recorded as test results following a particular detailed procedure has to be recorded on test form, which is normally recognized as test report. Standard report forms are generated for every NDT method and as a minimum, the following items must appear on any 'Report Form':

- The inspection report shall include at least the following information:

- The name of the laboratory or inspecting authority.

- The product standard, specification or code, or test procedure, including any applicable references.

- Identification of the items or areas inspected, and if 100% inspection was not carried out, the number or percentage of items or areas inspected.

- The surface condition of the items prior to inspection, and details of any surface preparation.

- The viewing conditions, including measured illumination at the time of inspection.

- The stage of manufacture, or known service history, at the time of inspection.

- Features observed during the inspection, and identification and location of discontinuities.

- Any deviations from the inspection procedure.

- Acceptability or compliance with the relevant product standards, specifications or codes where applicable.

- The date and place of inspection.

- The report number and date of issue.

- The name of the inspector and officer responsible for the test report.

- The client or representative to whom the above information has been passed.

An individual certified to NDT Level 1 is qualified to carry out NDT operations in accordance with the written instructions and under the supervision of Level 2 or Level 3 personnel. His tasks include: setting up the equipment; perform the tests; record and classify results in accordance with the documented criteria and report the results. The individual is however not responsible for choice of the method or technique to be used. The next stage of examination is the evaluation of the tasks performed by NDT operator that is carried out by the Level 2 or Level 3 person. In non-destructive testing evaluation implies a review, interpretation of the significance of indications produced by the testing process to determine whether the part should be accepted or rejected. Before initiation of the evaluation process, the indications observed are interpreted as relevant and non- relevant. Evaluation is normally carried out in accordance with the accept/reject criteria of the applicable code, standard, specification or other document mutually agreed by the manufacturer and the client.

7.3. Instructions for testing in special situations

Where an inspection is required on a component where a current code, standard or specification does not exist, the development of a specific inspection procedure and instruction is required.

Typically the Level 3, in consultation with the client will develop a specific procedure and instruction.

The written procedure shall be proven by demonstration that a defined sensitivity can be achieved, and that anticipated defects can be detected utilising the techniques stated therein. Information as to the probable location of the discontinuities shall be included for the information of personnel conducting tests. Wherever possible a replica of the expected defects shall be available for reference.

A fully documented report of procedure qualification shall be maintained for verification by third parties.

There are many VT acceptance criteria in different codes and standards which are applied to specific area. Here are introduced some of them.

- Arc-welded joints in steel- Guidance on quality levels for imperfections

This international standard includes recommendations for the selections of assessments groups according to ISO 5817 for butt welds and fillet welds on steel depending on the types of stress. It may be used within a total quality system for the production of satisfactory welded joints. It provides three sets of dimensional values from which a selection can be made for a particular application. The quality level necessary in each case should be defined by the application standard or the responsible designer in conjunction with the manufacturer, user and/or other parties concerned.

- Visual testing acceptance criteria for items other than welds

IWF-3000 of ASME B&PV Code Sec. XI, requirements for class 1, 2, 3, and MC components supports of light-water cooled plants

IWF-3000 is standards for examination evaluations. IWF-3400 is acceptance standards for component support structural integrity.

8. SAFETY ASPECTS

8.1. Safety and environmental considerations

8.1.1. Safety for visual and optical tests

8.1.1.1. Need for safety

The human eye's visual functioning can be disrupted or even destroyed by improper use of any light source. Lighting is an important environmental factor which has the potential to greatly affect visual testing. It is well known that visual disorders of the eye such as incorrectly refracting lenses or muscular imbalances together with environmental factors such as improper illumination causes ocular discomfort, commonly known as 'eye strain'. The effects of ocular discomfort include headaches, migraine, dry sore eyes, watering, neck pain and a general feeling of discomfort. More serious disorders and diseases have been known to evolve from the above symptoms.

The introduction of high intensity light sources and artificial light sources through the advancement of optical testing technology has created a strong need to understand the potential health hazards involved in their use. Working environments illuminated directly or indirectly by sunlight are generally accepted as being more suitable as they provide a range of characteristic intensities different from most artificial sources. The amount of light absorbed by the human eye is limited by its geometry and as a result, the eye can handle only a limited range of night vision tasks.

A visual inspector is confronted at times with situations such as excessive exposure to light, radiation or insufficient lighting conditions. Failures in performance under the above mentioned situations require evaluation to identify the exact cause and thus work on a solution. There exists a belief that 20/20 foveal vision, in the absence of colour blindness, is all that is needed for optimal vision. In fact, this is not so, the inspector may have poor stereoscopic vision, visual ability may be impaired by glare or reflection; or actual vision may be affected by medical or psychological conditions.

8.1.1.2. Hazards from lasers

Lasers, in general, are used in specialised environments by technicians familiar with the hazards and trained to avoid exposure through the use of protective eyewear and clothing. Laser hazard controls are common sense procedures designed to restrict personnel from entering the beam path or prevent the beam path from operating in occupied areas. In cases of accidental exposure to laser light, the probability of damage to the retina is high because of the high-energy pulse capabilities of lasers. However the probability of visual impairment is relatively low because of the small area of damage on the retina. Once the initial flash blindness and pain has subsided, the resulting scotomas (damaged unresponsive areas) can sometimes be ignored by the accident victim.

During incidents of excessively bright light entering the eye, retinal damage is dependent on both the energy associated with the light beam and the area of contact on the retina. The greater the energy per unit area of the beam the greater is the possible damage.

In Fig. 8.1, an illustration of typical retinal beam thresholds for different light sources is depicted. As is illustrated, the sun produces a 160 μm diameter image on the retina.

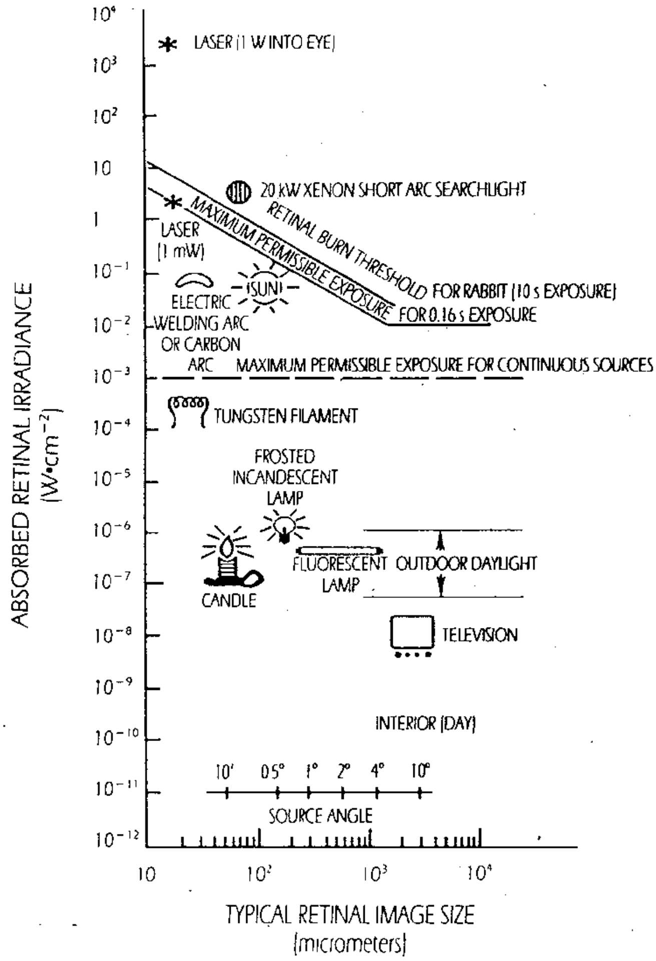


FIG. 8.1. Typical retinal burn thresholds.

8.1.1.3. Infrared hazards

Radiation outside the visible spectrum with wavelengths between 0.7 µm and 1000 µm is characterised as infrared radiation. Infrared radiation is absorbed by a number of substances and their main biological effect is known as hyperthermia, heating that can be lethal to cells. The normal response to intensive radiation is a feeling of heating followed by pain with the natural reaction being to get away from the source, so that burns do not develop.

8.1.1.4. Ultraviolet hazards

In industry, the visual inspector may encounter many sources of visible and invisible radiation: incandescent lamps, compact arc sources (solar simulators), quartz halogen lamps, metal vapour (sodium and mercury), metal halide discharge lamps, fluorescent lamps and flash lamps among others. These sources emit a considerable amount of ultraviolet radiation, which may be deleterious. Ultraviolet radiation (UV) is invisible radiation beyond the violet end of the visible spectrum with wavelengths down to about 185 nm. The principal hazards when exposed to intense light sources are potential eye and the skin injuries from UV radiation. Sources emitting ultraviolet light are often enclosed in ultraviolet absorbing glass or plastic lenses to prevent exposure to occupants in the same environment. Where high intensity ultraviolet light is used the thickness of the absorbent material is increased to compensate.

Adverse effects of ultraviolet light on the eye can result from both short and long term exposure. The most common short term effect is photokeratitis, inflammation of the cornea with symptoms including painful red eyes, foreign body sensation, extreme light sensitivity and excessive tearing of the eyes. In most cases symptoms resolve themselves within 36 hours with no permanent damage. Common causes include welders flash, sun reflecting off snow or water, glare from glossy surfaces and looking at or in the direction of the sun for an extended time.

Long term exposure can lead to the formation of cataracts, a clouding of the crystalline lens inside the eye. Symptoms include blurred vision, glare or light sensitivity, poor night vision and fading colour perception. Treatment for cataracts comes in the form of surgery where the crystalline lens is removed and replaced by an artificial lens. Poor welding practices can lead to welding personnel developing permanently affected vision.

Longer wavelength UV radiation can lead to fluorescence of the eyes and ocular media, eyestrain and headache. These conditions lead, in turn, to low task performance resulting from the fatigue associated with increased effort. Chronic exposure to UV radiation accelerates skin aging and possibly increases the risk of developing certain forms of skin cancer.

8.1.1.5. Photo-sensitizers

A large number of commonly used drugs, food additives, soaps and cosmetics have been identified as photo toxic or photo allergic agents even at the longer wavelengths of the visible spectrum. Coloured drugs and food additives are possible photo-sensitizers for organs below the skin because visible radiation of longer wavelengths penetrates deep into the body.

The potential of chorioretinal injury from visible radiations should not be overlooked while studying the hazards & health risks involved with UV radiation emitted from the high intensity light sources.

8.1.1.6. Damage to retina

During incidences of high intensity light often at shorter wavelengths than the visible spectrum, there is a potential risk for retinal burning. In practice, the evaluation of potentially hazardous environments may be simple or complicated. The hazard level depends on maximum luminance, spectral distribution of the source, possible scattering and absorption by the cornea, aqueous humour, lens and vitreous humour; and absorption and scattering in the various retinal layers.

8.1.1.7. Thermal factor

Visible and near infrared radiation up to nearly 1400 nm is transmitted through the eye's ocular media and absorbed in significant doses mainly on the retina. As radiation passes through the neural layers of the retina, a small amount of radiation is absorbed by the visual pigments in the rods and cones to initiate the visual response. The remaining energy is absorbed in the retinal pigment epithelium and choroid. The retinal pigment epithelium is most dense and the greatest temperature change arises in this layer. For short accidental exposures (0.1 s to 100 s) to the sun or artificial radiation sources, the mechanism of injury is generally thought to be hyperthermia resulting in protein denaturisation and enzyme inactivation.

Different regions of the retina play different roles in vision with the greatest vision acuity concentrated on the central (foveal) vision. Damage to the retina in the central region thus dramatically reduces visual capabilities.

With regards to the size of high intensity light sources, few arc sources are sufficiently large and bright enough to be a retinal burn hazard under normal viewing conditions. Only when an arc or hot filament is greatly magnified (in an optical projection system, for example) its hazardous irradiance can burn a large area of the retina. Nearly all accidents occur in hazardous situations where the observer is very near an arc. The intensity of light at close distances can burn the retina within the blink of an eye. An example of retinal damage is shown in Fig. 8.2. When first introduced to a low light level environment an inspector experiences a decrease in photopic (day light) sensitivity and increase in scotopic (dark adapted night vision). After a short period of adjustment the inspector is able to identify objects better in dark environments. This is why, the visual inspector in critical fluorescent penetrant and magnetic particle examination needs to undergo dark-adaption before actual inspection is initiated.

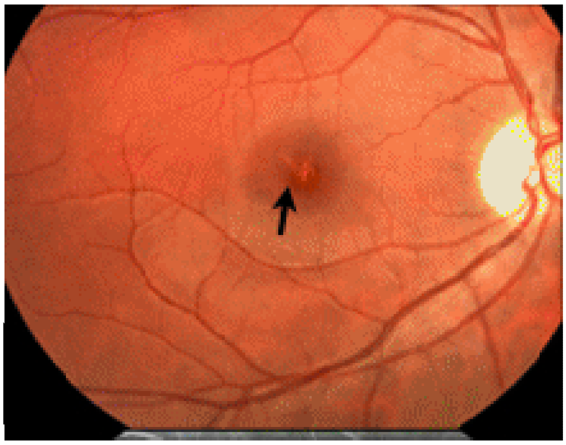


FIG. 8.2. Retinal damage to teenager who had shone a laser into his eyes.

8.1.1.8. Eye protection filters

Continuous visible light sources can cause pain response and this can protect the eye and skin from injury. Visual comfort has been thus often used as an approximate hazard index and eye protection and other hazard controls have been provided on this basis. Eye protection filters in the form of shades have been developed for a range of specific applications. Amongst other protective techniques the use of specialised filters to attenuate intense spectral lines in high ambient light environments are sometimes used.

Laser eye protection is designed to have an adequate optical density at the laser wavelengths along with the greatest visual transmission at all other wavelengths. In this way the inspector can absorb light from ambient objects but have harmful laser light blocked by the protective lenses, Fig. 8.3.

FIG. 8.3. Safety goggles containing narrow wavelength laser absorbing lenses.

8.1.1.9. Hazards of blue light

The blue hazard is based on the fact that the retina can be damaged by blue light at intensities that do not raise retinal temperatures sufficiently to cause a thermal hazard. It has been found that blue light can produce 10 to 100 times more retinal damage (permanent decrease in the spectral sensitivity in this spectral range) than longer visible wavelengths. There are some common situations in which both thermal and blue hazards may exist.

8.2. Industrial safety standards

The following is the description of some of the standards on safety issued & published by international organizations and publishers:

8.2.1. American National Standards Institute (ANSI)

ANSI/ASC Z49.1-88	Safety in welding and cutting.
ANSI Z87.1	Practice for occupational and educational eye and face protection
ANSI/NFPA 497	Classification of class-1 hazardous locations for electrical installation in chemical plants.
ANSI/Z88.2	Practices for respiratory protection
ANSI/Z89.1	Protective headwear for industrial workers.
ANSI/Z35.1	Specification for accident prevention signs.

8.2.2. American Welding Society (AWS)

AWS F4.1-88	Recommended safe practices for the preparation for welding and cutting containers and piping that have held hazards substances
AWS F2.2-84	Lens shade selection
AWS F2.1-78	Recommended safe practice for electron beam welding and cutting
AWS F1.3-83	Evaluating contaminants in the welding environment: A sampling strategy guide

8.2.3. American Petroleum Institute (API)

API - RP2009	Safe practices in gas and electric cutting and welding
API - RP2013	Cleaning mobiles tanks in flammable or combustible liquid service
API-RP2015	Cleaning petroleum storage tanks
API R D 2201	Procedures for welding or hot tapping on equipment containing flammables

8.2.4. Occupational Safety and Health Administration (OSHA)

29CFR 1910	OSHA occupational safety and health standards

29 CFR 1926	OSHA Safety and health regulations for construction

8.2.5. Compressed Gas Association (CGA)

CGA C-4	Method of making portable compressed gas cylinders to identify the material contained
CGA E-1	Regulator connection standards
CGA P-1	Safe handling of compressed gas cylinders
CGA V-1	Compressed gas cylinder valve outlet and inlet connections

8.2.6. National Safety Council (NSC)

Fundamentals of industrial hygiene. 5th edition,

8.2.7. National Institute of Occupational Safety and Health (NIOSH)

NIOSH 78-138	Safety and health in arc welding and gas cutting
NIOSH 80-144	Certified equipment list (with supplements)

8.2.8. National Fire Protection Association (NFPA)

NFPA-50	Bulk oxygen systems at consumer sites
NFPA-51	Oxygen-fuel gas systems for welding and cutting
NFPA-51B	Cutting and welding processes
NFPA-70	National electrical code
NFPA-306	Control of gas hazards on vessels to be repaired
NFPA-327	Cleaning or safeguarding small tanks and containers

8.2.9. Deutsches Institut fur Normung (DIN)

DIN 31000	Safety design of technical products- general principle
DIN 31001	Safety design of technical equipment safety devices material requirement applications

8.3. Visual and optical testing environment

8.3.1. Cleanliness

The phenomenon of vision depends upon the amount of light reaching the eye, which depends upon and is affected by various factors such as distance, reflectance, brightness, contrast or the cleanliness, texture, size and shape of the test object. Cleanliness is an important requirement of visual tests as it is impossible to examine & obtain visual data of a test part covered with thick opaque layer of dirt. The dirt besides obstructing the vision can also mask the actual discontinuities with false indications. Maintenance of cleanliness avoids the hazards of undetected discontinuities.

8.3.2. Texture and reflectance

Reflectance is one factor affecting the amount of light reaching the eye. An easy approach to have the maximum possible reflected light during a visual inspection is to place the light source and your eye as close to the test surface as the focal distance allows. Similarly the magnifier should be held as close to the eye as possible to ensure the maximum light from the test area reaches the eye.

Reflectance and texture are related characteristics. While making lighting arrangements to enhance the test area, care should be exercised to avoid glare that masks the test area. For test surfaces such as highly reflecting or dull, special lighting arrangements are required to illuminate without masking. Glare can also be reduced by increasing the angle between the glare source and line of vision, dimming the light source or by increasing the background light in the area surrounding the glare source.

8.3.3. Lighting for visual tests

An important factor affecting visual tests is lighting. If appropriate lighting is not achieved, no amount of magnification is going to improve the image. The amount of light required for a visual test is dependent the type of test, the importance of speed and accuracy, glare and an inspector's vision capability. Inspector variables such as physiological processes, psychological state, working experience, health and fatigue while not affecting the system of light travel and image projection all contribute to the accuracy of a visual inspector.

Reflection and shadows from background sources such as walls, ceiling, furniture and equipment are important considerations. Reflectance from the surrounding environment is also a desirable requirement as it can provide diffuse lighting across the work piece. Expected reflectance values are: ceiling 80 to 90%; walls 40 to 60%; floors not less than 20%; dark benches and equipment 25 to 45%.

8.3.4. Light intensities

For a successful visual examination, the primary requirement for a light source (natural or artificial) is to be of adequate intensity and spectral distribution to stimulate the human eye. For practical purposes, the visible spectrum may be considered to be between about 380 nm at the beginning of the violet and 770 nm at the end of red. The eye, when completely dark-adapted, may be extended down to 350 nm or shorter, with a corresponding reduction in the longest wavelength perceived. Similarly an eye adapted to a higher level of light, the longest wavelength boundary may extend up to 900 nm.

For general visual testing, a minimum intensity of 160 lx should be used. A minimum intensity of 500 lx should be used for finely detailed tests. The value of minimum intensity is the one obtained for light source held within a specified maximum distance. Alternatively, a light measuring device such as a photocell or phototube must be used. Table 8.1 gives the respective distance for human light sources to obtain a minimum of 500 lx illumination.

8.3.5. Vision in the testing environment

The eye is a critical variable in visual tests because of variations in the eye itself as well as variations in the brain and nervous system. For the above-mentioned reasons, visual inspectors must be examined to ensure their natural or corrected vision acuity meets a particular code, standard specification, recommended practice or company policy. The frequency of testing required should also be provided however annual examination is common practice.

TABLE 8.1. SOURCE TO OBJECT DISTANCES

Light Source	Maximum Source to Object Distance (millimetres)
2D Cell flashlight	250
60W incandescent bulb	250
75W incandescent bulb	380
100W incandescent bulb	460

For near vision acuity examination, the use of Jaeger eye chart requires an examiner to read the smallest letters possible on a page of decreasing text size at a distance of 30 cm. Visual inspectors with corrected vision and those the using photo-darkening lenses can be problematic in situations where significant ultraviolet light is by present. e.g. under some fluorescent lights.

8.4. Visual safety recommendations

Applicable national regulations, codes standards and specifications should be consulted for safety recommendations.

9. APPLICATIONS OF VISUAL TESTING

9.1. Applications of visual testing during manufacturing processes

9.1.1. Applications of visual and optical tests in electrical power industries

The electrical power industry, including the nuclear industry is one of the largest users of sophisticated remote visual inspection (RVI) systems. The use of RVI confers major benefits when inspecting in hostile environments. Typical structures to be inspected could include Fuel rods, Lifting equipment and Containment vessel structure.

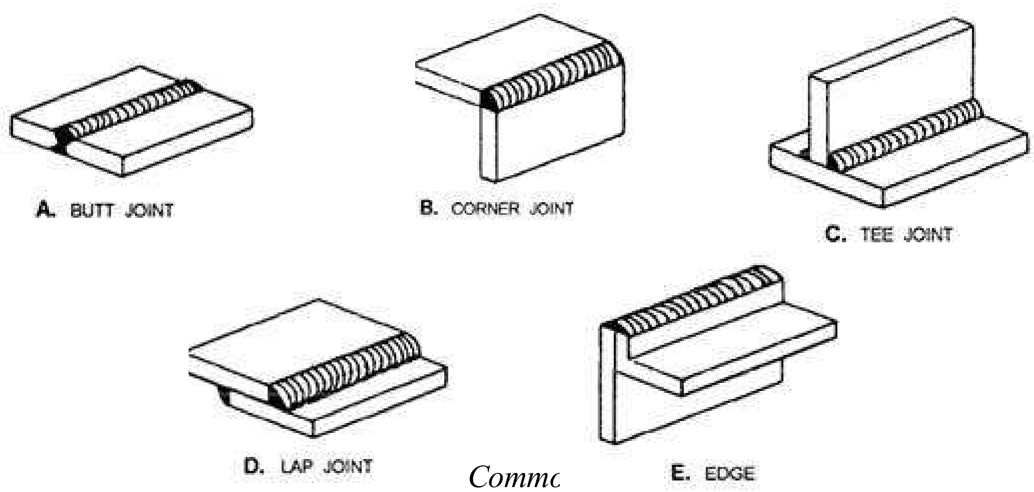
9.1.2. Joining processes

The five most commonly used basic metallurgical joint types include the butt, corner, edge, tee and lap joints (Fig 9.1). They are designed to produce either complete joint penetration or partial penetration joints depending on the particular application. The selection of a particular joint preparation depends on the load conditions (static, dynamic, impact etc.), material used, joint geometry and environmental factors surrounding the joint. Welded joints with complete penetration and fusion through the thickness of the base metal are equivalent or greater in strength than that of the base metal. Partial penetration, not fusing completely through the base metal generally does not offer an equivalent strength to the base metal.

Metal joints are formed through the processes i) Soldering, ii) Brazing, iii) Oxy-fuel gas welding, iv) Resistance welding, and v) Arc welding. Some other processes, including diffusion bonding and electron beam welding are also widely used in the industry. A brief description of the metallurgical preparing processes is given here.

9.1.3. Soldering

The soldering process involves joining materials by heating and using filler metal with a liquid state below 450°C (840°F) and below the solid state threshold, or solidus of the base metals. Solder is normally a non-ferrous alloy used to accelerate wetting and remove oxides.



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9.1.4. Brazing

Brazing joins materials by heating them to suitable temperature and by using a filler-metal with liquids above 450°C (840°F) and below the solidus of the base metal. Filler metals normally used for low carbon and alloy steels are silver alloys and copper zinc alloys.

9.1.5. Oxyfuel gas welding

Oxyfuel gas welding joins materials by heating with an oxy-fuel gas flame with or without the application of pressure and with or without the use of filler metal. The process normally uses acetylene gas as the fuel gas and pure oxygen instead of air. The oxyfuel gas welding is ideally used for thin sheets, tubes and small diameter pipes, as well as repair operations.

9.1.6. Resistance welding

The process includes two processes, namely, resistance spot welding and resistance seam welding.

In resistance spot welding an electric current is passed through the metal. Resistance to flow of electrical current heats the metal to welding temperature. The process is used to weld together two or more overlapping pieces. The current, electrode pressure and length of time the current flows controls the quality of a resistance weld. Resistance seam welding is a special application of spot welding involving a continuously rolling electrode.

9.1.7. Arc welding

Arc welding joins metals by heating with an electric current, with or without pressure and with or without filler metal. All forms of welds require a means of shielding the arc to block out harmful elements found in the atmosphere. The work piece serves as a circuit element. The other electrode can be a consumable or non-consumable material. An electric arc is generated between these two electrodes. Welding processes that use a non-consumable electrodes include carbon arc welding (CAW), plasma arc welding (PAW) and gas tungsten arc welding (GTAW). Consumable electrodes melt in the arc and are transferred across the arc to become deposited filler metal. Welding processes using consumable electrodes are shielded metal arc welding (SMAW), gas metal arc welding (GMAW), flux cored arc welding and submerged arc welding (SAW).

9.1.8. Visual tests of metal joints

The visual inspector performing weld inspection and is required to perform tasks in accordance with the relevant codes & standards at all stages of welding i.e. before welding, during welding and after welding. The respective test procedure plan against the respective weld preparation stages should be in accordance with the relevant codes & standards.

9.1.9. Acceptance standards

Acceptance criteria are stipulated in the code, standard or specification.

9.1.10. Recording and reporting of visual test results

The visual inspector should record all test results as required by the relevant codes & standards.

Specific visual inspection applications; pumps, valves, bolting, forged, rolled stock and casting

9.1.11. Visual testing of pumps

For carrying out visual testing, dismantling of pumps should be done following the manufacturers instruction manual. During the dismantling process the following tasks may be performed:

- Check impellers visually for signs of erosion and cavitation damage.
- Diffuser elements for pumps to be visually inspected for erosion and cracks.
- Sleeves and rings should be tested to verify their dimensions to be within tolerance limits.
- Check the pump shaft to see its straightness by taking a dial test indicator reading.

- Shaft bearing journals should be checked for correct finish.

- Bearing surfaces should be inspected for smoothness and wear.

- Pump casing should be visually inspected for erosion and washout. Casing points should be checked for erosion and effective flange sealing.

- All sleeve bearings should be visually inspected for pitting, finish, scoring and dimension.

9.1.12. Visual testing of valves

For visual inspection purposes, before dismantling a valve, the inspector must know the type of valve, its function, temperature range, pressure, how long it has been in service and maintenance history. Dismantling of valves should be done following the manufacturers instruction manual. A brief description of some of the tasks that may be performed during visual inspection of some types of valves is outlined as follows:

9.1.12.1. a) ___Testing of gate valves

i) Inspect sealing surfaces of the wedge and body for evidence of physical damage i.e. presence of cracks, scratches, pits and indentations.

ii) Guide surfaces (stuffing box and yoke area) are to be inspected for evidence of wear or galling.

iii) Check stem-to-wedge connection for wear or corrosion. Excessive wear, allowing the stem to turn or to become disengaged, renders the valve inoperative. Check stem-to-stem nut threads for excessive wear (Fig. 9.2).

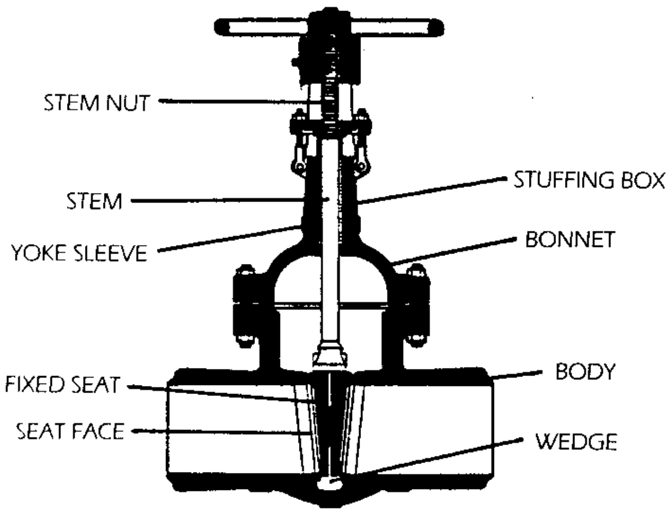


FIG. 9.2. Bonnet gate valve.

9.1.12.2. Testing of plug and butterfly valves

In butterfly valves the following may be inspected (Fig. 9.3):

i) Seating surface of the disk for evidence of physical, damage, wear or corrosion. The horizontal plate at the centre line is the most vulnerable point.

ii) Plastic seal or liner for evidence of damage. Check alignment of seal and disk when closed.

iii) Bearing surfaces and position stops for excessive wear.

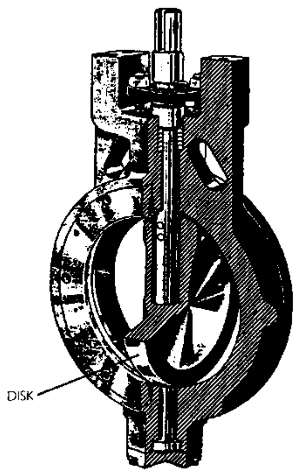


FIG. 9.3. Butterfly valve.

9.1.12.3. Visual testing of bolting

Visual testing of bolts is normally done to detect the presence of cracks, wear, corrosion, erosion or physical damage on the surface of components (Fig. 9.4).

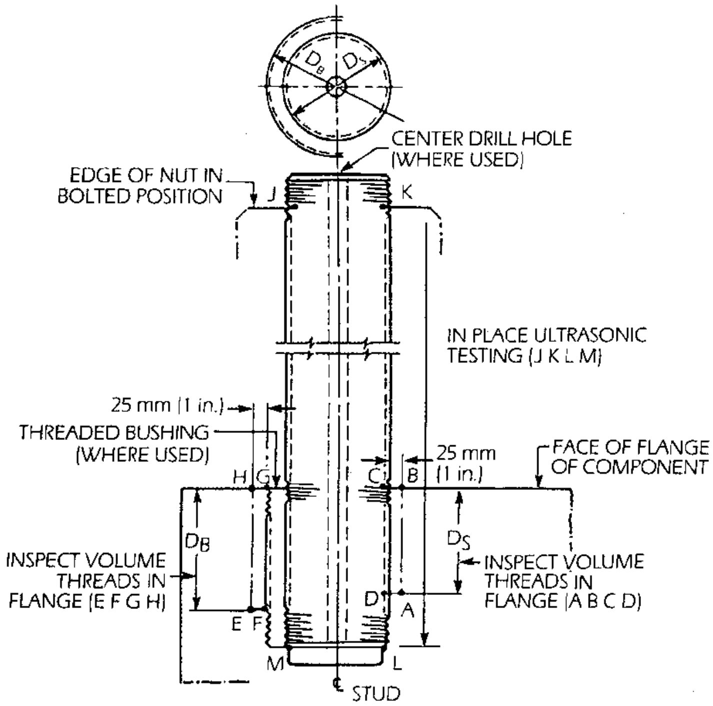


FIG. 9.4. Non-destructive testing of bolting.

The tools necessary for carrying out direct visual inspection include: steel rules, micrometers, Vernier callipers, depth micrometers, thread gauges and magnifying glasses.

9.1.12.4. Visual tests for forging discontinuities

Forgings are inspected visually to detect bursts, laps and cracks. It is helpful for the inspector to use a 5X to 10X magnifier during visual inspection. A burst, normally an internal discontinuity, shows up during secondary processing of a large forging.

9.1.12.5. Visual test for rolled stock

Visual testing must be performed before any fabrication operation that may hide a portion of the material is performed. In addition to magnifiers (5X to 10X), a mirror is useful for visual testing of rolled shapes with obstructed areas. The visual inspector should look for the following discontinuities:

i) Processing discontinuities that include tear and crack exhibit characteristics similar to some forging discontinuities including an oxidized, scaly interior.
ii) Laminations - normally are parallel to the rolling direction and appear on the edges of the shape (plate or pipe).
iii) Seams, stringer and cracks - they can appear anywhere on a rolled product. Seam & stringer follow the direction of rolling. Cracks caused by gas holes reaching the surface of the component during processing also follow the direction of rolling.

9.1.12.6. Visual testing of castings

Casting defects include entrapped gas, porosity, and blisters. Entrapped gas, if it reaches the surface, is revealed by visual examination. It may take the form of large pockets, pinhole porosity, or a blister-like thin skin of metal covering such a gas pocket. It is caused by many factors such as improper mould shape, melting practice, pouring practice and moisture.

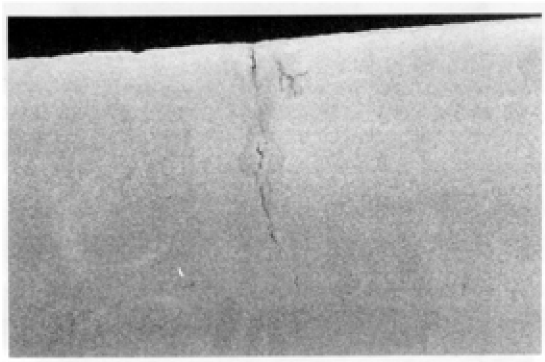
(a) Shrinkage

Shrinkage is caused by contraction of metal during solidification, generally because of use of improper risers and improper pouring procedures. The defect shows up as a depression in a casting wall, which often has a jagged dendrite appearance.

(b) Hot and cold tearing cracking

These are forms of cracks that may or may not surface. Hot tears are generally more widely opened and result from contraction during solidification if movement is restricted. Hot cracks are caused by the stress after solidification and during cooling. They are generally tighter cracks than hot tears (Fig. 9.5).

a)



b)

FIG 9.5. (a) *Illustrates hot tearing in steel castings (b) Section through a hot tear, in steel casting.*

(c) Incomplete castings

This relates to the conditions and various reasons for castings to fail to completely fill the mould. The following flaws arise:

i) Misrun or short pour which results due to failure of molten metal to fill the mould cavity completely.

ii) Cold shut, when two streams of metal within a casting are being poured and fail to fuse properly a round like crack or seam results.

iii) Scars that occur as a result of entrapped gas preventing complete filling of the mould.

iv) Plate which is the material formed when metal fills a scar but does not fuse. Fig. 9.6 represents flaws arising due to incomplete casting.

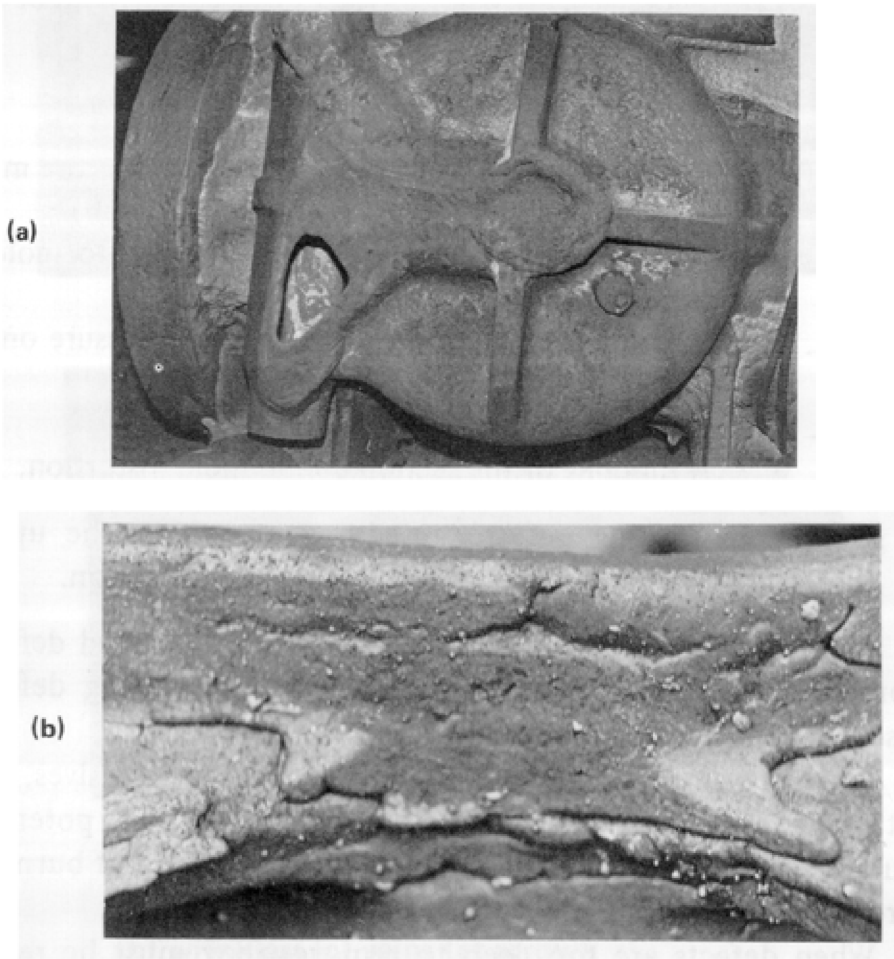


FIG. 9.6. Incomplete castings: (a) a short pour; (b) a run out.

9.1.12.7. Applications of visual and optical tests in the transportation industries (surface and air)

(a) Optical tests in automobile industries

Use of machine vision technology is being used by the automotive industry successfully for the following applications:

i) The appearance of metallic finishes used in the automotive industry is affected by their colour and their visual texture. Ideally the texture obtained should be of uniform finish. The texture analysis plays an important role in automatic visual testing of surfaces. The objective of texture analysis programme is to find the characteristics of the metallic finish texture. These texture features are then used to grade the uniformity of finish samples.

ii) Manufacturers that refurbish brake shoes are faced with difficulties in the sorting process for two reasons:

   a) certain models are identical in all respects except for specific, often very small details.

   b) because of wide manufacturing tolerances, brake shoes can vary significantly.

Errors thus arising due to assigning wrong model numbers can be very costly in subsequent processes, including cleaning and recovering the shoes with a new lining. Machine vision helps in sorting brake shoes by loading into a conveyor that transports them through a measuring device and an optical contour detection station. The back-lighted parts are analyzed by special purpose software that extracts only the significant characteristics from the image. These data are combined with the width measurement to determine the model number. There are several hundred brake shoe models in use and these can differ from each other in minute details, while identical models can vary significantly, depending on the manufacturer. Sorting becomes further complex when brake shoes from other cars are modified to fit current vehicles.

The optical recognition system is virtually error-free, and performs the inspections at a rate of 4000 units per hour.

(b) Optically aided visual testing of aircraft structure

Optically aided visual testing is a viable and economical method that can be used to monitor aircraft structural integrity. Optically aided visual tests include the use of magnifiers and borescopes.

Some of the typical examples of optically aided visual tests used by airline maintenance personnel to ensure the structural integrity of aircraft are as follows:

(c) Inspection of spoiler torsion bars

Spoiler torsion bars are borescopically examined for pitting leading to failures due to stress corrosion cracking. Prior to visual examination, sealant and primer are removed from the bore and it is visually examined for corrosion pits using a 70 degree or 90 degree borescope (Fig. 9.7).

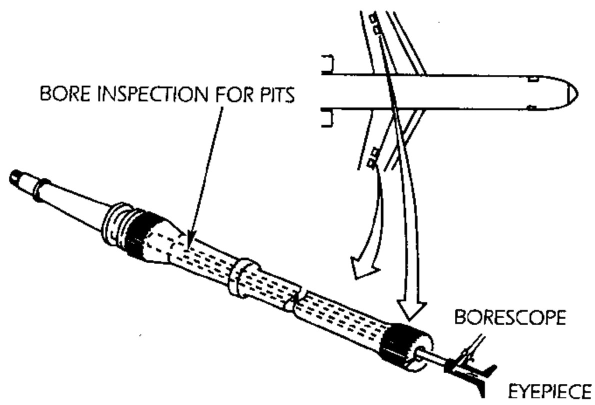


FIG. 9.7. Borescope inspection of spoiler torsion bar.

(d) Slat drive mechanism bell crank

Failure in these components is caused by fatigue cracks that initiated at the bell crank-to-collar attachment holes (Fig. 9.8). With the bell crank installed on the aircraft, the access to crack locations is very poor, and as such the only option of inspecting the job is by using right-angle flexible borescope with deflecting tip, 5mm in diameter and about 1m in length. Before inspection, the bore of the bell crank is cleaned with solvent to remove grease (Fig. 9.8).

9.2. Interface of visual testing with other non-destructive testing methods

Almost all non-destructive testing methods can be described as visual testing methods since the data recorded is interpreted visually. This linkage between visual and other non-destructive methods is greater in certain cases. The discussion to follow is an illustration of such a linkage for the respective non-destructive testing methods.

Aside from the evaluation and interpretation of results, a visual inspection is normal practice prior to the implementation to the majority of non-destructive tests.

9.2.1. Visual aspects of leak testing

Leak Testing is done visually, aurally or electronically. Leak testing method is carried out by detecting a tracer medium a `gas`, or a liquid that has escaped from the confinement. The visual part of the typical leak test is that of determining the presence and location of leakage. The extent of leakage and its effect on fluid flow can be determined by visual observation.

9.2.2. Visual aspects of liquid penetrant testing

The evaluation and interpretation of liquid penetrant indications is a direct function of visual inspection. Visual inspections are also carried out to monitor the penetrant process.

9.2.3. Visual aspect of magnetic particle testing

The evaluation and interpretation of magnetic particle indications is a direct function of visual inspection.

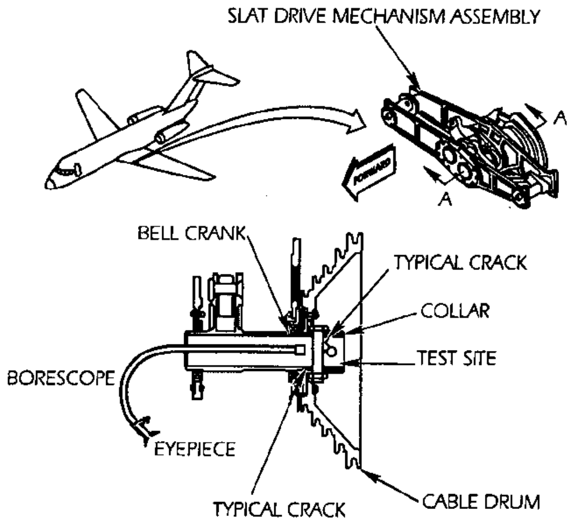


FIG. 9.8. Flexible borescope inspection of the slat drive bell crank.

9.2.4. Visual aspects of radiography

The evaluation and interpretation of radiographs is a direct function of visual inspection. As radiographs are viewed under subdued lighting conditions, the principles of eye adaption, glare minimisation and masking must be applied.

9.2.5. Visual aspects of ultrasonic and eddy current testing

Visual aspects of ultrasonic and eddy current testing are generally confined to viewing and interpretation of digital displays, which include a requirement for the ability to discriminate colour and contrast.

9.3. Applications of photography in visual testing

9.3.1. Photographs as a permanent record of visual testing

In visual testing a permanent visual record is often needed for engineering purposes, personnel training, failure analysis and crack growth monitoring. Photography is most practical and least expensive way to preserve visual test result permanently. The permanent records of test, makes it possible to subsequently review, scrutinize and evaluate a discontinuity. Photographs can be used as reference documents.

9.3.2. Photogrammetry

Photogrammetry is the science of obtaining quantitative measurements of physical objects through process of recording, measuring and interpreting photographic images. Close range photogrammetry involves camera-to-object distances less than 30 m.

Most of the close range applications, involves taking a pair of photographs with the camera oriented normal to the object at a known distance. By viewing this pair of stereo photographs through a stereoscope, a three-dimensional image of the object is reconstructed.

Another way of reconstructing the three-dimensional image of the object is of photographing the test object from two points analogous to the location of the two eyes. If these pictures are then viewed, left picture with left eye and right picture with right eye, the object appears again in three dimensions (Fig. 9.9).

9.3.3. Stereo photogrammetry applied to measurements of furnace components

The objective of measuring parallax difference between two object points is to develop the contour or shape of a surface so that information on deformation, relief (contour) or movement of the component can be determined. Parallax difference between corresponding points on stereo photographs can be measured by means of a parallax bar.

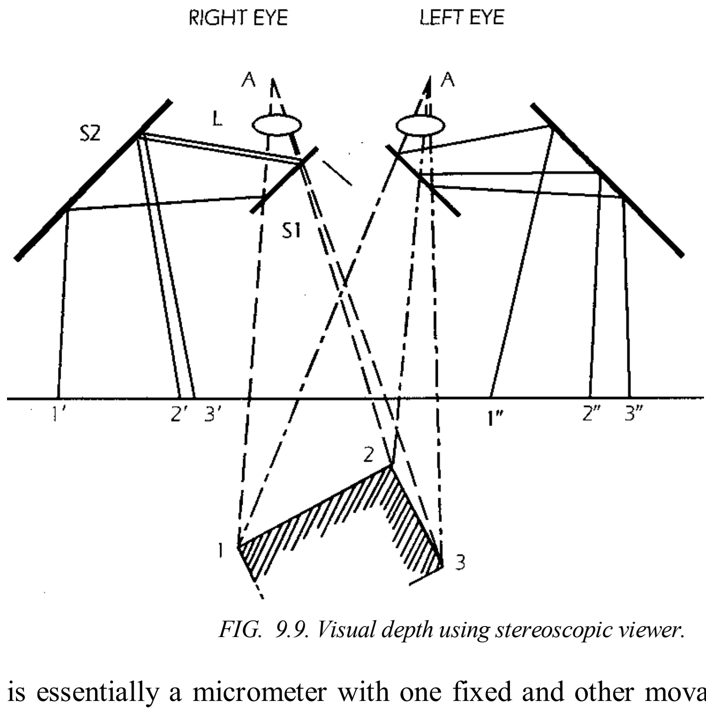


FIG. 9.9. Visual depth using stereoscopic viewer.

The parallax bar is essentially a micrometer with one fixed and other movable measuring mark on a glass reticule. After appropriate positioning under the stereoscope, the parallax bar is placed on the photographs, aligning the two reference plates on the parallax bar to exactly coincide with one point on the two photographs. As viewed through the stereoscope, when this condition is achieved, both marks on the parallax bar appear to fuse together into one point, apparently floating into space above the model of the object. If two points of different and known elevation can be identified in a stereo model, their difference Δp is measured by:

$$c = \frac{h^2}{f \times b} = \frac{\Delta h}{\Delta p} \qquad (9.1)$$

where

h = the object-to-lens distance

f = focal length of the camera lens

b = the distance between exposure stations or camera bases; and

Using conventional and readily available photogrammatic cameras and plotting equipment, sufficient accuracy is attainable to measure distortions and deformations associated with creep and bulging of components such as furnace tubes.

9.4. Visual testing of ceramics

Among the non-destructive testing methods such as liquid penetrant, radiographic and ultrasonic techniques used for detection of discontinuities in the ceramic materials, visual methods are also being used for this purpose. The text to follow describes in brief, the role of visual methods for the inspection of specific jobs made of ceramic materials.

9.4.1. Visual tests of injection molded turbine blades

Turbine blades from aerospace-engines undergo thermal and mechanical loading during service and thus there is a strong requirement to detect minute cracks before they can propagate further. Ceramic blades of silicon nitride and 6% glass are inspected in particular for surface breaking cracks visually using an optical magnification of 5X to 40X. Visual tests can also be used for detection of pores in thick sections of such turbine blades.

9.4.2. Automatic testing of thin ceramic components

Thin ceramic pre-fired materials are used in radio-frequency filters and as insulation in capacitors. In such materials, minute but critical discontinuities that can be missed by normal visual inspection are discovered using a neon light source in a reflecting chamber. The light intensified in this chamber, is directed through a slot onto the ceramic wafer. The light transmitted through the discontinuities in the test object is sensed by photocell and amplified. The amplified signal is applied to the logic circuit that in turn activates an electromechanical marking system and count discontinuities. Fig. 9.10 is an illustration of automatic optical system used to detect discontinuities in ceramic wafers.

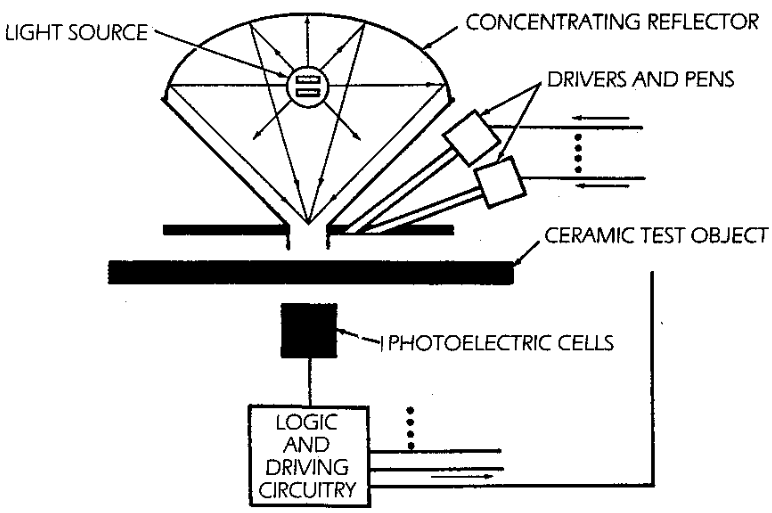


FIG. 9.10. Automatic optical system used to detect discontinuities in ceramic wafers.

9.5. Visual testing of threads in oil industry tubular goods

Tubular products such as casing and tubing threads, used in the oil fields are referred to as oil industry tubular goods (OITG). The terminology "Casing" applies to many strings of pipe that are used to line the hole during and after drilling. This pipe serves many useful purposes such as protecting the hole from collapse, guiding the fluid out of the hole and keeping the oil well fluids out of the water table. The term tubing string is referred to as the production string. Oil or gas comes and is brought to the surface through this tubing. Visual testing of casing and tubular products is of vital importance before the assembly of the down hole structure of an oil well.

9.5.1. Requirements and visual testing of threads

Visual Testing is carried out to look for the presence of corrosion damage caused by handling and other defects such as manufacturing faults, which can affect the ability to seal.

9.5.2. Use of a profile gauge

For threads that exhibit an excessive narrowness of thread width, a thread profile gauge is used to detect threads that are shaved, stripped or worn. The profile gauge can help in detecting conditions such as improper thread height and steps on the thread flank or roots, leading to thread failure in service. Fig. 9.10(a) gives an illustration on the use of the profile thread gauge.

9.5.3. Visual testing of composite materials

Visual testing is utilised as a quality control technique during the manufacture of the composite material. The anomalies to be identified are: excessive wrinkles, holes, gaps between adjacent plies, surface voids, cracking, buckling, entrapped release film, etc. This examination is normally done by the un-aided eye i.e. without use of optical magnification by the inspector.

The equipment or tools required for performing the visual test include light sources and wetting agents such as alcohol and dyes. The use of magnifiers with magnification of 5X to 10X is also beneficial. The procedure used for detection of voids & edge discontinuities is to apply alcohol as a penetrant. Areas with discontinuities will show up as dark marks. For greater contrast and visibility ink/dye is used.

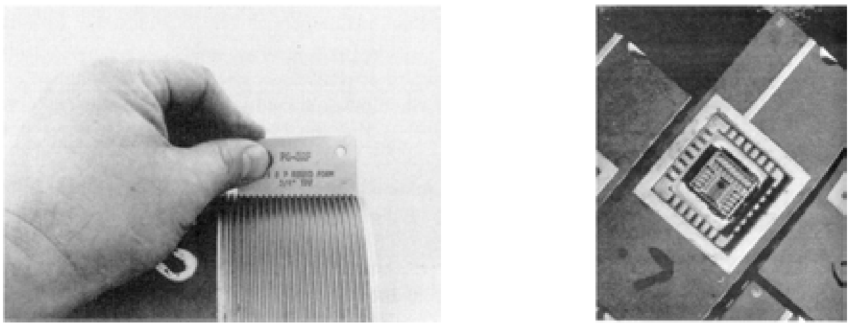
9.6. Visual testing of microelectronics components

The electronic industry relies heavily on visual testing and electrical (performance) testing of discrete electronic components and complex electrical assemblies to determine electrical system reliabilities. Microelectronics, a miniaturization of electronic circuits, has resulted in the design and development of integrated circuits and micro-chips which can contain thousands of transistors. These devices have helped in attaining small compact electronic devices with greater reliability, as typically shown in Fig. 11 (b). Visual testing requirements, however, have also become more stringent and demanding to achieve the desired reliability in their operation.

Visual inspection of microelectronic components is typically carried out by personnel with specialist electronic knowledge or increasingly by automated computerised visual systems. Typical inspections include: Quality/accuracy of soldering, correct assembly, contamination and board cracking.

9.7. Visual and optical testing in the metal industry

Visual tests are widely used for in-process and final product inspections. Visual inspection can instantly perceive many material characteristics such as shape, colour, shades, speeds, perspective etc. and recognize patterns. Visual tests are performed in the metal industry for a wide range of applications. Typical examples include:



a) *b)*

FIG. 9.11 (a) Handheld pipe thread gauge, (b) Typical ceramic packed IC.

i) Effect of stress concentration and wear.
ii) Contact stress fatigue.
iii) Cavitation fatigue.
iv) Corrosion.
v) Stress corrosion cracking.
vi) Corrosion fatigue fracture.
vii) Elevated temperature discontinuities.
viii) Microscopy for structure of metals, phase diagrams, effect of deformation and heat treatment, phase transformation, hardenability.
ix) Surface inspection in manufacturing processes for hot slabs, large section steel products, hot and cold strip steel, hot rolled steel.
x) Surface measurements including gloss, reflectance, surface roughness, and surface properties related to surface roughness.

9.8. In-service inspection

Protection of health and safety of the public is a number one priority throughout the world in plant operation. During the service life of plant, equipment and components are liable to be exposed to various degradation mechanisms whose single or the combined effects cannot be predicted with accuracy. Varying environments will result in changes of material performance due to ageing, embrittlement, fatigue and formation and/ or growth of discontinuities.

It is thus a necessary requirement to examine the systems and components of the plant for possible deterioration, so as to judge and ensure the continued safe operation of the plant. Emphasis is placed on examining critical systems due to their potential to cause harm in the event of a plant failure. Such examinations performed during the operating life of a plant are called as in-service inspection (ISI).

ISI is relied upon to detect and characterise degradation before it can pose a threat to safety. In addition to preventing incidences of critical component failures regular testing supplies plant owners with accurate information necessary to support strategic decisions regarding repairs, replacements, degradation, life extensions, license renewal, efficiency improvement and personnel safety.

9.8.1. ISI of plants in the light of call up maintenance card

Call-up maintenance card is a work request made by the technical division of any plant to the respective heads regarding carrying out in-service inspection through preventive maintenance and surveillance checks.

9.8.2. The surveillance programme

In-service inspection and preventive maintenance are necessary compliments to a surveillance programme. Surveillance includes planned activities carried out to verify that the plant is operated within the prescribed operational limits and conditions and to detect in time any deterioration of structure, systems and components that could result in an unsafe condition.

These activities can be classified as:

i) Monitoring plant parameters and system status.

ii) Checking and calibrating instrumentation.

iii) Testing and inspecting structures, systems and components.

iv) Evaluating the results of items 1 to 3.

9.8.3. Preventive maintenance measures

Preventive measures are those that are taken to avoid accidents, and mitigating measures are those that decrease the adverse consequences. Essentially, preventive measures are the set of design and operating rules that are intended to make certain that the plant is operated safely, while mitigating measures are systems and structures that prevent accidents that do occur from proceeding to a catastrophic conclusion.

Displacement measurement of moving parts of components i.e. pumps, compressor and motors etc.

Stroboscopic visual inspection systems can be used to visualise the displacement of rotating assemblies.

9.8.4. Optical vibration monitoring

9.8.4.1. Static measurement

Vibration measuring instruments based on static measurement are categorized as 'proximity probes'. These instruments measure the distance of the vibrating mass from a stationary component. The three most common ways of measuring the distance are shown in Fig. 9.12 (a-c). In Fig. 9.15 (a), a LVDT (Linear Voltage Differential Transducer) is shown. One end is attached to the stationary member and the other to the vibrating one. The relative position of the two ends is made proportional to the voltage of a magnet coil system. Changes in the voltage are proportional to the motion of the vibrating member. An integrator (2) is provided in order to measure the vibration amplitude y_{max} rather than the motion of y(t). A voltmeter connected before the integrator, due to its inertia will not be able to follow the motion of y(t). It will thus indicate the average voltage which will be equal to the static relative displacement of the two members.

In Fig. 9.12 (b), the capacitive probe is shown. Two small plates are placed at some distance from the vibrating surface. The capacitance will be proportional to the distance. The average and maximum capacitance fluctuation will again be proportional to the static displacement and vibrating amplitude respectively. In Fig. 9.12 (c), the inductance probe is shown. An electromagnet excited by a high frequency voltage is placed close to the vibrating member. As the gap fluctuates, the inductance of the coil changes due to the change of the air gap or the change in eddy currents in the vibrating member. Measurement of the coil inductance, will yield the static displacement and vibration.

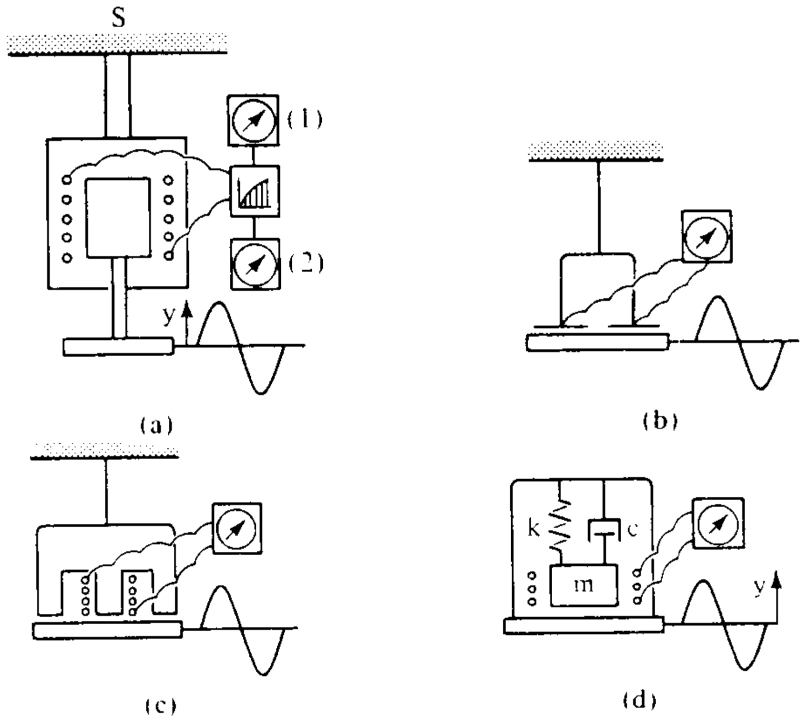


FIG. 9.12. Static & dynamic measurement.

9.8.4.2. Dynamic measurement

'Riding probes' are form of vibrating measuring instrument categorized as dynamic measuring instruments. These probes are mounted on the vibrating member and measure absolute vibration with respect to the inertial coordinate system. A mass m is supported on the instrument base by a spring k and a damper C. The instrument is placed on the vibrating member, with vibration of y = y (t), Fig. 9.12 (d). The mass m moving in a coil produces a voltage which is proportional to the velocity and the relative motion between the seismic mass m and the cage. This type of instrument is called a 'velocity probe'. In other type of instruments, the spring k is really a piezoelectric crystal which gives a voltage proportional to its deformation. This is called an 'accelerometer'.

10. GLOSSARY OF TERMS

Black body	A theoretical object that radiates more total power of any wavelength than any other source at the same temperature.
Black light	A term used for ultraviolet radiation.
Blind spot	Part of the eye's retina without any rods or cones, where the optic nerve enters the eye.
Blue hazard	Overheating damage to the retina caused by exposure to high frequency visible light.
Borescope	A device of lenses and a light source for the inspection of inaccessible cavities. The word originates from its use in inspection of gun bores.
Candela	The SI unit of luminous intensity.
Colour	The sensation produced at the human eye by rays of light of different wavelengths.
Colour blindness	The inability to assess all the individual wavelengths of white light correctly.
Colour temperature	The temperature of a black body which radiates predominantly the same wavelength as the source being described.
Cone	A receptor in the retina which dominates response when the light level is high.
Contrast	The difference between the amounts of light reflected or transmitted by an object.
Dark adaption	The process by which the retina of the eye adapts to light of less than 0.034 candelas per sq meter.
Depth of field	The distance over which the image is in focus.
Diffraction	The phenomenon in which waves spread out beyond the geometric shadow of an obstacle.
Directional lighting	Lighting from a preferred direction or angle.
Direct viewing	Viewing an object in the immediate location.
Endoscope	A flexible device for inside viewing or inspection.
Far vision	Viewing an object beyond arms length.
Fibre optics	The transmission of light through fibres of glass, quartz, or plastics.

Field of view	The range of area where things can be seen through lens or aperture.
Glare	Excessive brightness which interferes with clear vision and judgement.
Grey body	A radiator whose spectral emissivity is uniform for all wavelengths.
Hue	The perception of colour which discriminates different colours as a result of their wavelength.
Illuminance	The density of luminous flux measured in lux (SI unit).
Incandescent	Emitting visible radiation as a result of heating.
Infrared	Electromagnetic radiation in the wavelength range 730 nm to 1000000 nm approximately.
Interference	Interaction between two or more waves of the same frequency emitted from coherent sources.
Laser	An acronym - Light Amplification by the Stimulated Emission of Radiation.
Lumen	SI unit of luminous flux measurement equivalent to candela times steradian.
Luminance	The measure of the brightness of a surface. Measured in candelas per square metre.
Lux	SI unit for illuminance. Equivalent to lumens per square metre.
Machine vision	An automated system which acquires, processes and analyses images.
Monochromatic	Light of only one wavelength or, in practice, a very narrow band of wavelengths.
Near vision	Vision of objects generally within arms length.
Near sightedness	Adequate vision acuity to view objects within arms length.
Peripheral vision	The seeing of objects outside the central vision field.
Phase contrast	A technique in microscopy where phase differences are converted to differences of light intensity, thereby giving contrasts in the image wherever a change in thickness or refractive index occurs.
Photochemical	A chemical which changes when exposed to light.
Photoconductive cell	A cell using photoconductive material, often cadmium sulphide, between electrodes.

Photoconductivity	The property of certain materials to change their electrical conductivity under the influence of light.
Photodiode	A semiconductor diode fitted with a small lens which can focus light on the p-n junction. They can be used as light sensors.
Photometry	The science and practice of measuring light.
Photopic vision	Vision adapted to daylight. Also known as Foveal vision and light adapted vision.
Phototransistor	A 3-electrode photosensitive semiconductor device.
Pixel	A light point on a screen of a digital image.
Polarisation	Non-random orientation of electric and magnetic fields of electromagnetic waves.
Psychophysics	Interaction between vision performance and the physical or psychological factors.
Radiance	The luminous flux radiated per unit area. Measured in lumens per square metre.
Radiation	The emission of energy as electromagnetic waves or particles.
Radiometer	An instrument for measuring radiant power of specified wavelengths or frequencies.
Reflectance	The ratio of reflected wave energy to incident wave energy.
Refraction	The change in direction of a wave front which occurs when the wave travels through a material boundary.
Resolving power	The ability of vision or other detection systems to separate two points.
Rods	A receptor in the retina that response to low levels of luminance. They are not colour sensitive.
Scotopic vision	Dark adapted vision using only the rods of the retina. Also known as parafoveal vision.
SI units	Internationally system of units.
Spectral response	The comparative response to light of constant intensity but different wavelengths.
Spectroscope	General term for an instrument which produces or records different wavelengths of light.
Spectrum	Representation of radiant energy in adjacent bands.

Specular	Mirror like.
Specular reflection	When reflected and incident waves form equal angles.
Ultraviolet radiation	Electromagnetic radiation between 100 and 400 nm between visible light and x-rays.
Vision	Perception by eyesight.
Visual acuity	A term used to express the spatial resolving power of the eye. It is measured by determining the minimum angle of separation which has to be subtended at the eye between two points before they can be seen as two separate points.

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