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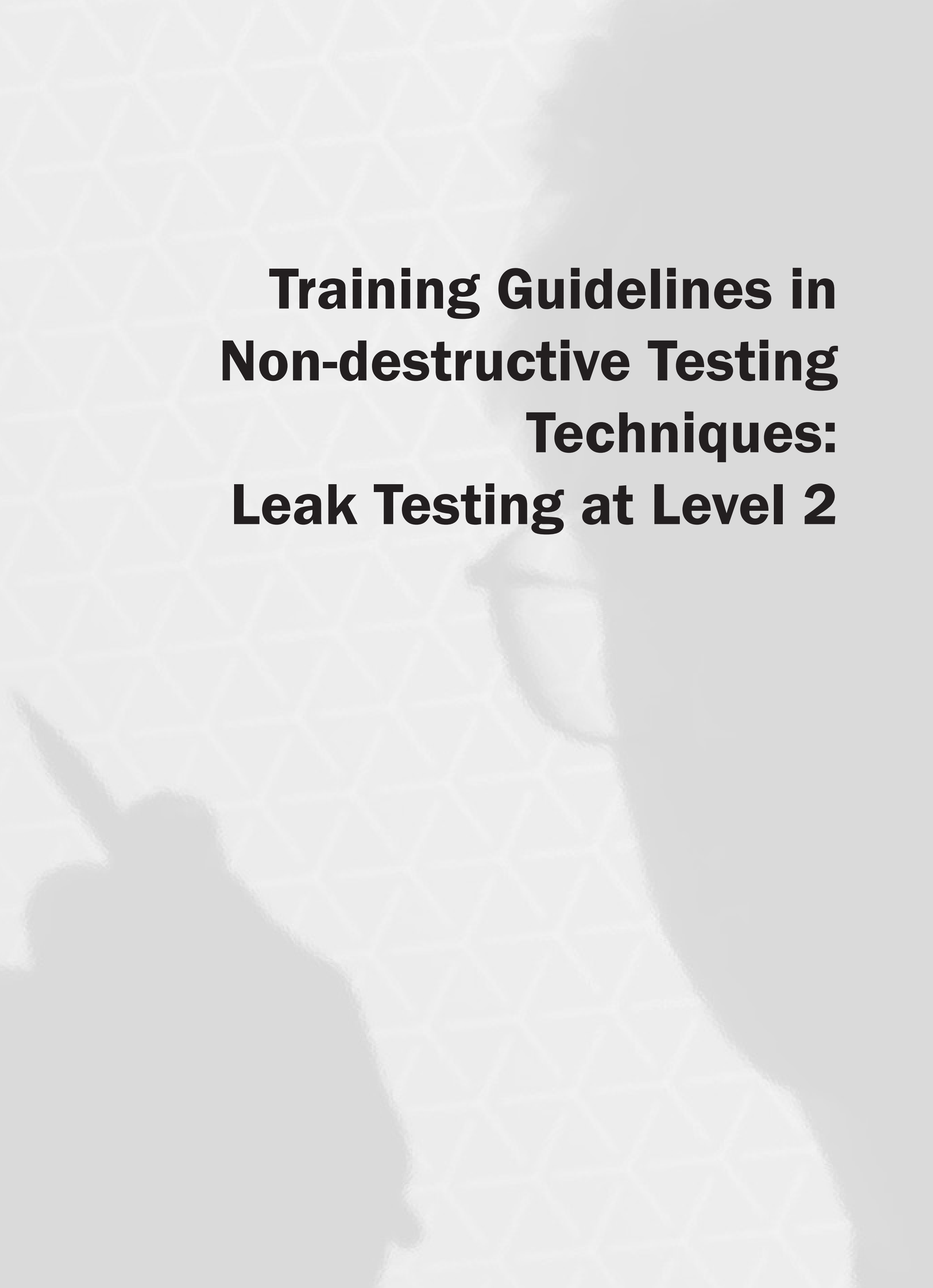

Training Guidelines in Non-destructive Testing Techniques: Leak Testing at Level 2

VIENNA, 2012

TRAINING COURSE SERIES 52

Training Guidelines in
Non-destructive Testing Techniques:
Leak Testing at Level 2

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TRAINING GUIDELINES IN NON-DESTRUCTIVE TESTING TECHNIQUES: LEAK 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 standards for quality assurance for safe operation of nuclear and other industrial installations. The IAEA successfully executed a number of programmes, including technical cooperation projects (national and regional) and coordinated research projects (CRPs), in which NDT was an important part. Through these programmes, a large number of personnel have been trained in Member States, leading to the establishment of national certifying bodies responsible for the training and certification of NDT personnel. Consequently, a state of self-sufficiency in this area of technology has been achieved in many Member States.

All along there has been a realization of the need to have well established training guidelines, in order to orient the IAEA experts who were involved in training and certification programmes, and to achieve some level of international uniformity and harmonization of training materials and certification processes, and consequent competence of NDT personnel.

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

The next logical step after finalizing the syllabi was to compile textbooks and training manuals in accordance with the syllabi. Manuals on liquid penetrant testing, magnetic particle testing, radiographic testing, ultrasonic testing and eddy current testing have already been published in the IAEA's Training Course Series. These play a vital role for training and certification of NDT personnel throughout the world.

Compilation of the present book is a continuation of that effort. The first draft was developed with the help of experts from the Canadian Institute for Non-Destructive Evaluation (CINDE). The introduction to basic NDT methods, materials, manufacturing processes and defects, and quality assurance common to all the NDT methods, has been adapted from previous publications in the Training Course Series.

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

EDITORIAL NOTE

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1. INTRODUCTION

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

1.1.1. Definition and importance of NDT

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

(a) Raw materials which are used in the construction of the product.

(b) Fabrication processes which are used to manufacture the product.

(c) Finished product before it is put into service.

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

(a) It increases the safety and reliability of the product during operation.

(b) It decreases the cost of the product by reducing scrap and conserving materials, labour and energy.

(c) It enhances the reputation of the manufacturer as producer of quality goods.

(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. Types of 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.

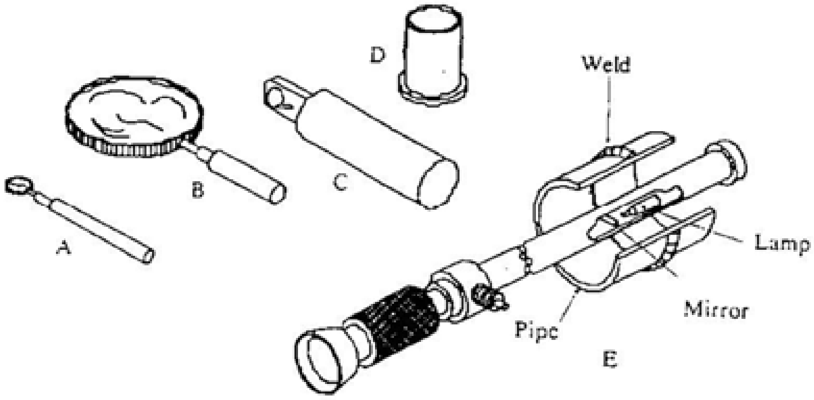


FIG. 1.1. Various optical aids used in visual inspection:
(A) Mirror
(B) Hand magnifying glass (magnification usually 2–3X).
(C) Illuminated magnifier; field of view more restricted than D (magnification 5–10X)
(D) Inspection glass (magnification 5–10X)
(E) Borescope or intrascope with built-in illumination (magnification 2–3X).

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
(c) Cost is low
(d) Less training
(e) On-line testing possibility
(f) Permanent record available

Some of the limitations of visual testing are as follows:

(a) Can detect only surface defects
(b) Difficulty in sizing depth of defects

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 penetrant needs to be dissolved in a solvent to remove it from the component surface.

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

(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:

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

The limitations of liquid penetrant testing are:

(a) Test surface must be free of all contaminants (dirt, oil, grease, paint, rust, etc.).
(b) Detects surface defects only.
(c) Cannot be used on porous surfaces and is difficult to use on very rough surfaces.
(d) No permanent record.

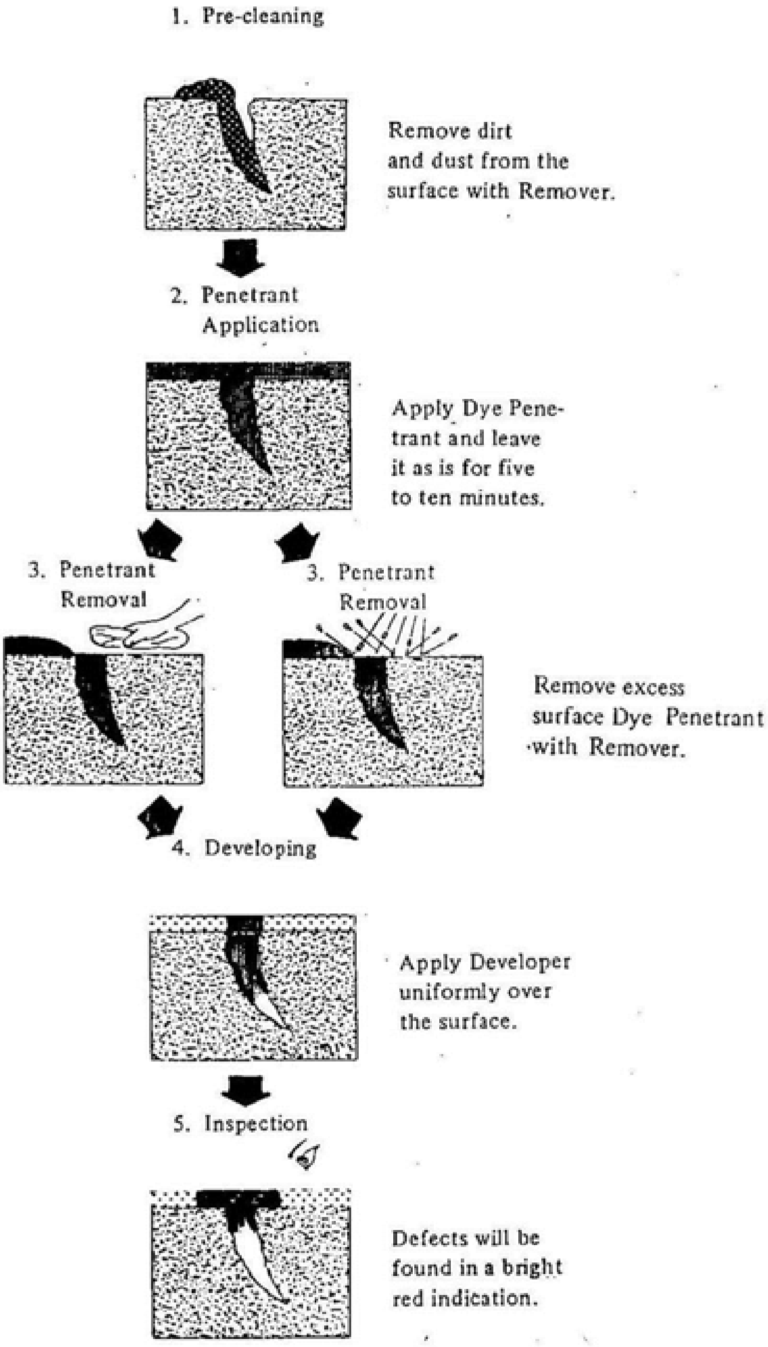


FIG. 1.2. Different stages of liquid penetrant testing.

1.1.2.3. Magnetic particle testing (MT)

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

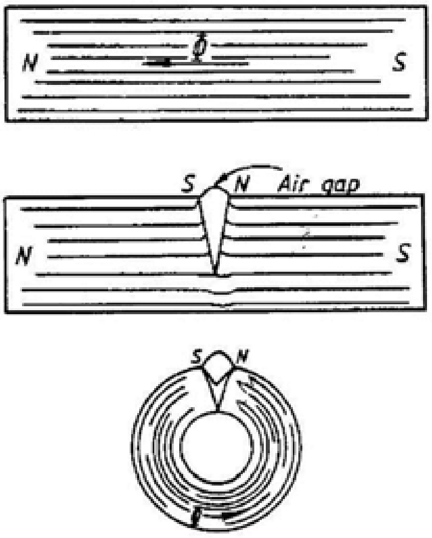


FIG. 1.3. Basic principle of magnetic particle testing.

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

(a) Direct current techniques: These are the techniques in which the current flows through the test object 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 object either by the use of a permanent magnet or by flowing current through a coil or a conductor. These techniques are shown in Fig. 1.4 (d–g).

Advantages of magnetic particle testing:

(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.

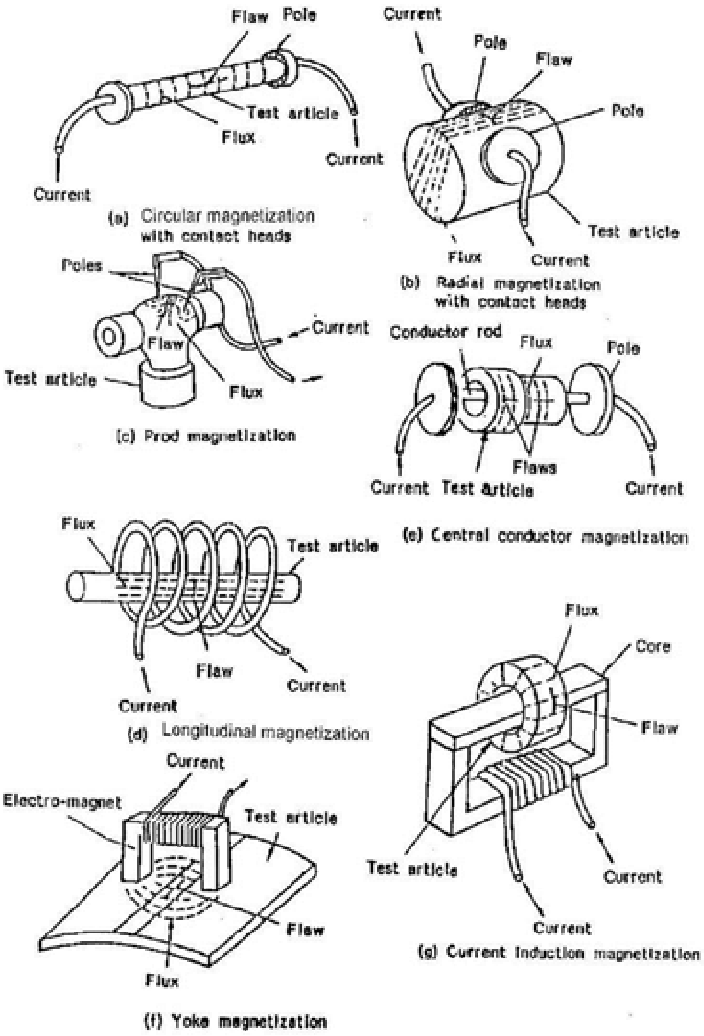
The limitations of magnetic particle testing include the following:

(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.



(a) Circular magnetization with contact heads

(b) Radial magnetization with contact heads

(c) Prod magnetization

(e) Central conductor magnetization

(d) Longitudinal magnetization

(g) Current induction magnetization

(f) Yoke magnetization

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

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.

The ET method may be used for:

(a) Detection of defects in tubes.

(b) Sorting materials.

(c) Measurement of thin wall thickness from one surface access.

(d) Measurement of thickness of thin coatings and case depth.

(e) Non contact testing of hot defects.

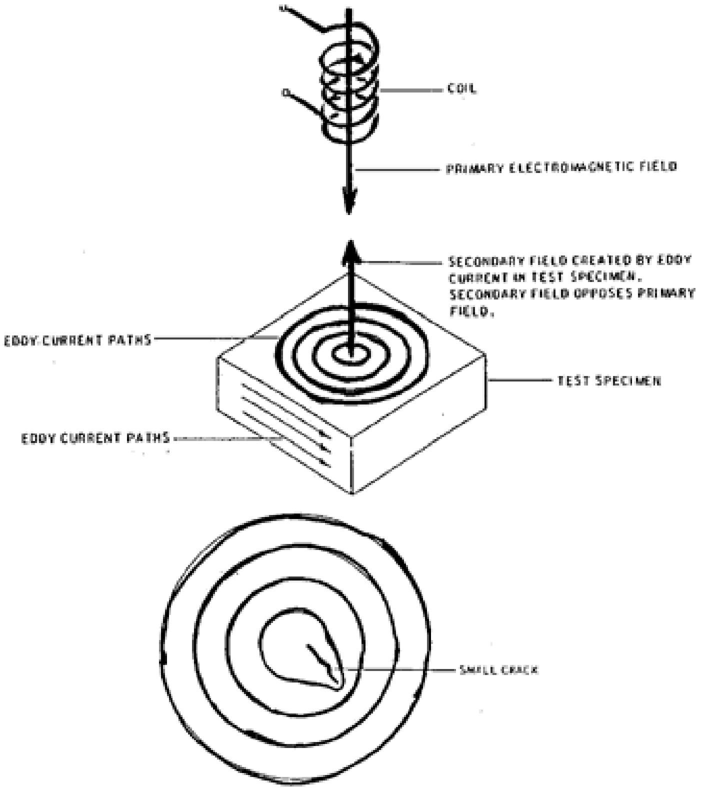


FIG. 1.5. (a) Generation of eddy currents in the test object.
(b) Distortion of eddy currents due to defect.

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.

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.

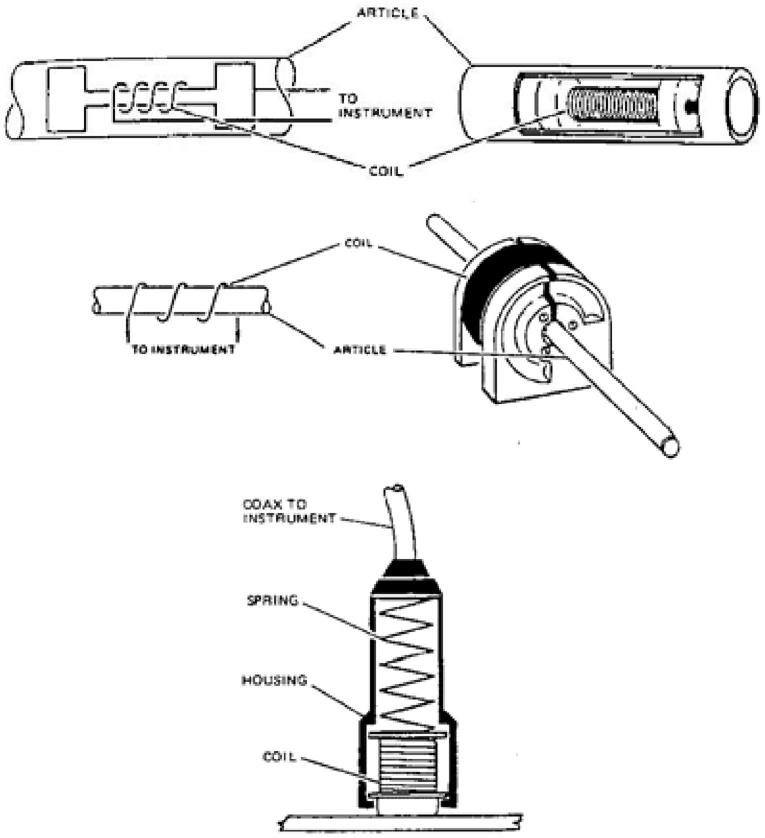


FIG. 1.6. Types of probes used in eddy current testing.
(a) Internal Coil
(b) Encircling Coil
(c) Surface Probe.

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 object (Fig. 1.7) and is exposed by passing X rays or gamma rays (Co-60 & Ir-192 radioisotopes) through it. The intensity of the rays while passing through the object is modified according to its internal structure and thus the exposed film, after processing, reveals a shadow picture known as a radiograph. It is then interpreted to obtain data about the present defects. This method is used on a wide variety of objects such as forgings, castings and weldments.

The advantages of radiographic testing include that:

(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 that:

(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.

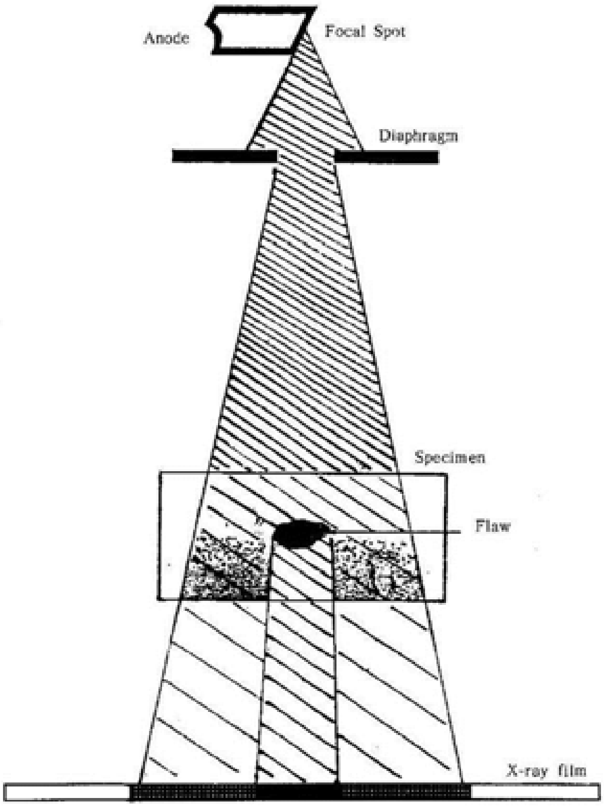


Fig. 1.7. Arrangement for radiographic testing method.

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.

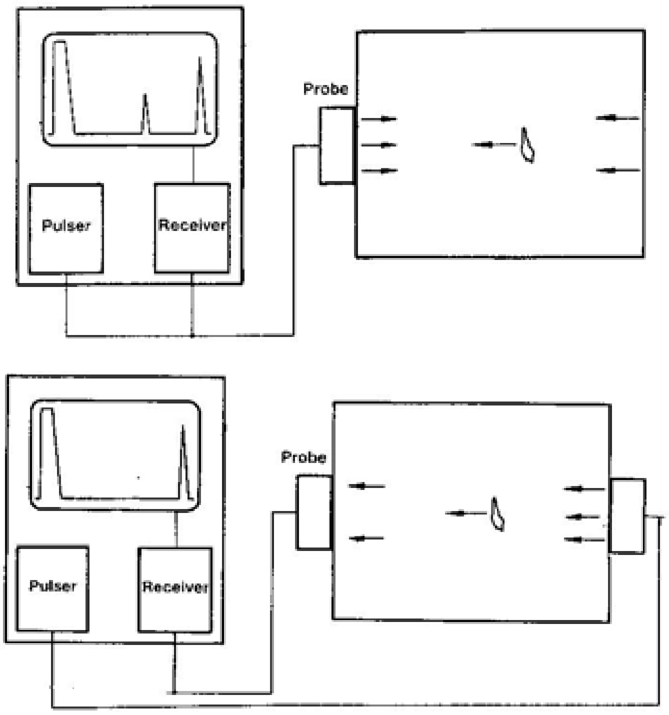


FIG. 1.8. Basic components of an ultrasonic flaw detection system.
(a) Pulse echo method
(b) Through transmission method.

1.1.2.7. Leak testing (LT)

The leak testing method of NDT includes several techniques to detect, locate and measure leaks which have occurred in the pressure boundary or envelope of a component, vessel, pipeline or piping component.

Many modern designs are based on the “leak before break” principle, in which critical thicknesses and other dimensions are selected so that a vessel will crack and leak before the crack grows to catastrophic proportions. In these applications, the ability to detect the leak at a very early stage is important. In other applications, checking for a through leak is the only way to fully assure the integrity of a component or weld.

The pressure envelope separates two areas which are or could be at different pressures. The contained fluid will try to travel from the region of higher pressure to that of lower pressure.

The relative pressures may be natural or imposed (where the envelope is pressurized or the potential exit point is subjected to a vacuum as part of the inspection procedure.)

Techniques for leak testing include visual examination for escaping fluids or bubbles (Figure 1.9), electronic sensing of the noise emitted by the escaping fluids, or chemical or radiological detection of small quantities of contained fluids or fluids specifically introduced as tracers (Figure 1.10).

FIG. 1.9. A simple bubble test for leak detection.

FIG. 1.10. Portable Helium Leak Testing System.

The basic functions of leak detection are the detection, location and size measurement of leaks in sealed systems.

Advantages of leak testing include the following:

(a) It can be applied on-line, permitting continuous monitoring of critical operating systems.
(b) Basic equipment for the simple techniques is economical, portable and easily applied.
(c) It is nonintrusive and can often be applied while the system is operating.

Limitations in the application of leak testing are the following:

(a) Only applicable to situations where a discontinuity has breached the pressure envelope.
(b) Not effective for the detection of cracks or other defects at an earlier stage.
(c) Wrong interpretation due to noise, liquid or other background contamination.

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

Technique	Access requirements	Equipment cost	Inspection cost	Remarks
Visual	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.
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 side access is sufficient.	B	B/C	Requires point-by-point search hence extensive work needed on large structures; skilled personnel required.
Magnetic particle	Requires a clean surface.	C	C/D	Only useful on magnetic materials such as steel; little skill required; cannot detect buried defects.
Penetrant	Requires flaw to be open to the penetrant (i.e. clean and at the surface).	D	C/D	For all materials; some skill required; only detects surface-breaking defects.
Eddy current	Requires reasonably smooth and clean surface	B/C	C/D	For electrically conductive materials only; for surface breaking flaws; variations in thickness of coatings, or comparison of materials; considerable skill is usually required.

[*] (A: Highest cost, D: Lowest cost)

1.1.4. New developments in NDT

Many modern developments in all areas of technology require use of stronger, lighter materials, with other exotic properties and made of as little raw materials as possible. This is aimed at increasing the efficiency, durability and reliability of components made of such materials. There are stringent requirements for detecting and characterizing the extremely small sizes of flaws. Consequently there is a great challenge to improve upon the existing NDT techniques 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 to make it as independent of operator errors as possible. This has led to a greater use of computers and automation. We see most of the modern NDT with microprocessors and computers with enhanced capabilities for data acquisition, analysis and image processing. There is a growing trend towards using multiple transducers and multi-channel systems both for ultrasonic and eddy current testing. Similarly the concept of using multiple methods of inspection simultaneously 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 the good quality assurance concept of making the products with zero defects. 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 infrared techniques. 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 integrateability, 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.

A few recent developments in some areas of NDT are briefly reviewed below.

1.1.4.1. Radiographic testing (RT)

With the availability of X ray tubes with focal spots as small as a few micros, high definition microfocal radiography with magnification is possible.

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 and Digital Detector Arrays 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 be reused, for example, close to 1000 times. The conventional fluoroscopic methods have moved into the digital domain through the use of high quality image intensifiers: images can be directly photographed using the Charge Coupled Device (CCD) cameras which convert visual signals to electrical signals that can be processed by a computer. This offers the possibility of producing low cost real-time digital radiographic systems as against more expensive systems. Computed Tomography, having the capability of producing three-dimensional images of internal structures of specimens, is now in use. High resolution Digital Micro-radiography is in the market; it uses X-ray machines with micron level focal spots.

Characteristics corresponding to those of conventional radiographic images have been defined for digital images. The equivalent of optical film density is Signal to Noise Ratio (SNR). The equivalent of film contrast is Contrast to Noise Ratio (CNR), that of film resolution and granularity is Basic Spatial Resolution and that of dynamic range is Specific Material Thickness Range. 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.

1.1.4.2. Ultrasonic testing (UT)

Automated and remote control systems of ultrasonic examination have seen rapid development and are now used in a wide range of industries in many different applications. Such systems comprise 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) and Synthetic Aperture Focusing Technique (SAFT) for flaw characterization. TOFD depends on the principle that when ultrasound is incident on 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. This is quite helpful in sizing such flaws. However, a more accurate technique for flaw sizing may be found on signal processing based on a semi-empirical approach of Weiner filtering with autoregressive spectral extrapolation using ultrasonic B- and C-scans.

Another area which has seen increase in applications is the phased array technique, a process by which 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, beam scanning at fixed angle, 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.

Use of ultrasonic guided waves is suitable for bulk fast inspection of pipes over long distance and can be efficiently used instead of conventional ultrasonic methods 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.

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. For this situation, air coupled transducers such as bimorphic, electrostatic, piezoelectric and ceramic are being used.

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

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 in inspection of a 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 do not limit the application of this technique.

1.1.4.3. Acoustic emission (AE)

Acoustic Emission is another technique with growing 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. Commonly studied AE events in material failure processes include the extension of a fatigue crack or fibre breakage in composite materials.

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 and its growth. A group of transducers can be used to record signals and then locate the precise area of crack 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. 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.

1.1.4.5. Visual Testing (VT)

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 other 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.

1.1.4.6. Infrared Thermography (IRT)

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 Testing, Electrical Potential Method, Schmidt Rebound Hammer Test, Windsor Probe Test, Electromagnetic Covermeters, Radiographic Testing, Ultrasonic Testing, IRT, Ground Penetrating Radar (GPR), Radioisotpe 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.

1.1.5. 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 and 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 recently 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 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 ENIQ documents has been confirmed by an official survey on nuclear safety performed under the European Council, as well as by the Western Nuclear Regulators Association (WENRA).

1.1.5.3. Life assessment and life management

NDT has proved to be of great value to perform the condition evaluation and subsequently the lifetime assessment of components. For this a combination of non-destructive evaluation (NDE), metallurgical evaluations, fracture mechanics and computational skills is necessary. This provides information needed to evaluate the severity of cracks in components and, with proper engineering analysis, sometimes provide an estimate of crack growth and the remaining life of components. This cycle of evaluation can help to provide plant operators with the ability to continue the operation of their equipment in a prudent manner even beyond their originally designed life. This also enables implementation of effective life management of components.

1.1.5.4. Performance based qualification

Performance based qualification is becoming a necessity in view of the stringent inspection requirements imposed by 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 consistently meets certain standards under real working conditions. It places candidates in situations where they must demonstrate their knowledge and practical 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 a 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 NDT.
(c) Record and classify the NDT results of the tests in terms of written criteria.
(d) Report the results.

However, a person having a Level-1 certificate shall neither be responsible for the choice of the test method or technique to be used nor for the assessment of test results.

1.1.6.2. Level-2

An individual certified to Level 2 has demonstrated competence to perform non-destructive testing according to established procedures. Within the scope of the competence defined on the certificate, Level 2 personnel may be authorized by the employer to:

(a) select the NDT technique for the test method to be used;
(b) define the limitations of application of the testing method;
(c) translate NDT codes, standards, specifications and procedures into 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. 1.11. The end of the straight line portion is known as the elastic limit. A point on the curve slightly higher than the elastic limit is known as the yield point or yield strength. The allowable or safe load for a metal in service should be well below the elastic limit. If higher loads are applied, however, the range of elasticity or elastic deformation is exceeded and the metal is now permanently deformed. Now it will not return to its original dimensions even when the load is removed. For this reason, the area of the stress strain curve beyond the elastic limit is called the plastic range. It is this property that makes metals so useful. When enough force is applied by rolling, pressing or hammer blows, metals can be formed, when hot or cold, into useful shapes. If the application of load is increased in the plastic region a stage comes when the material fractures.

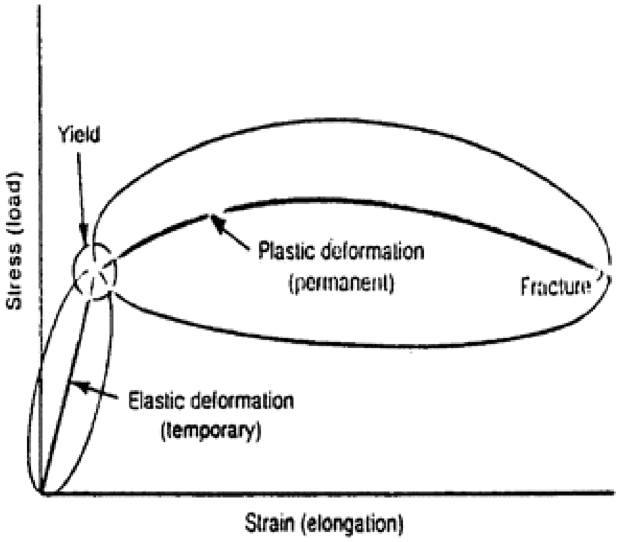


FIG. 1.11. Stress-strain curve showing elastic and plastic deformation and fracture.

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, which 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. The stiffness of any metal varies inversely with its temperature; that is, as temperature increases, stiffness decreases, and vice versa.

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 as:

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

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 (see Fig. 1.11). 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.

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 is said to 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.

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 resin systems used with paper, cotton fabric, glass fabric and asbestos as the main alternative reinforcing materials.

Ceramic and metal composites find several applications in engineering industry.

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, reinforcement, 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", which is formed among similar metal atoms, when some electrons in the valence shell separate from their atom and exist in a cloud surrounding all the positively charged atoms. These positively charged atoms arrange themselves in a very orderly pattern. The atoms are held together because of their mutual attraction for the negative electron cloud (Fig. 1.12).

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.

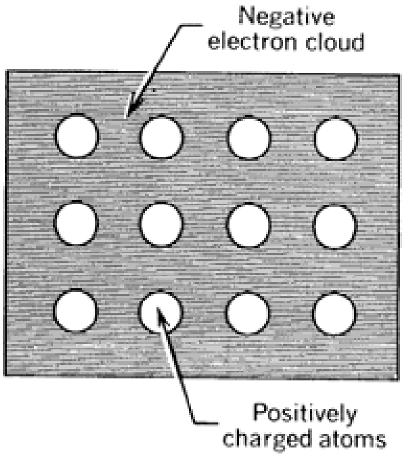


FIG. 1.12. Schematic illustration of a metallic bond.

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-centred cubic (BCC)

The body-centred cubic cell is made up of nine atoms. Eight are located on the corners of the cube with the ninth positioned centrally between them Fig. 1.13a. 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-centred cubic (FCC)

Face-centred cubic cells consist of fourteen atoms with eight at the corners and the other six centred in the cube faces Fig. 1.13b. This structure is characteristic of ductile metals, which include aluminium, copper, gold, lead, nickel, platinum and silver. Iron, which is body-centred cubic at room temperature, is also of the face-centred structure in the temperature range from about 910°C to 1400°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. 1.13c. 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. 1.14 illustrates the process of the formation of grains and grain boundaries.

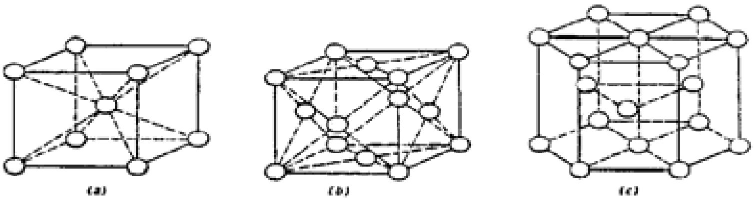


FIG. 1.13. Crystal structure types.
(a) Body-centred cubic (BCC)
(b) Face-centred cubic (FCC)
(c) Hexagonal close-packed (HCP).

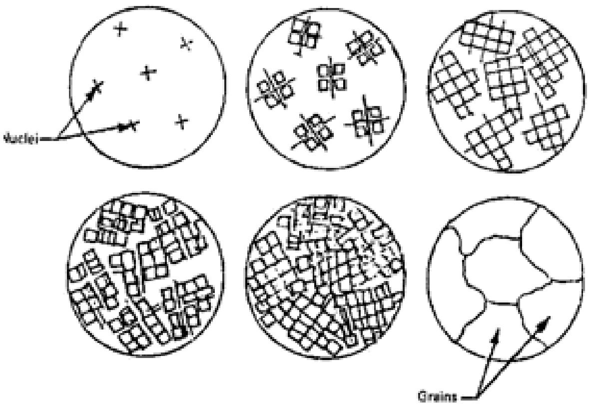


FIG. 1.14. Growth of crystals and grains during solidification.

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

1.2.3.3. Structure of alloys

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

(a) Pure metal

There exist no B-atoms in A-crystal grains and no A-atoms in B-grains, i.e. mixture of pure A- and B-crystal grains. A and B metals are mutually insoluble. This complete lack of inter-solubility is theoretically almost impossible (The solubility of one component in 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.

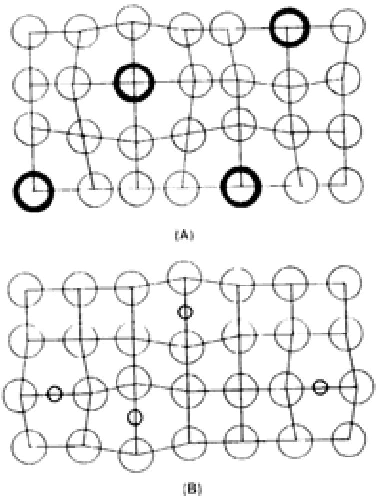


FIG. 1.15. Schematic illustration of (A) substitutional and (B) interstitial solid solutions.

(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. 1.15 (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. 1.15 (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°F or 723°C), FCC (above 1670°F or 911°C), and delta iron (between 2550°F or 1398°C and 2800°F or 1538°C). The exact temperature is determined by the amount of carbon and other alloying elements in the metal. The properties of iron and steel are governed by the phase transformations they undergo during processing. Understanding these transformations is essential to the successful welding of these metals. Steel is an iron alloy containing less than two per cent carbon. The presence of carbon alters the temperatures at which freezing and phase transformations take place. The addition of other alloying elements also affects the transformation temperatures. Variations in carbon content have a profound affect on both the transformation temperatures and the proportions and distributions of the various phases (austenite, ferrite, and cementite). The iron-carbon phase diagram is shown in Fig. 1.16. On cooling, delta ferrite to austenite transformation occurs at 2535°F (1390°C) in essentially pure iron, but in steel, the transformation temperature increases with increasing carbon content to a maximum of 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. 1.16. 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: An eutectic mixture of austenite & cementite.

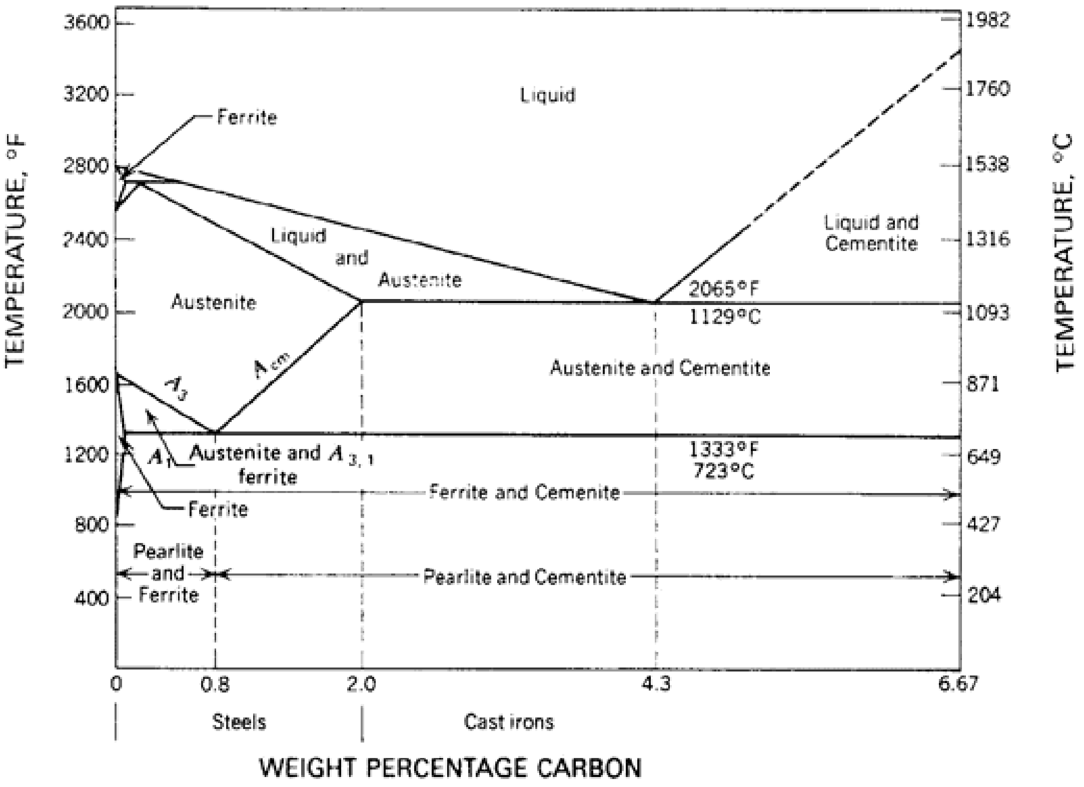


FIG. 1.16. The iron-carbon phase diagram.

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.

1.2.4.1. Inherent discontinuities

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.

1.2.4.2. Process discontinuities

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 may open to the surface.

1.2.4.3. Service discontinuities

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.

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. 1.17 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. 1.18.

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. 1.19. 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.

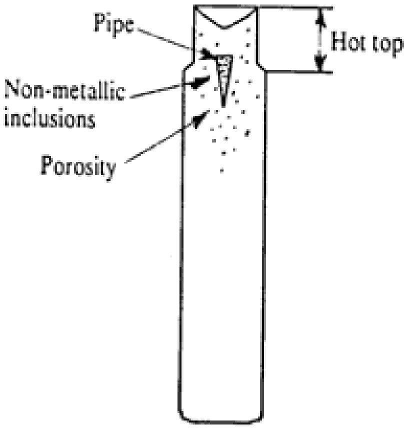


FIG. 1.17. Typical defects in an ingot.

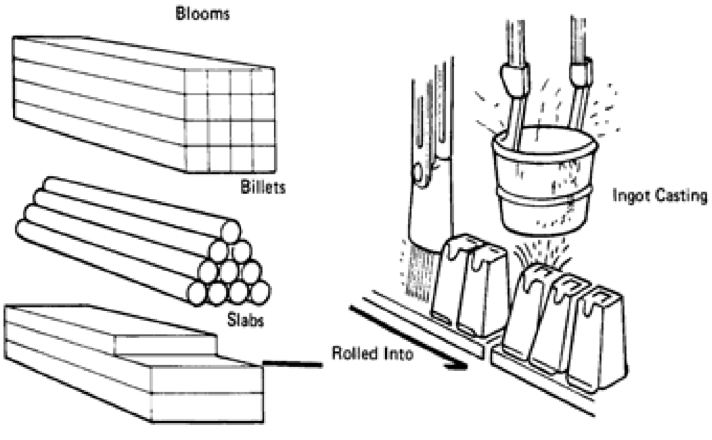


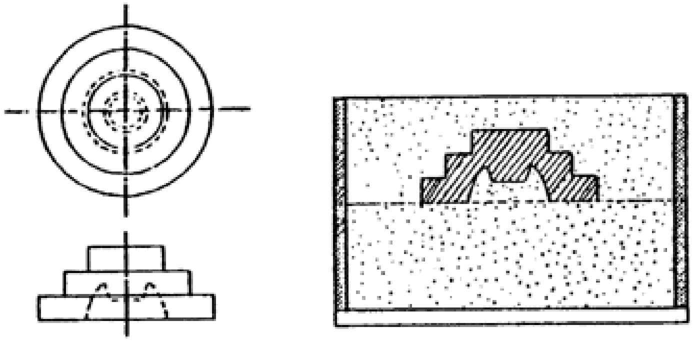
FIG. 1.18. Typical primary material processes after casting.

(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.

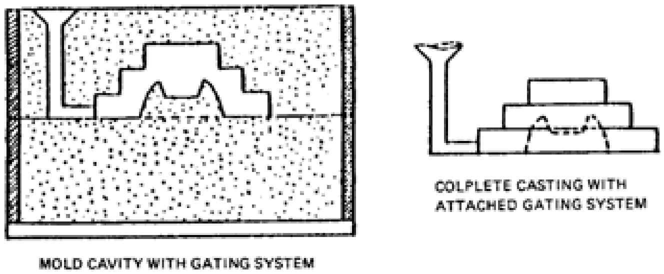
Different types of sand moulds can be made for making different castings. Green sand moulds are made from moist sand and are used for practically all ferrous and non-ferrous castings. They have the disadvantage of not being very strong as well as requiring moisture during manufacture which may cause 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.



PATTERN

PATTERN IN SAND MOLD



MOLD CAVITY WITH GATING SYSTEM

COLPLETE CASTING WITH ATTACHED GATING SYSTEM

FIG. 1.19. Typical casting steps.

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

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

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

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

(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. 1.20. shows hot chamber die casting.

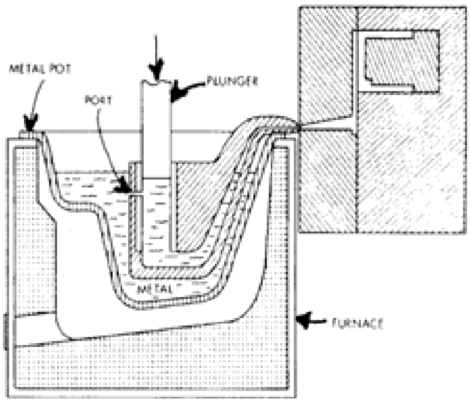


FIG. 1.20. Hot chamber die casting.

- 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. 1.21. 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.

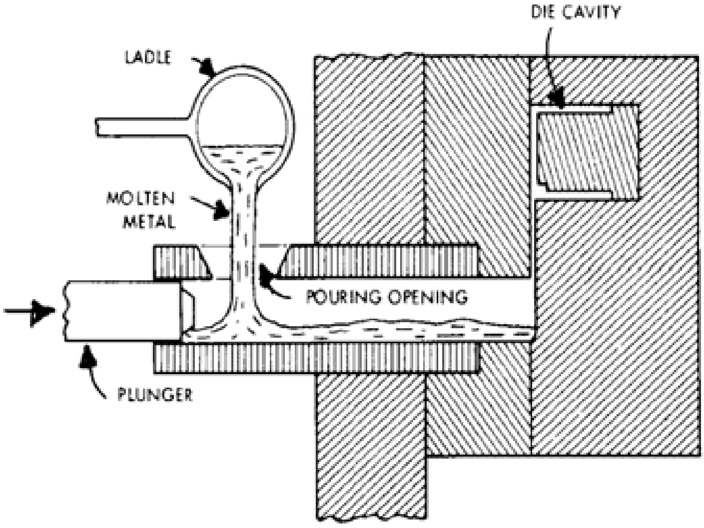


FIG. 1.21. Cold chamber die casting.

(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. 1.22. 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.

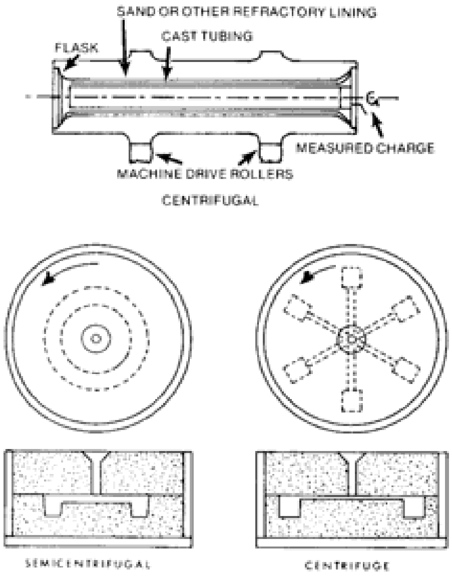


FIG. 1.22. Centrifugal casting.

(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. 1.23.

Various types and grades of wax are the common materials, used 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 a refractory sand, placed in a metal flask and sealed to the pallet. Then the investment or moulding material, in viscous slurry form, is poured around the pre-coated tree. When the investment has set, the mould is heated by putting it in an oven at 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.

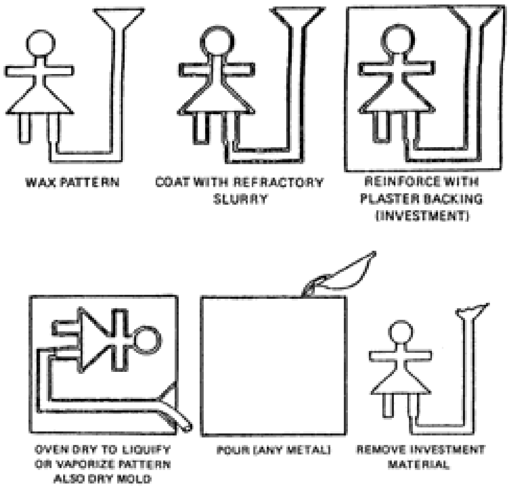


FIG. 1.23. Steps for investment casting.

(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. 1.24 molten metal enters at one end of the mould, and solid metal is drawn from the other. Control of the mould temperature and the speed of drawing is essential for satisfactory results. Exclusion of contact with oxygen, while molten and during solidification, produces high quality metal. Gears and other shapes in small sizes can be cast in bar form and later sliced into multiple parts.

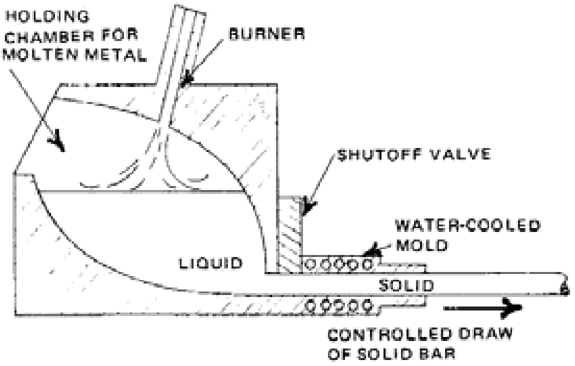


FIG. 1.24. Schematic diagram of continuous casting process.

TABLE 1.2. COMPARISON OF CASTING METHODS (APPROXIMATE)

	Sand casting	Permanent mould casting	Die- casting	Centrifugal casting	Investment casting	Shell mould casting
Relative cost in large quantity	Medium	Low	Lowest	High	Highest	Medium
Relative cost for small number	Lowest	High	Highest	Medium	Low	Low
Permissible weight of casting	Unlimited	100 lb	300 lb	Several tons	5 lb	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.

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. 1.25. 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

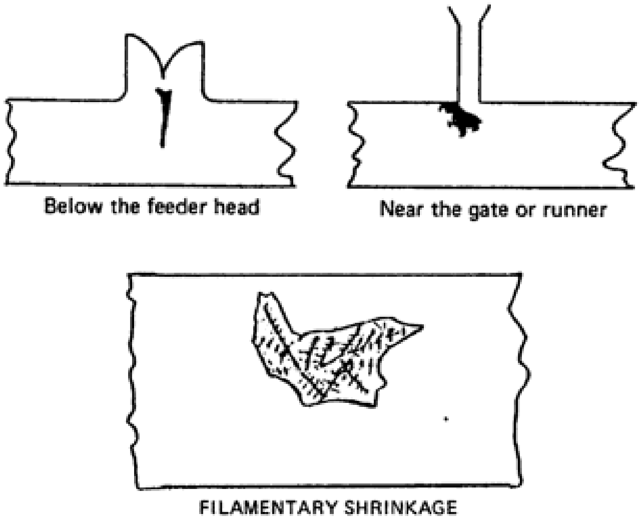
These are discontinuities that result from stresses developed close to the solidification temperature while the metal is still weak. These, again, are attributed to resistance of the mould and core, which hinder contraction of the casting, causing thermal stress. Hot tears resemble ragged cracks. They 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. 1.26.

(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. 1.27. 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.



Below the feeder head

Near the gate or runner

FILAMENTARY SHRINKAGE

FIG. 1.25. Formation of shrinkage defects.

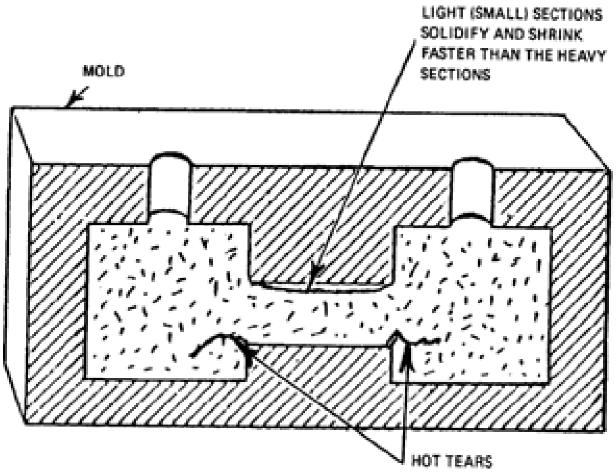


FIG. 1.26. Hot tears.

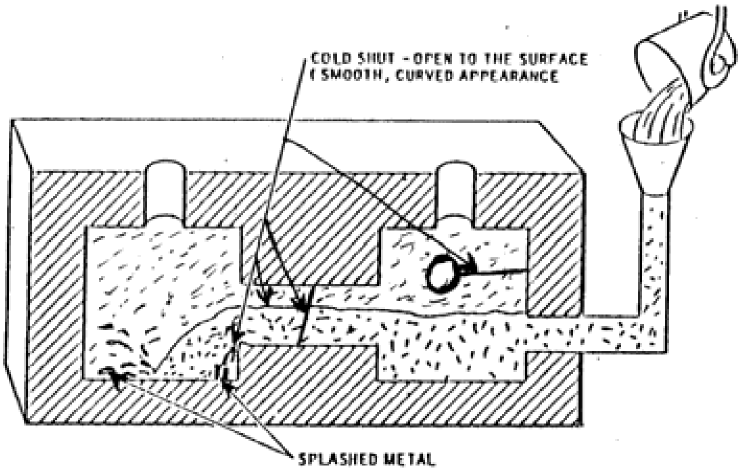


FIG. 1.27. Types of cold shuts.

(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 sintered to produce a coherent mass, either without fusion or with the fusion of a low melting constituent only'. Fig. 1.28 shows the steps ordinarily required in the production of a part by the powder metallurgy process. Suitable powder must first be produced. While theoretically any crystalline material may be fabricated by powder metallurgy, the production of suitable powder has presented restrictions in many cases, either because of difficulty in obtaining adequate purity or because of economic reasons. After selection and blending of the powder and manufacture of a die for the shape to be produced, the powder is pressed to size and shape. The application of heat results in crystalline growth and the production of a homogeneous body.

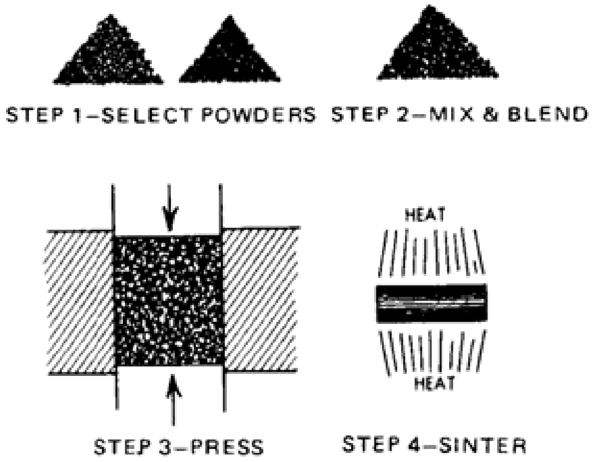


FIG. 1.28. Elements of powder metallurgy.

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 machineability 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°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. 1.29. 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. 1.30 and 1.31 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. 1.30 (A).

Horizontal position (2G). The test plates are placed in an approximately vertical plane with the welding groove approximately horizontal Fig. 1.30 (B).

Vertical position (3G). The test plates are placed in an approximately vertical plane with the welding groove approximately vertical Fig. 1.30 (C).

Overhead position (4G). The test plates are placed in an approximately horizontal plane and the weld metal deposited from the underside Fig. 1.30 (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. 1.30 (A).

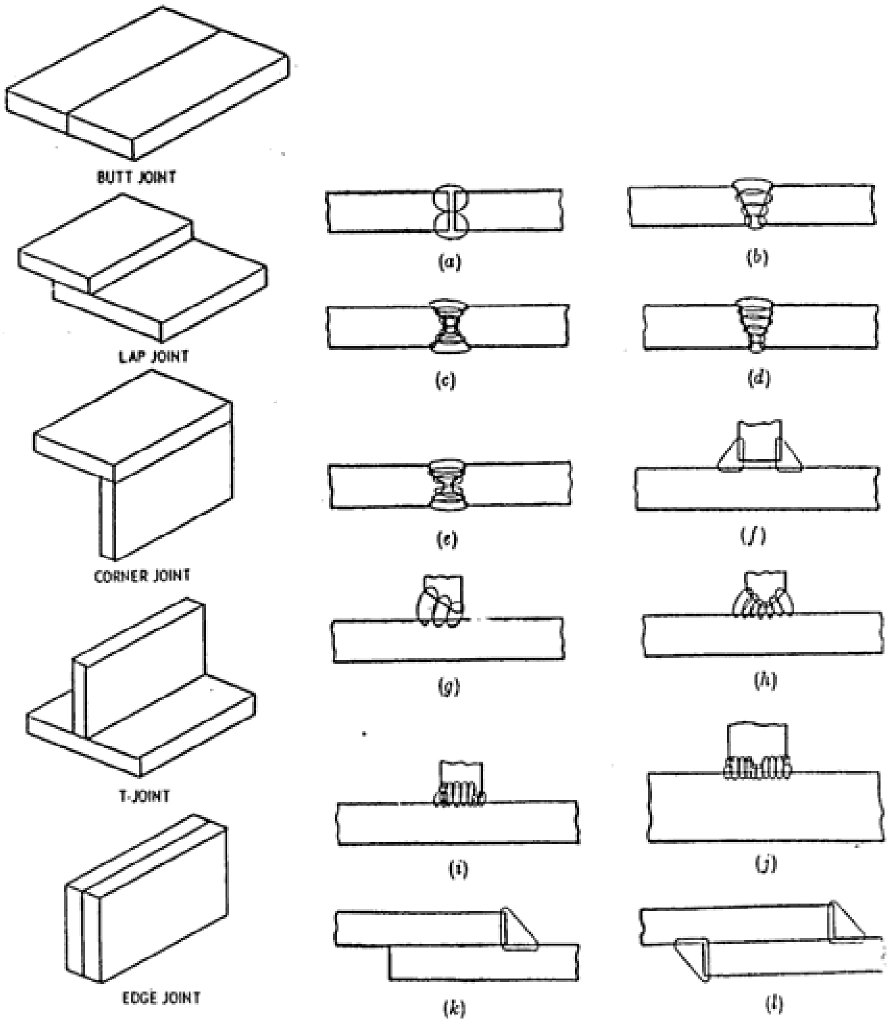
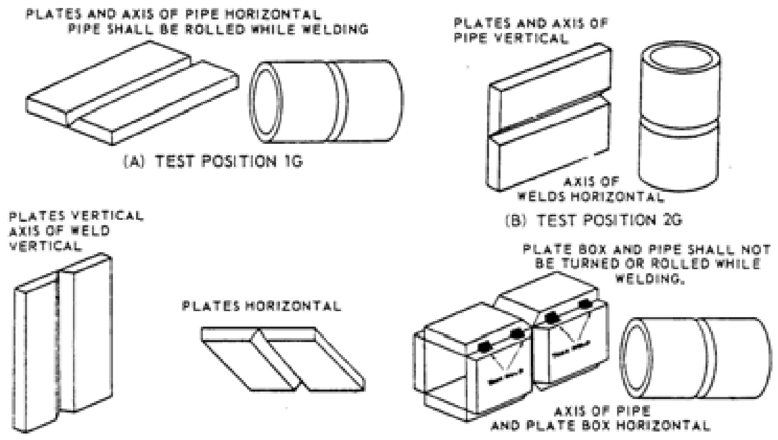


FIG. 1.29. Types of welding joints: (a) square butt , (b) single-v butt , (c) double-v butt , (d) single-u butt , (e) double-u butt , (f) square-t , (g) single-bevel t , (h) double-bevel t , (i)single-u t , (j) double-u t , (k) single-bead lap , (l) double-bead lap.



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

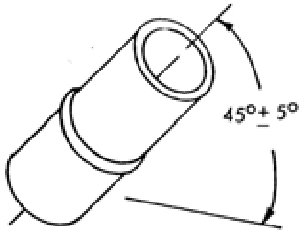


FIG. 1.30. Positions of plates and pipes for groove weld.

Vertical (2G). The pipe is placed with its axis in an approximately vertical position with the welding groove in an approximately horizontal plane Fig. 1.30 (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. 1.30 (E)

Inclined fixed (6G). The pipe is inclined fixed ($45^o \pm 5^o$) and not rotating during welding Fig. 1.30 (F).

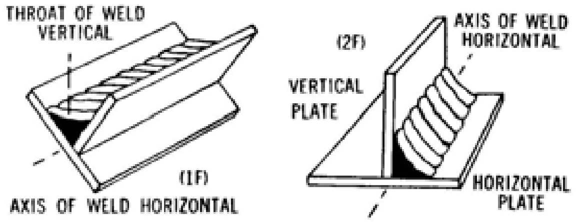
For fillet welds in plates, different positions are defined as below:

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. 1.31 (A).

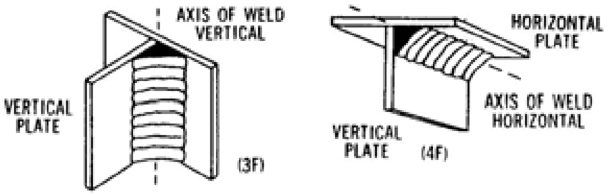
Horizontal position (2F). The test plates are so placed that each fillet weld is deposited on the upper side of the horizontal surface and against the vertical surface Fig. 1.31 (B).

Vertical position (3F). Each fillet weld is made vertically Fig. 1.31 (C).

Overhead position (4F). The test plates are so placed that each fillet weld is deposited on the underside of the horizontal surface and against the vertical surface Fig. 1.31 (D).



(A) FLAT POSITION (B) HORIZONTAL POSITION



(C) VERTICAL POSITION (D) OVERHEAD POSITION

FIG. 1.31. 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. 1.32.

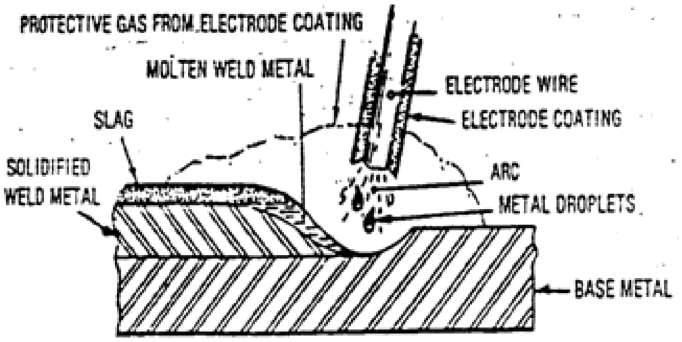


FIG. 1.32. Shielded metal arc welding process.

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. 1.33. 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.

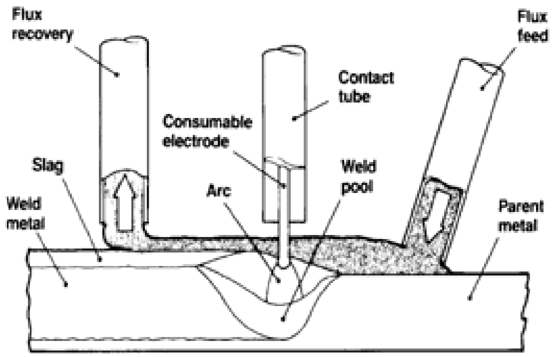


FIG. 1.33. Submerged arc welding process.

(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. 1.34.

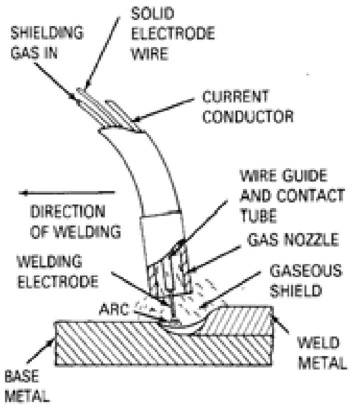


FIG. 1.34. Gas metal arc welding process.

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. 1.35.

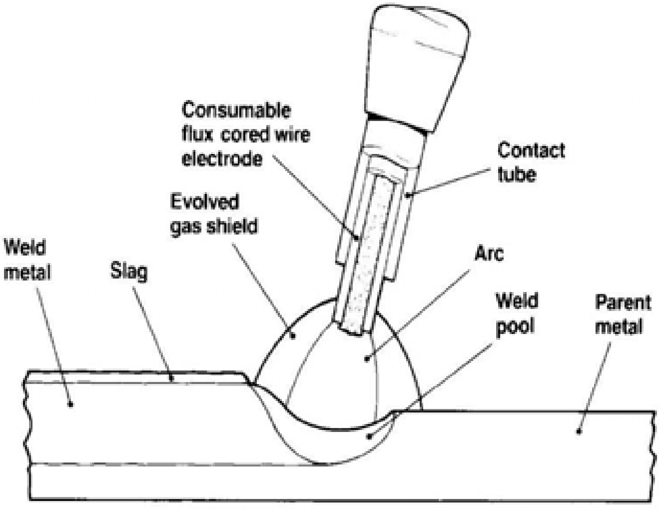


FIG. 1.35. Flux cored arc welding.

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

(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. 1.36 and is also sometimes called TIG welding.

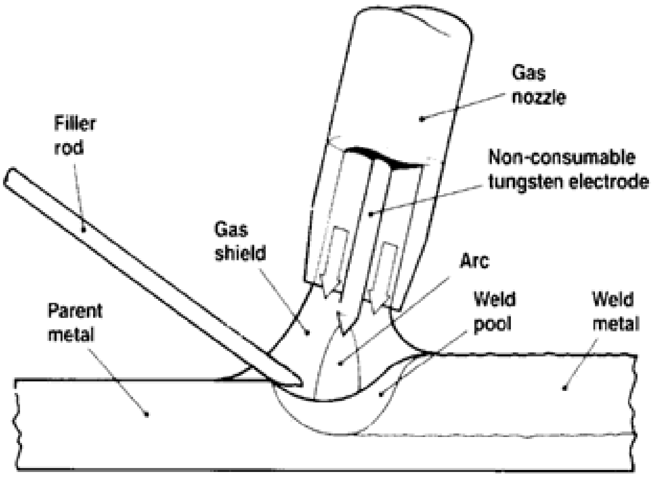


FIG. 1.36. Gas tungsten arc welding.

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. However, if large disposals are anticipated, it would be worthwhile to have some preliminary discussions with the local landfill operator and the regulatory body concerned.

(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. 1.37. 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.

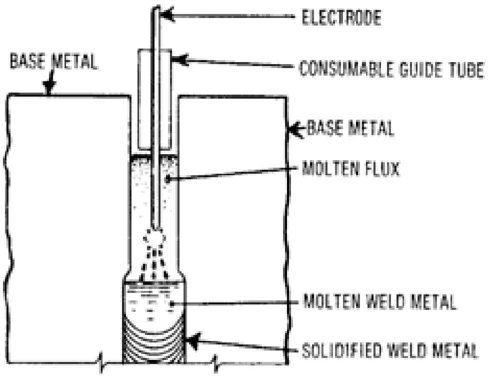


FIG. 1.37. Electroslag welding process.

(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. 1.38). 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.

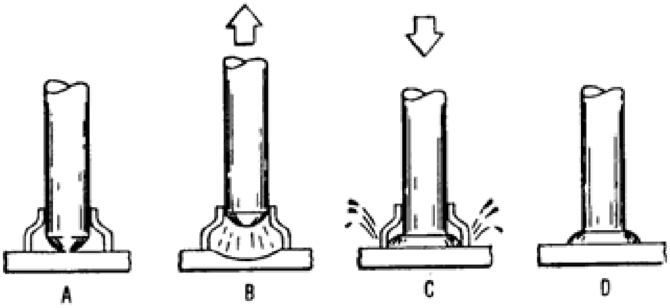


FIG. 1.38. Stud welding sequence.

(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. 1.39, 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.

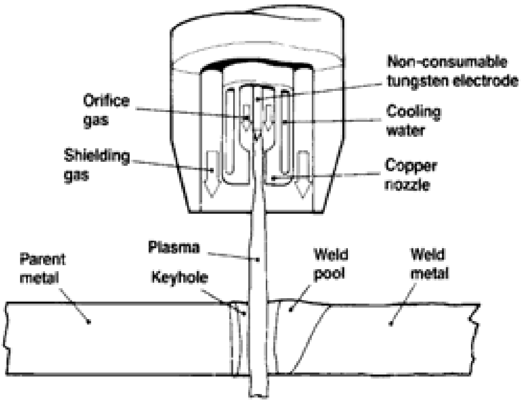


FIG. 1.39. Plasma arc welding.

(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. 1.40. 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.

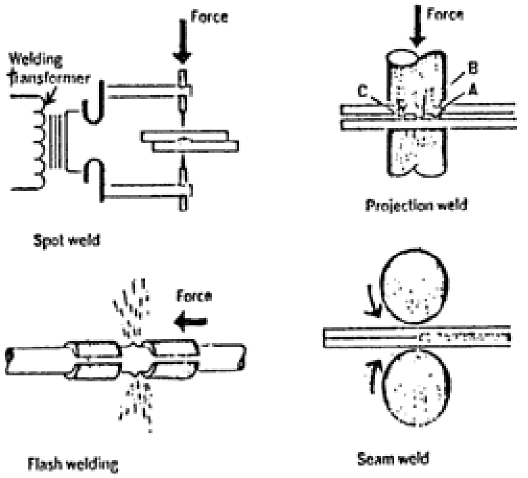


FIG. 1.40. Basic resistance welding methods.

(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. 1.41.

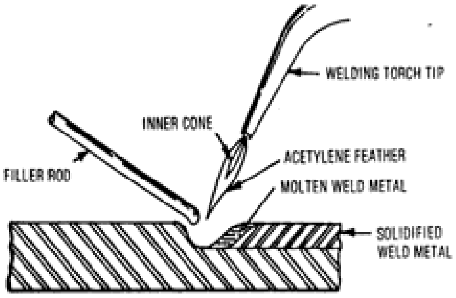


FIG. 1.41. Oxyfuel gas welding process.

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. 1.42.

(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. 1.43. 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.

(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.

(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.

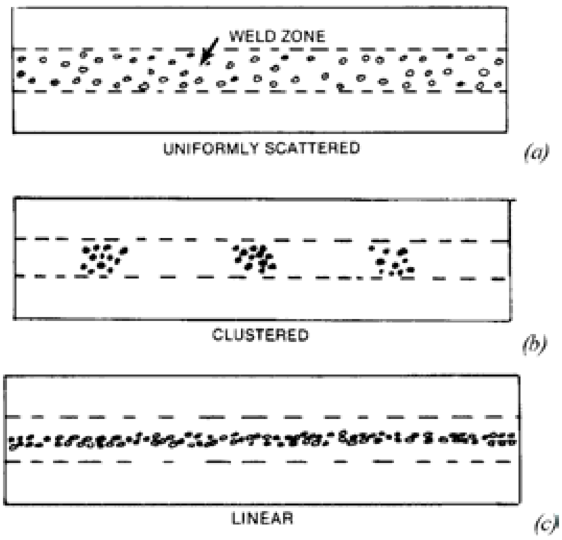


FIG. 1.42. Three types of weld porosity.
(a) Uniformly scattered porosity
(b) Clustered porosity
(c) Linear porosity.

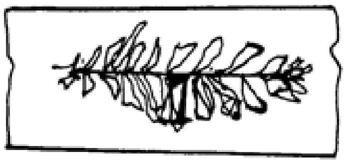


FIG. 1.43. Piping in weld.

TABLE 1.3. COMMON CAUSES AND REMEDIES OF POROSITY

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

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

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. 1.44. 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).

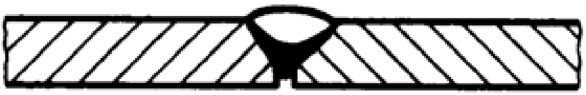


FIG. 1.44. Incomplete root penetration.

(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. 1.45.

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 intergranularly as a result of hot shortness or localized planar shrinkage, or they can be transgranular separations produced by stresses exceeding the strength of the material. Transverse cracks lie in a plane normal to the axis of the weld and are usually open to the surface. They usually extend across the entire face of the weld and sometimes propagate into the base metal.

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

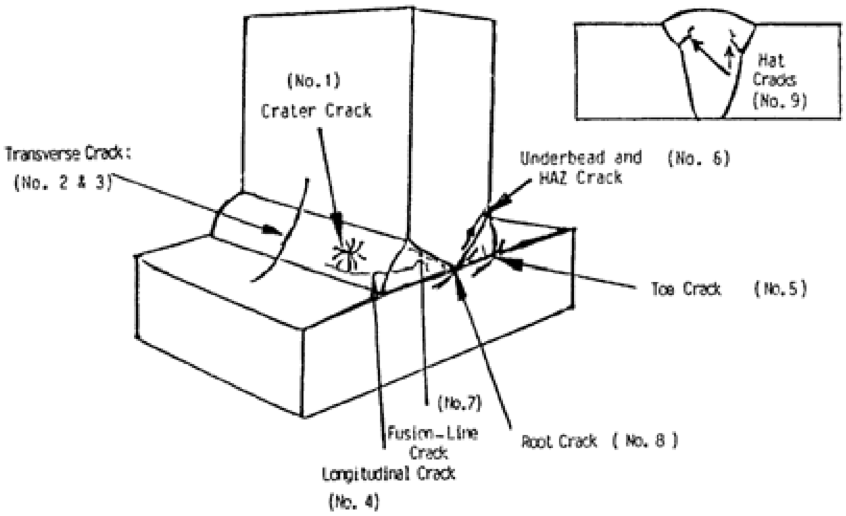


FIG. 1.45. Different types of cracks located in and around a welded joint.

— 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. 1.45).

— 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. 1.45). 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. 1.45). 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 .1.45).

(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. 1.46.

FIG. 1.46. 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 downhand welding with a backing strip at the root of the weld groove if slag is trapped between the molten metal and the backing strip Fig. 1.47.

FIG. 1.47. Root concavity.

TABLE 1.6: COMMON CAUSES AND REMEDIES OF CRACKING

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

(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. 1.48.

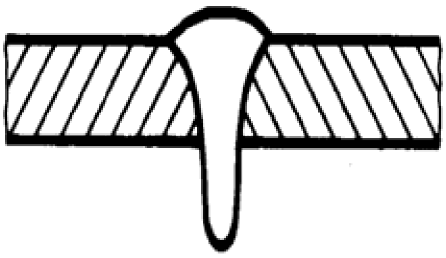


FIG. 1.48. Excessive penetration.

(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. 1.49. 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.

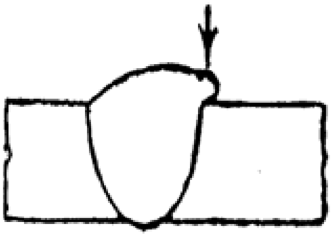


FIG. 1.49. Overlap.

(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. This 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. 1.50.

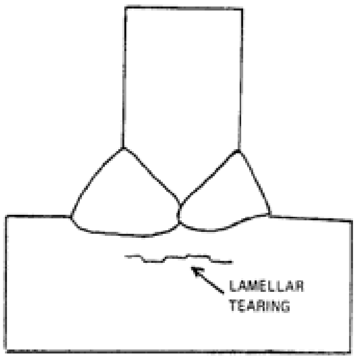


FIG. 1.50. Lamellar tearing.

(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. 1.51.

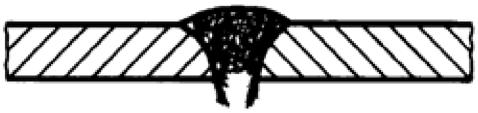


FIG. 1.51. Burn through.

(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. 1.52.

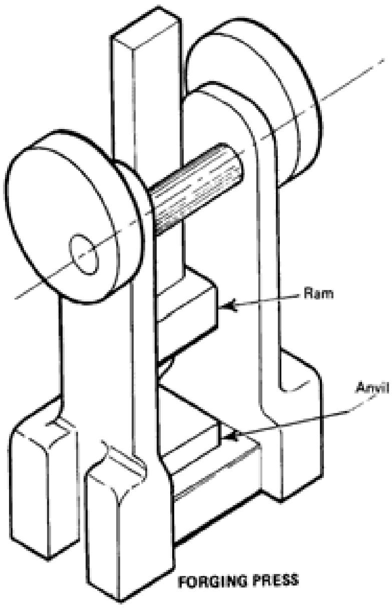


FIG. 1.52. Vertical forging press.

Forging may be considered under two categories. First where the working surface of the dies is flat or of uniform curved contour and shaping is done by manipulation using tools of simple shape. This is called open-die forging. The second is where impression dies are used and the metal is shaped by being forced into the die impressions. This is called closed-die forging. In the first category are forgings of simple, round or rectangular cross-section and forgings of more complicated shapes which are so large that sinking of closed dies would be impractical or too costly. Small forgings of complicated final shape may be rough forged on simple dies and then machined to final form if the number required is too small to justify the cost of an impression die. In this category also are hollow forged parts. For these, the centre metal of the rough piece of proper size is either machined out cold (trepanned), or is punched out hot using suitable dies on a press. The part is then forged on a mandrel passing through the centre hole and supported at both ends so that the mandrel acts as the bottom die. In closed die forging on a hammer or vertical press the lower die has an impression corresponding to one half of the part to be made while the upper die has an impression corresponding to the other half. For relatively simple shapes the dies may have only one impression but more commonly they incorporate a series of impressions in which the part is successively shaped to the final form. Closed die forging is commonly known as ‘drop forging’. Around the impressions the dies are shaped to provide space for the excess stock, as it is not practical to have exactly the amount of metal required to fill the impressions. The excess metal that is forced into this space is referred to as flashing or flash. After forging this is trimmed off in suitable dies. The closed die forging business Fig. 1.53 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.

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.

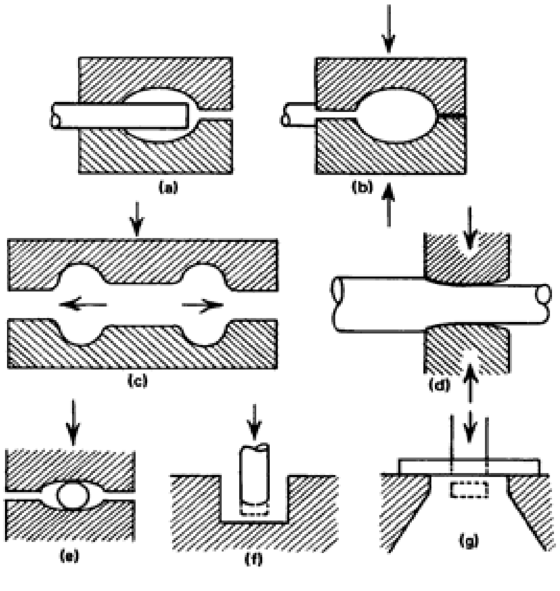


FIG. 1.53. Forging operations; (a, b) edding; (c) fullering; (d) drawing, (e) swaging (f) back extruding; (g) punching.

Rolling mills are described according to the arrangement of the rolls. The simplest is the two-high reversing mill Fig. 1.54 (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. 1.54 (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. 1.54 (d) and the cluster mill Fig. 1.54 (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. 1.55.

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. 1.56.

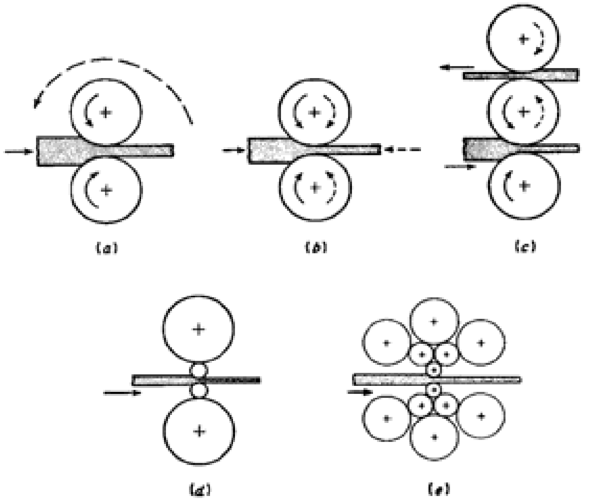


FIG. 1.54. Typical arrangements of rolls for rolling mills; (a) Two-high pullover, two-high reversing, (c) three-high, (d) four-high, (e) cluster.

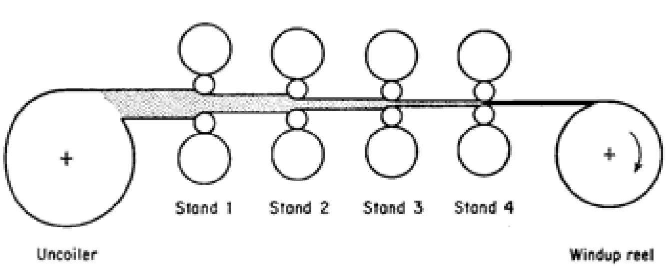


FIG. 1.55. Schematic drawing of strip rolling on a four-stand continuous mill.

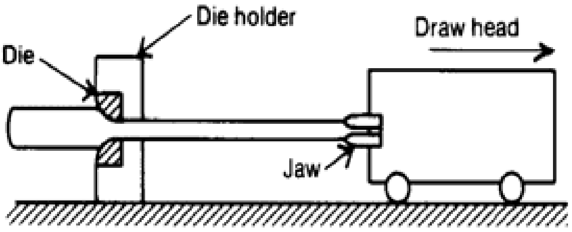


FIG. 1.56. Schematic drawing of a draw bench.

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. 1.57.

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.

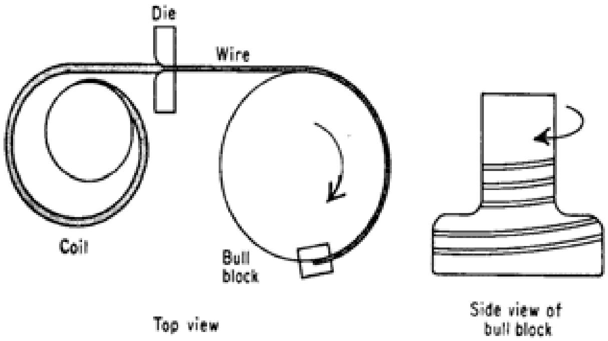


FIG. 1.57. Schematic wiredrawing equipment.

1.3.5.1. 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. 1.64.

(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. 1.64.

(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. 1.64.

(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.

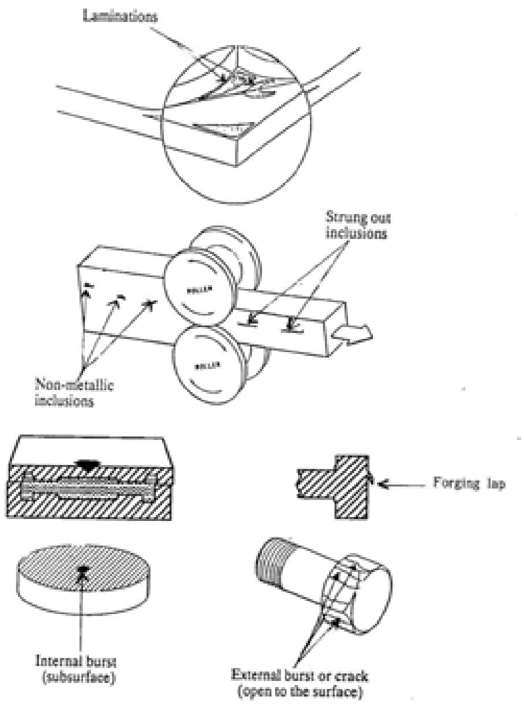


FIG. 1.64. Forging and rolling defects.

(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. 1.64.

(i) Overheating

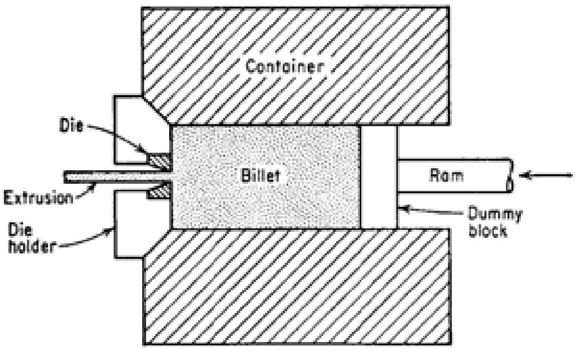
Normally identified by the facets seen on the fractured surfaces of a test-piece, but in extreme cases can manifest itself as a severely broken-up surface.

(j) Pipe

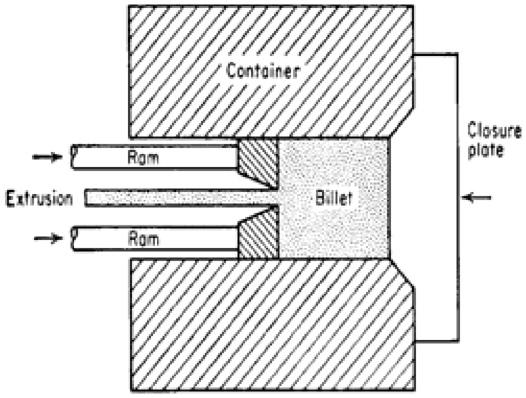
If there has been insufficient discard from the original ingot, remnant primary pipe will normally show up axially. Secondary pipe that has never been exposed to the atmosphere will be welded-up if there has been sufficient forging.

1.3.6. Extrusion processes

Another process which is similar to rolling is extrusion. In principle, extrusion is similar to squeezing toothpaste from a toothpaste tube. The raw material is a heated cast billet of the required metal. Usually this is either a copper alloy, an aluminium alloy or lead. The pressure necessary to force the metal through the die is provided by the hydraulic ram. Since the billet is reduced to the size of the finished section in one pass through the die, extrusion is a highly productive process. However, the plant is extremely costly and so is its operation and maintenance. Like most hot processes the finish and dimensional accuracy of the section is lower than that associated with cold drawing. Therefore, where greater accuracy is required, the extruded section is given a light draw to strengthen the section and finish, and improve its dimensional accuracy Fig. 1.58 (a, b).



Direct extrusion



Indirect extrusion

FIG. 1.58. Types of extrusion.

The Mannesmann mills, plug rolling mills, three-roll piercing mills, and reeling mills are also used for producing seamless pipe and tubing Fig. 1.59. The Mannesmann mill Fig. 1.59 (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. 1.59 (b) have been widely adopted. This has led to the development of three-roll piercing machines Fig. 1.59 (c) which produce more concentric tubes with smoother inside and outside surfaces than the older Mannesmann design. A reeling mill Fig. 1.59 (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.

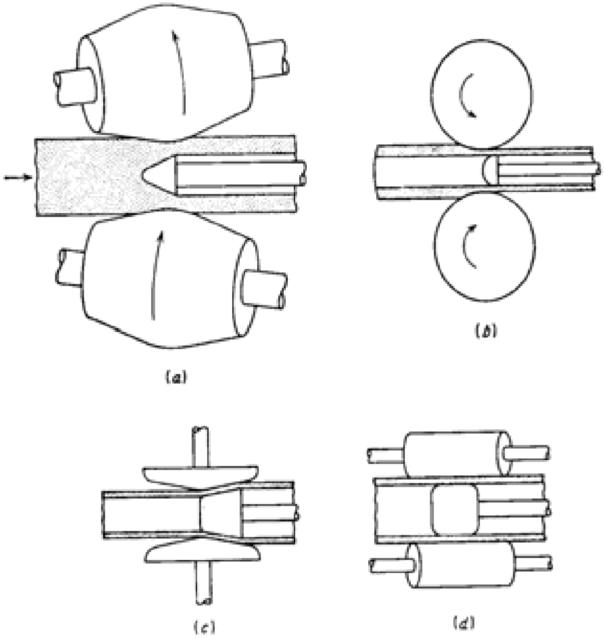


FIG. 1.59. (a) Mannesmann mill (b) plug rolling mill (c) three-roll piercing mill (d) reeling mill.

1.3.7. Spinning processes

A method of making tank heads, television cones, and other deep parts of circular symmetry is called spinning Fig. 1.60 (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. 1.60 (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.

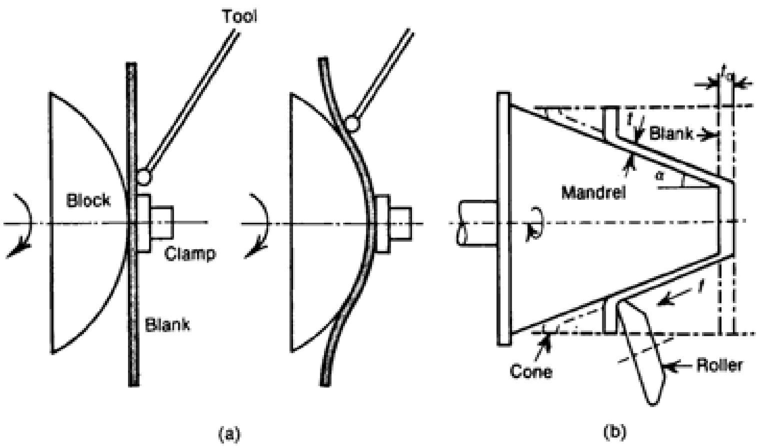


FIG. 1.60. Schematic representation of spinning processes
(a) manual spinning (b) shear spinning.

1.3.8. Shearing and blanking

Shearing is the separation of metal by two blades moving as shown in Fig. 1.61. 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. 1.61 (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.

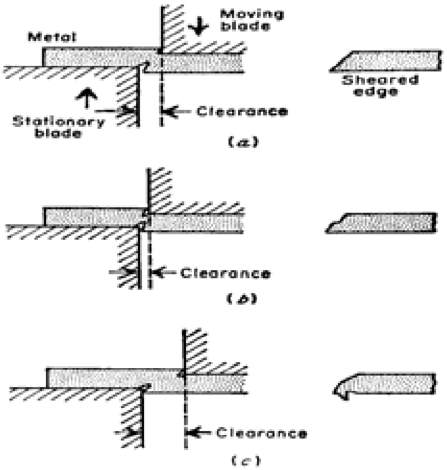


FIG. 1.61. Shearing of metal; (a) proper clearance (b) insufficient clearance (c) excessive clearance.

1.3.9. 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. 1.62. 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.

1.3.10. 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. 1.63. 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.

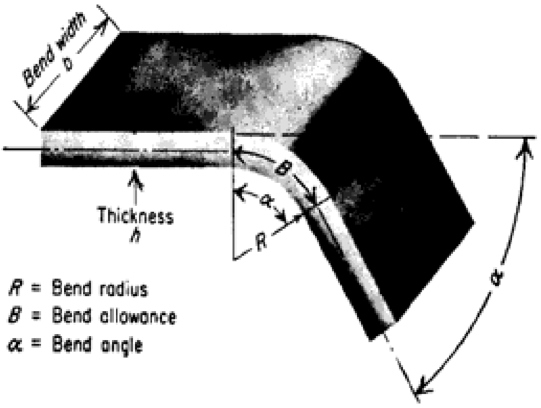


FIG. 1.62. Definition of terms used in bending.

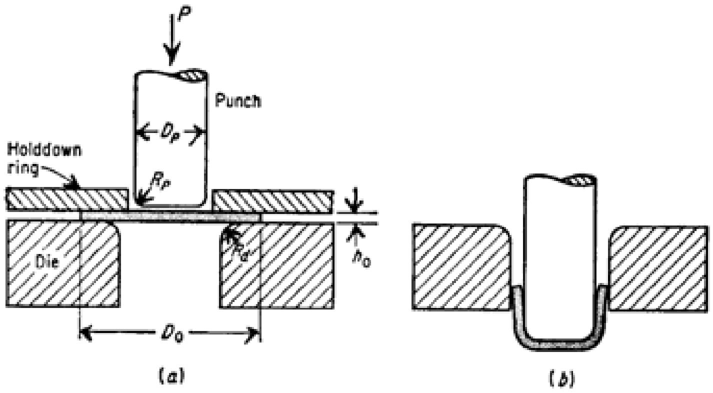


FIG. 1.63. Deep-drawing of a cylindrical cup; (a) before bending, (b) after drawing.

1.3.11. Finishing processes and related defects

1.3.11.1. 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. 1.65.

1.3.11.2. 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.

1.3.11.3. 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.

1.3.11.4. 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.

1.3.11.5. Straight line machines

One group of machine tools provides 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.

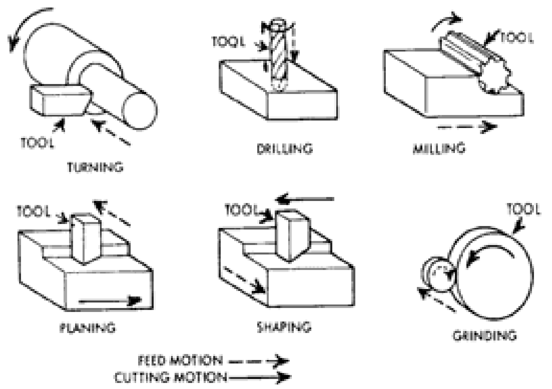


FIG. 1.65. Feed and cutting motions.

1.3.11.6. 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.

1.3.12. 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 1.66. 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.

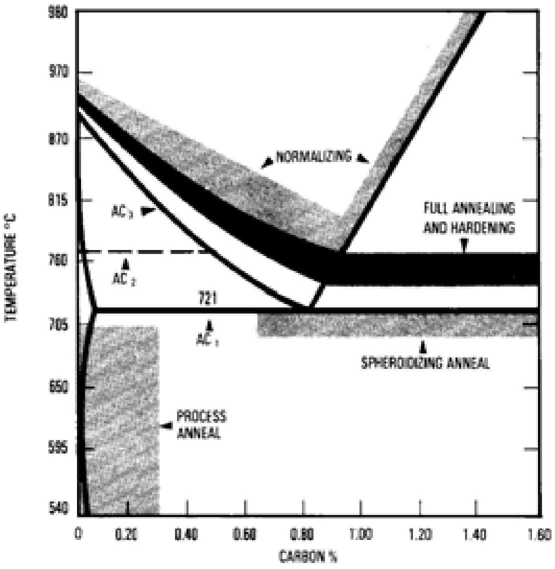


FIG. 1.66. Temperature ranges for various heat treating processes.

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).

1.3.12.1. 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 fulfill 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.

1.3.12.2. 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.

1.3.12.3. 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 illustrated in Fig. 1.67.

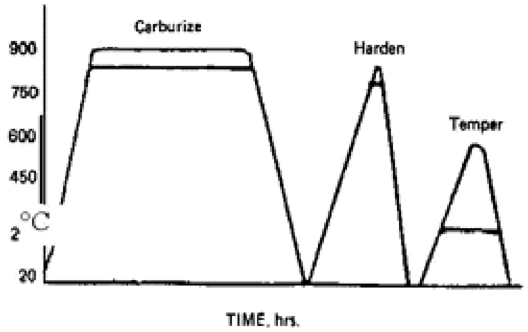


FIG. 1.60. Typical heat treatment cycle for carburizing.

1.3.12.4. 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.

1.3.12.5. 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.

1.3.12.6. 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.

1.3.12.7. 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. 1.68. 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.

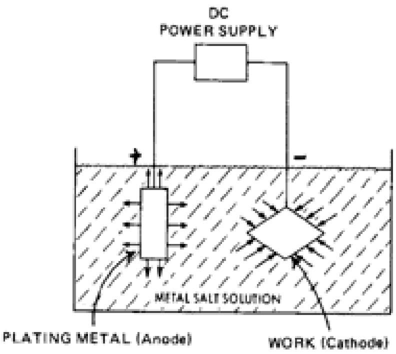


FIG. 1.62. Electroplating.

1.3.12.8. 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. Behaviour of materials in service

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

1.4.2. 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. 1.69. 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.

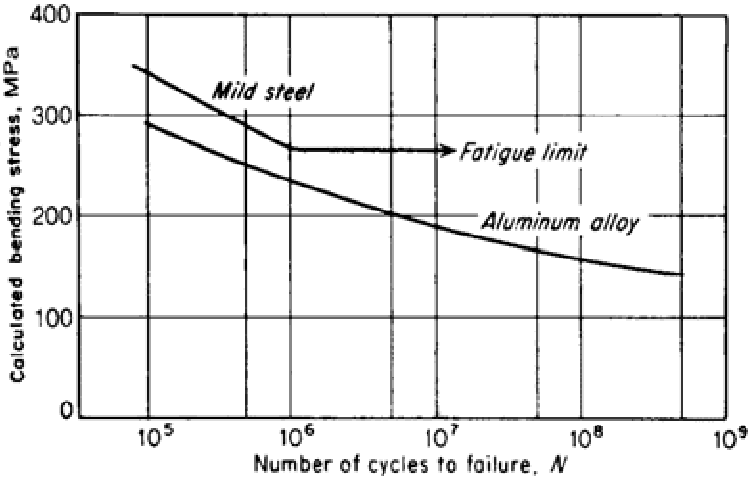


FIG. 1.69. Typical fatigue curves for ferrous and non-ferrous metals.

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.

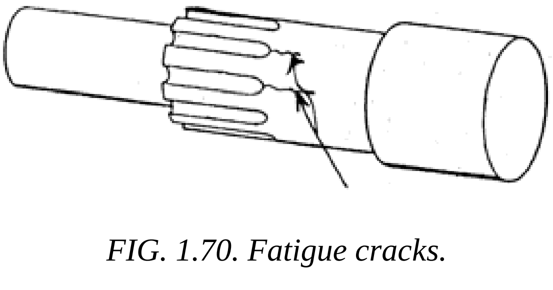


FIG. 1.70. Fatigue cracks.

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. 1.70).

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. 1.71 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.

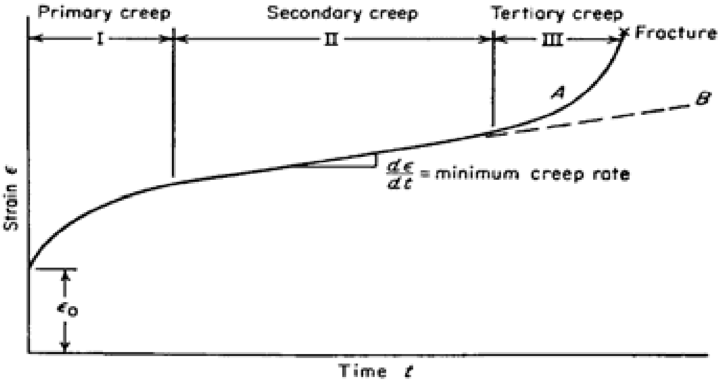


FIG. 1.71. Typical creep curve showing the three stages of creep A, constant-load test; curve B, constant-stress test.

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

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

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

1.4.3. Concepts of rupture development in metals

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

1.5. Quality and standardization

1.5.1. 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 judgment. 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 labeled 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. Reports and records

1.5.5.1. 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.

1.5.5.2. 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. Gases

There are three states of matter: solid, liquid and gas. The gaseous state is the most useful for leak detection, however liquids can also be used in some specific applications. The contained matter can be in gaseous, liquid or solid state.

In the context of this training manual, it is important to understand that gases can be the gases used for testing, or gases which constitute the contained substance. It is also important to note that safety dictates that there be no contact between oxidizing gases (i.e. oxygen or chlorine) and gases (or other materials) containing hydrocarbons.

2.1.1. Types of gases

It is convenient to recognize three classifications of gases. These are oxidizers, inert gases, and flammable gases.

Oxidizers are not flammable by themselves but will contribute to combustion as an oxidant. Examples include air, chlorine, fluorine, nitric oxide, nitrogen dioxide and oxygen.

Inert gases do not take part in combustion processes and they do not react with other materials. Examples include argon, carbon dioxide, helium, neon, nitrogen, and xenon.

Flammable gases, when mixed in the right concentrations with an oxidizer, will burn or explode if ignited. Some examples include acetylene, ammonia, butane, carbon monoxide, hydrogen, propane, and methane.

2.1.2. General equation of gases

A series of laws or standard formulae have been developed to explain the behaviour of gases as the temperature, pressure and concentrations are changed. While these relationships can be applied to test or contained gases, they are individually based on maintaining one or more properties constant.

2.1.3. Ideal gas law (formula and application)

The ideal gas law applies to all ideal[1] gases and mixtures of ideal gases. It is based on several more basic laws (Boyle’s law, Charles’ law, and Avagadro’s principle) which explain the relationships between volume and pressure, volume and temperature, and volume and quantity respectively. The general equation combines all variables into one equation, which becomes the equation of state for a classical ideal gas.

The ideal gas law is expressed as:

$$PV = nRT \tag{2.1}$$

where

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[1] An **ideal gas** is a theoretical gas composed of a set of randomly-moving, non-interacting point particles. Most gases act as ideal gases within normal temperature and pressure ranges.

P is the pressure

V is the volume

n is the amount of substance of the gas (in moles)

R is the gas constant (8.314 $J \cdot K^{-1} mol^{-1}$)

T is the absolute temperature

2.1.4. Pressurization of gases

The relationship between pressure and volume and temperature for gases is an important consideration for leak testing. From this law, we understand that at a given temperature, pressure and volume are inversely proportional. That is, if the pressure increases, the volume decreases, and vice-versa. If temperature is increased, then the pressure-volume combination must increase so pressure increases if volume is kept constant or volume increases if pressure is kept constant or both components may change. The practical meaning of this can be illustrated by considering a simple gas cylinder, such as that used for cooking gas or propane. The container is fixed in volume; therefore if heat is applied to the contents, then the pressure will increase. Most containers for which leak detection is considered will be fixed in volume.

Fluid pressure is defined as a force per unit area. In liquids and gases, the pressure at a given point is the same in all directions. In general, for all gases and liquids the greater the depth of immersion, the greater the internal pressure. Gas pressure is a measure of the work done to compress gas into a specific volume, and to contain it at that volume.

It helps to consider that one mole (a measurable quantity) of gas will, if unconstrained, occupy 22.4 litres of volume. Any restraint imposed, such as containment, will result in the gas applying a force to its containing envelope.

2.1.5. Effects of temperature, atmospheric pressure and vapour pressure

In accordance with the Ideal Gas Law, any increase in temperature, if volume is constant, will result in an increase in pressure, directly proportional to the increase in temperature.

Atmospheric pressure is the pressure exerted by the total weight of the blanket of gas that surrounds the planet, distributed evenly over all surfaces that support the blanket, in direct proportion to the area of the surface. This pressure is expressed in pounds per square inch or Pascals.

Vapour pressure is the pressure exerted above a liquid as its molecules leave and return to the surface.

When a solid or a liquid evapourates to a gas in a closed container, the molecules cannot escape. Some of the gas molecules will eventually strike the condensed phase and condense back into it. When the rate of condensation of the gas becomes equal to the rate of evapouration of the liquid or solid, the amount of gas, liquid and/or solid no longer changes.

The gas in the container is said to be in equilibrium with the liquid or solid.

From these considerations, it can be noted that there is an atmospheric pressure that results from the amount of air supported by the surface. This pressure is generally accepted to be 15 pounds per square inch at sea level. If the vapour pressure in a closed container is the same as the atmospheric pressure, it can be seen that there is no extra force to be exerted, the gases on the two sides of the container are the same, and leaks will not occur.

If the vapour pressure inside the container exceeds the atmospheric pressure, then a breach will result in the escape of the contained gas. If on the other hand, the container is kept at a pressure below the atmospheric pressure (in a vacuum), then a breach will result in the outside gas, air, being drawn into the container.

2.2. Basic knowledge of leaks and leakage

2.2.1. Basic knowledge of leaks and leakage through a confining wall

Some terms used in this manual are specific to the leak testing method. Reference is made to the *pressure envelope* or *pressure boundary*. Any opening across this boundary is referred to as a *breach*. Movement of any material, gas, liquid or solid, across this pressure boundary (through this breach) is a *leak*. The direction of movement of this material across the boundary is the *leak path*.

In more formal terms, any undesirable interconnection between isolated parts of a system or between two systems is a leak. A leak is suspected if there is any abnormal behaviour of a system, such as loss of pressure, contamination of product or loss of process efficiency. A leak could be the result of an unintended crack, hole or porosity in an enveloping wall or joint. Leak testing might also be a quality assurance method, to prove the integrity of the pressure boundary.

There is an increasing need for products and technologies that for their realization require hermetically closed elements, vessels and tubes. Leaks create serious problems in process plants or in pipelines, spoiling the quality of the final product, rendering the entire process inefficient due to content or coolant losses, or reducing the transportation capacity of water or commodity pipelines. If a small leak remains undetected, it could become a major leak, catastrophic in its effect on ground water, streams, or soil.

A leak, therefore, is an ‘unintended’ breach of a fluid envelope such as a pipe or tube, a vessel, a membrane, a container or, generally a confining wall. A leak allows contents to either leak out from the containment or to be contaminated by allowing entry to an external component. Leaks are generally specific to fluids: liquids and gases, however there are other applications where the contained material is a solid, such as a powder or slurry, as long as it flows. It is also important in an increasing number of applications to measure the leak rate, perhaps to determine the significance of the breach.

2.2.1.1. Mechanism of outgassing

Outgassing is the release of a gas that was dissolved, trapped, frozen, absorbed or adsorbed in some material. It can include sublimation and evapouration which are phase transitions of a substance into a gas, as well as desorption, seepage from cracks or internal volumes and gaseous products of slow chemical reactions. Boiling is generally thought of as a separate phenomenon from outgassing because it consists of a phase transition of a liquid into a vapour made of the same substance.

2.2.1.2. Real leaks and virtual leaks

Virtual leaks are leaks which are a source of gas being released slowly within the envelope. An internal weld crack would be an example. It would be pressurized due to a pressure test or due to operating pressures. The trapped gas, in its own little pressure “container”, will slowly return to the main container, at a rate determined largely by the physical dimensions of the gas trap and potential flow paths, and the pressure differential between the trap and the main chamber.

There are four general categories of virtual leaks: gaps, cracks, surface contacts, and trapped pockets. The significant difference between a real leak and a virtual leak is that the virtual leak does not exit the test envelope.

2.2.1.3. Pressure-time relationship

The effect of time on the pressure within the pressure boundary will depend on the rate of flow through the leak. This in turn depends on the type of fluid flow in the leak, and the pressure differential. In general, one would expect to see pressure drop gradually with time.

2.2.1.4. Different types of fluid flow in the leakage

Different basic laws relate leakage rate to pressure difference across the leak, the range of absolute pressures involved, and the nature of the fluid escaping through the leak. The three types of gas flow are:

(i) Viscous flow, which typically occurs in probing applications with gases leaking at atmospheric or higher pressures
(ii) Molecular flow, which usually occurs in leaks under vacuum testing conditions.
(iii) Transitional flow, which occurs under test conditions intermediate between vacuum and pressures higher than atmospheric pressure.

Liquid phase leak detection systems include water based systems and oil based systems, and usually carry a dye for ease of visible leak location.

2.2.2. Leak conductance

The property of a gas flow system that permits gas to flow is called conductance. Conductance (C) is analogous to electrical conductance (G-the reciprocal of electrical resistance R).

With gas flow through the conductance of a leak path, the flow rate Q is analogous to the electric current i. The pressure drop (R_1-R_2) over the length of the path is similar to the voltage drop across a resistance in an electrical circuit, V. The gaseous conductance of a tubular passageway permits the leakage of a gaseous constituent when the pressure drop exists between the ends of passageway.

2.2.2.1. Sensitivity of detector and sensitivity of test

While it is possible to tabulate the relative sensitivities of the leak testing techniques, any such tabulation must as well consider other factors which influence the test, such as geometry, sampling efficiency, tracer economy and noise (or contamination).

2.2.2.2. Calculation of leakage

The leakage rate will depend on the type of gas flow, the pressure differential, and the size of the breach. The leak detection system used will dictate whether it will be possible to actual calculate leakage rate. It is clear that in many applications it is sufficient to know that a leak exists.

2.2.2.3. Calculation of conductance from nomograms and conductance in series and in parallel

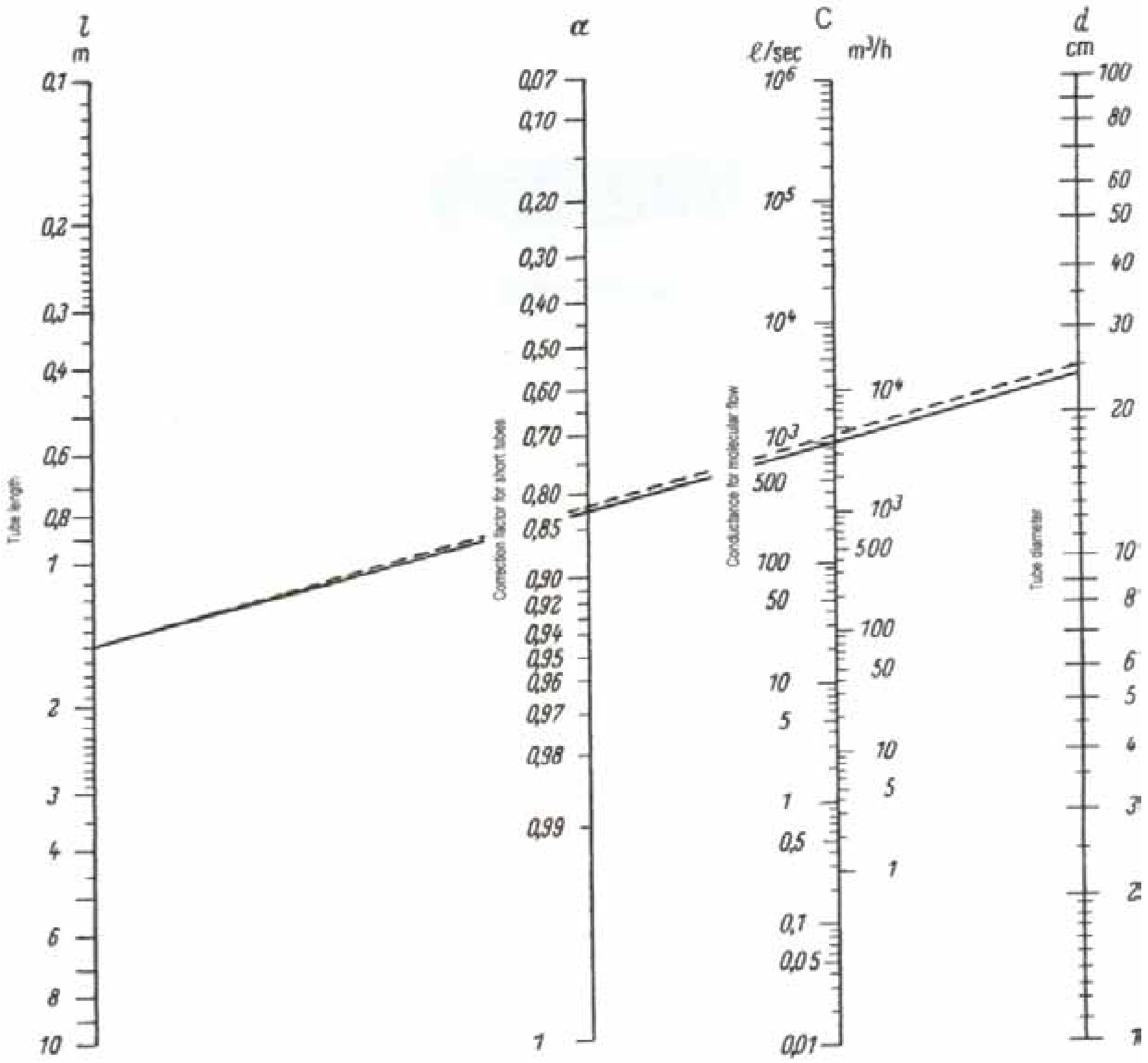
A nomogram is a graphic calculating device used to closely estimate a third value from two known values. Typically, the nomogram consists of two vertical scales which represent known values, and a third vertical scale from which a result can be obtained. A straight edge connects the two known values; on the third scale, the point where this straight edge crosses the scale is the derived value. In fig. 2.1, the example quoted has a fixed length of pipe, and a desired conductance (C), so a line connecting the two values is extended to determine the necessary diameter (fourth scale, d).

Nomograms are widely used in the calculation of fluid flow rates and can be effectively used in the calculation of leak rates.

Because fluid conductance (G) and electrical resistance (R) have similarities, it is possible to use this relationship to model the effect of parallel and series fluid paths.

TABLE 2.1. RELATIVE SENSITIVITIES OF SPECIFIC LEAK TESTING TECHNIQUES

Technique	Minimum Detectable Leakage Rate, Mbar-L/s	Comments
Pressure Change (Mass Loss)	Time limited	Good overall quantitative measure, no information on location.
Acoustical	10^{-3}	Leak detection only, fast, can detect from a distance.
Chemical Penetrants	10^{-5}	Simple to use, good for location, requires cleanup.
Bubbles	10^{-5}	For leak location, requires clean up
Thermal Conductivity	10^{-5}	Simple, compact, portable, inexpensive. Operates in air.
Halogen	10^{-6}	Operates in air, sensitive, portable loses sensitivity with use, sensitive to ambient halide gases
Mass Spectrometer	10^{-9}	Most accurate for vacuum testing, expensive, relatively complex.
Radioactive Tracers	10^{-10}	Requires a radioactive material with associated handling restrictions and control.



Example: What diameter d must a 1.5-m-long pipe have so that it has a conductance of about C = 1000 l / sec in the region of molecular flow? The points l = 1.5 m and C = 1000 l/sec are joined by a straight line which is extended to intersect the scale for the diameter d. The value d = 24 cm is obtained. The input conductance of the tube, which depends on the ratio d / l and must not be neglected in the case of short tubes, is taken into account by means of a correction factor α. For d / l < 0.1, α can be set equal to 1. In our example d/l = 0.16 and α = 0.83 (intersection point of the straight line with the a scale). Hence, the effective conductance of the pipeline is reduced to C · α = 1000 · 0.83 = 830 l/sec. If d is increased to 25 cm, one obtains a conductance of 1200 · 0.82 = 985 l / sec (dashed straight line).

FIG. 2.1. Nomogram used to calculate conductance through a fluid path.

Resistance, by definition, is the measure of ‘friction’ a component presents to the flow of a fluid through it.

Mathematically, conductance is the reciprocal, or inverse, of resistance:

$$\text{Conductance} = \frac{1}{\text{Resistance}} \tag{2.2}$$

The greater the resistance, less the conductance, and vice versa. In a parallel circuit, having multiple paths (branches) for fluid flow reduces total resistance for the whole circuit, as electrons are able to flow easier through the whole network of multiple branches than through any one of those branch resistances alone. In terms of resistance, additional branches result in a lesser total (fluid flow meets with less opposition). In terms of conductance, however, additional branches results in a greater total (fluids flow with greater conductance):

Total parallel resistance is less than any one of the individual branch resistances because parallel resistors resist less together than they would separately, as depicted in fig. 2.2:

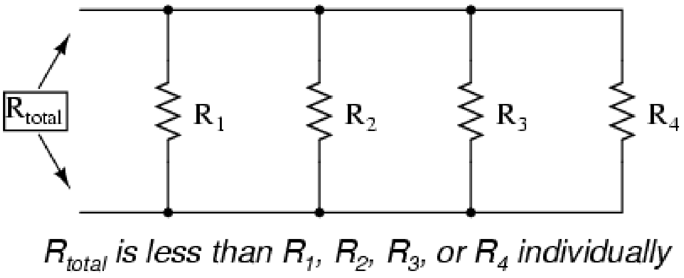


FIG. 2.2. Multiple flow paths result in lower resistance.

Total parallel conductance is *greater* than any of the individual branch conductances because parallel resistors conduct better together than they would separately as depicted in fig. 2.3:

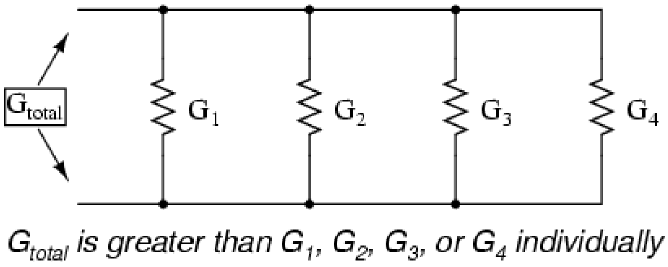


FIG. 2.3. Parallel flow paths result in greater total flow. This example uses the analogical equivalence between electrical current and fluid flow.

The total conductance in a parallel circuit is equal to the sum of the individual conductances:

$$G_{total} = G_1 + G_2 + G_3 + G_4 \tag{2.3}$$

Similarly, for a series fluid flow circuit, it can be shown that the conductance is the reciprocal of the total resistance. In this case the resistances are added together.

An example of a parallel flow path would be multiple leaks in a boiler header, as shown in fig. 2.4. A series flow path would be the flow of a fluid through pipes of varying diameters, each diameter contributing to the total resistance.

FIG. 2.4. Leaking tube to header welds provide multiple parallel leak paths.

2.2.3. Definitions and units

2.2.3.1. Units of pressure, volume and flow rate in leak testing

For many applications of leak testing, the objective is simply to detect whether leakage is occurring and perhaps, to locate the exit point of the leak.

For other applications, it is desirable or even critical to assign a quantity to the leakage, to identify the rate of loss and hence the criticality of the escape. The leakage rate indicates how much gas is flowing through a leak per unit of time.

The significant quantitative measurement resulting from leak testing is the leakage rate or mass flow rate of fluid through one or more leaks. Since the volume and pressure are mutually dependent, it is necessary, when specifying the volume of a leak in a volume unit (Litre) per unit of time (sec), to also specify at which pressure this volume exists.

Let us take the example of a single litre of gas which is held in a container under a pressure of 10 bars. After it has flowed through a leak in the wall of the container to the outside world, then, under normal atmospheric conditions (1 bar absolute pressure), it will take up a volume of 10 litres. With liquids, a statement of the volume is sufficient to describe the amount of liquid, but with gases the compression factor has to be taken into account.

Leakage rate thus has dimensions equivalent to pressure times volume divided by time.

In considering leakage rate units, it is useful to look at their components.

Pressure is expressed in atmospheres (atm), in bars, torrs, pounds per square inch (psi), or Pascals (Pa), often depending on local custom and history.

Volume is expressed as litres (L), cubic centimetres (cc), or cubic metres (m^3).

One common unit system measures leakage rate in terms of Pascal-cubic metres per second (Pa-m^3/s). In this publication, however, the more internationally accepted unit, the millibar-litre/s (mbar-L/s) system is used.

The equivalence of some of the most used units is listed below.

Volume:

1 L = 1000 cc = 10^3 cc
1 cc = 10^{-3} L
1 m^3 = 10^6 cc = 10^3 L

Pressure:

The term 'standard' (std) means at atmospheric pressure as in: std-cc/s, defining the pressure at which the volume is measured.

1 bar = 1 atm (1 mbar=10^{-3} bar)
1 mbar = 100 Pa; 1 Pa = 0.01 mbar
1 mbar-L = 1 bar-cc = 100 Pa-cc;
1 atm = 760 torr (used for vacuum measurements)

2.2.3.2. Relationship between the main measurement units

The principal unit used in this publication for the measurement of leakage is the **mbar-L/s**. This is equal to **std – cc/s**, and to **10 Pa-m^3/s**.

$$1\,\text{mbar-L/s} = 1\,\text{std-cc/s} = 10\,\text{Pa-m}^3/\text{s} \qquad (2.4)$$

2.2.3.3. Measurement of vapour pressure

Vapour pressure is measured in the standard units of pressure. The International System of Units (SI) recognizes pressure as a derived unit with the dimension of force per area and designates the pascal (Pa) as its standard unit. One pascal is one newton per square meter ($N \cdot m^{-2}$ or $kg \cdot m^{-1} \cdot s^{-2}$).

Experimental measurement of vapour pressure is a simple procedure for common pressures between 1 and 200 kPa. Most accurate results are obtained near the boiling point of substances and large errors result for measurements smaller than 1 kPa. Procedures often consist of purifying the substance to be tested, isolating the substance in a container, evacuating any foreign gas, and then measuring the equilibrium pressure of the gaseous phase of the substance in the container at different temperatures. Better accuracy is achieved when care is taken to ensure that the entire substance and its vapour are at the prescribed temperature. This is often done by submerging the containment area in a liquid bath.

2.3. Tracer fluids

Tracer fluids are gases or liquids that are added to the contents of a pressure envelope for the specific purpose of identifying leaks. Tracer fluids are selected to produce an odour, colour or other detection enhancing property, thus enabling the timely detection of a leak of a substance which is odourless or otherwise undetectable.

2.3.1. Liquid and gaseous tracers

There are a wide range of tracer fluids, depending on the industry, the application, and the precision required. Tracer fluids must have certain physical properties, they should be nontoxic and easy to handle. There must be no chemical interaction between the tracer and the contained fluid. They must offer an easy means of detection, perhaps through odour or enhanced visibility.

2.3.2. Physical principles for the detection of different types of tracers

Odour based tracers are detectable through human or electronic sniffers. Visible tracers are detectable by the aided (such as by a boroscope or video camera) or unaided human eye because their colour has been chosen to present a strong contrast to the background of the system.

2.3.3. Ionization of gases and mass spectrometry

Ionization is the physical process of converting an atom or molecule into an ion by adding or removing charged particles such as electrons or other ions. A positively-charged ion is produced when an electron bonded to an atom (or molecule) absorbs enough energy to escape from the electric potential barrier that originally confined it, thus breaking the bond and freeing it to move. The amount of energy required is called the ionization potential. A negatively-charged ion is produced when a free electron collides with an atom and is subsequently caught inside the electric potential barrier, releasing any excess energy.

The result of the ionization process is the presence of ions which can then be detected.

A mass spectrometer is used as a very sensitive instrument for determining the existence of a leak and to pin-point its exact location in industrial components. For components under pressure, helium gas is added at a suitable test pressure.

Measurement at locations where helium may leak is then carried out using a portable helium mass spectrometer. The sensitivity of this method is up to 10^{-9} mbarL/s.

The mass spectrometer works by deflecting gas particles through a magnetic field which deflects the ionized particles. When helium is added to the contained gas, the mass spectrometer measures the mass of helium ions that are escaping the envelope.

2.3.4. Ionizing radiation

Ionizing radiation is radiation with enough energy that, during its interaction with an atom, can remove tightly bound electrons from the orbit of an atom, causing the atom to become charged or ionized.

The use of radioactive materials as tracer materials builds upon two factors. Firstly, the state of the art of radiation detection is such that very minute quantities of radioactive materials can be easily detected. Secondly, the introduction of a radioactive tracer into a pressure envelope (or transport system) will result in no chemical interaction with the product, no long term changes in the product and an easily dispersed tracer material.

3. TEST TECHNIQUES

3.1. Characteristics of methods and techniques of leak testing

The leak testing method collates a number of conventional and unconventional NDT methods to address a common function—the detection, location and measurement of leaks. Each of these methods is considered to be a technique within the LT method, and each has characteristics that dictate its use in different applications. It is convenient to compare sensitivity, and to this end, a standard unit of leak rate has been adopted for this publication. This unit is mbar-L/s (equivalent to atm^3*s^{-1}).

Visual examination as a formalized NDT method is carried out in all industrial plants, either looking for or accidentally discovering leaks of process fluids. (No instrument is necessary to observe a puddle of fluid underneath a vessel.)

Overpressure tests (hydrostatic tests) are regularly performed on pressure vessels, hydraulic components and a wide variety of pressure containing equipment. If the test is performed with a liquid, one can examine for leakage or wetting due to the escape of the pressurizing fluid. If the test is performed with a gas, then it is common to coat the area of inspection with a suitable fluid and to watch for the formation of bubbles. This technique permits the detection of leaks in the order of 10^{-5} mbar-L/s (refer to Table 2.1).

The systematic observation of pressure change can reveal leakage of a pressurized vessel or a vacuum system. The system can use on-line pressure gauges to record pressure drops, or a test liquid can be coated on the outside of a vacuum container, and its effect on internal pressure, as it is drawn through any leak, can be noted.

It may be convenient to use a change in a chemical reagent as an indicator of a leak. For example, leaking ammonia gas may be detected by its reaction with hydrogen chloride producing dense white fumes of ammonia chloride.

Fluorescent or visible dye liquid penetrants are widely used for the detection of flaws which are open to the surface. They can equally applied to the detection of leaks. A low viscosity fluid has a high degree of surface migration; it can be painted on one side of a surface and the opposite side is observed for seepage. It can also be added to a service liquid as a tracer. The technique is simple, low cost, and the sensitivity can be as high as 10^{-6} mbar-L/s.

Leaks emit sound of a frequency that is related to the pressure, hole size and geometry of the breach. Acoustical leak detection uses the sonic or ultrasonic signal generated by the escaping fluid as it expands through the leak orifice. The technique uses a sensitive microphone or an accelerometer. It is simple, fast and non-contacting, however, it is sensitive to other environmental noises. It enables detection of leak rates as low as 10^{-3} mbar-L/s. A similar approach, acoustic emission leak detection, detects equipment transmitted high frequency sound waves, travelling along a solid path.

A helium mass spectrometer leak detection instrument can be used to determine leak existence and location for many industrial components. For units under pressure, helium is added to the vessel at a suitable test pressure. Measurement at locations of interest can find leak rates as low as 10^{-9} mbar-L/s.

Radiotracers provide a powerful alternative to other leak detection techniques. They are the most sensitive tools (10^{-10} mbar-L/s) available and they can be used on-line (while the system or equipment is operating). The addition of very small concentrations of radioactive isotope provides an extremely detectable level of measureable and detectable radiation.

3.1.1. Locations of leaks

3.1.1.1. Pressurized systems and evacuated systems

For a system whose internal pressure exceeds the atmospheric pressure, it follows that a leak will force contents out through the breach in the envelope. For those systems where there is an internal vacuum, then the leak will be inwards through the envelope. Systems may also be pressurized to a specified level for a test, or a vacuum may be created, usually in a small system.

3.1.1.2. Tracers inherent to the system and incorporated systems

If the contents permit, then they may serve as an inherent leak detection system during operation. A sudden or even a slow pressure drop will signify a leak. The system must have on-line instrumentation that is sensitive enough to detect this drop in pressure. The contents may themselves have the properties of a tracer, perhaps in odour or colour. A rust stain around a tank valve is a good visual indication that there is a continuous, though small, leak at that valve.

3.1.1.3. Detector inherent to the system and detector applied to the system

One of the factors involved in using system fluid as an inherent detection system is when the system fluid is hazardous. For example, natural gas is odourless, and it is normal practice to add a tracer gas so that leaks may be sensed by the odour. This is particularly effective in populated areas. Were the system to rely on a pressure drop, which would also signal a leak, there would be an opportunity for large quantities of highly flammable gas to escape before detection. Hydrogen sulphide gas (H_2S), on the other hand, is both odourous and hazardous. A leak of this gas would be readily detected without the addition of a tracer. The decision to rely on an added tracer or on the indicating properties of the content gas is one which can only be made for the specific system under consideration. Both approaches are effective, and use of inherent properties is more economical.

3.1.1.4. Dynamic and static tests

Tracer gas tests can be conducted while the system is working (for example, the natural gas tracer additive discussed in the previous section). Where there is an operational or safety reason, the test can be static, involving slight or greater over pressurizing with a tracer added to the system.

3.1.2. Leakage measurements

3.1.2.1. Multiple closed systems: in vacuum with tracer gas, closed with air

The pressure envelope may be simple, i.e. one vessel, one pressure, or complex, perhaps one vessel with several subcomponents at different pressures. If multiple closed systems are involved, then it will be necessary to measure the gas leakage rate at the interface between two systems. The point here is that an overall closed system may hide internal leaks that contaminate the system but do not escape to the environment.

3.1.2.2. Mass balance system

Simple systems are those which involve one working fluid and one pressure boundary. One technique that can be used with a closed system, operating or static, is the Mass Balance System. This technique presupposes that it is possible to accurately and continuously measure the mass of the system or partial system contents. This technique detects spontaneous changes in the mass balance of the contents of a system and can be easily automated. When a leak occurs, the mass balance system usually first gives an alarm. Specific instructions are provided for response to the alarm. When no operator action follows in a pre-determined period (e.g. 10 minutes), some systems automatically close the isolation valves in the affected part of the system or in the entire system. The consequences can be that production and storage are likely to be affected. The mass balance system is believed not to be very accurate and can result in false indications of leakage.

3.1.2.3. Leakage to vacuum or to atmospheric pressure

Whether the system contents leak to a vacuum or to atmospheric pressure depends on the pressure differential. Where the receiving environment is at a lower pressure than atmospheric pressure, then a vacuum should be used. Measurement is based on flow rate.

Leak tests can be conducted while the pressurized system is at rest or when it is operating. Measurement is more difficult with a dynamic system because there is continuous replenishment, whereas for a static system there is no inflow, and thus measurement begins with a fixed mass.

3.2. Different techniques for the application of leak tests

A basic non-destructive test for leaks is visual examination. Escaping fluid can create puddles, drips or stains. These may or may not be accompanied by observable pressure loss. The hydrostatic test used to prove the condition of a new boiler, for example, consists of pressurizing the boiler or one of its components to an internal pressure somewhere in the range of 1.25 to 1.5 times its working pressure, to hold at that pressure for a defined period of time, and to examine the entire pressure boundary for leakage.

3.2.1. Bubble test

3.2.1.1. Establishing operative conditions for bubble and foam testing

The bubble emission method requires a gas pressure differential to be established across the pressure boundary to be tested. A test liquid is placed in contact with the lower pressure side of the pressure boundary. Gas leakage through the pressure boundary can then be detected by observation of bubbles formed in the detection liquid or liquid film at the exit points of leakage through the pressure boundary. This method provides immediate indications of the existence and location of large leaks (10^{-2} to 10^{-4} mbar-L/s). Longer inspection times may be needed for the detection of small leaks (10^{-4} to 10^{-5} mbar-L /s).

In bubble testing, the probing medium is the gas that flows through the leak due to the pressure differential. The test indication is the formation of visible bubbles at the exit point of the leak. Rate of bubble formation, size of bubbles formed, and rate of growth in size of individual bubbles provide the means for estimating the size of leak.

3.2.1.2. *Liquids for bubbles and solutions for foams*

Bubble tests are often classified according to the test liquid and means of application. In the liquid immersion ("dunking") technique, the pressurized test system is submerged in the test medium. In the liquid film application method, a thin layer of the test medium is flowed over the low pressure surface of the object. For large leaks, a foam blanket is established by the applied liquid; the rapid escape of gas through this blanket blows through the blanket and reveals the location of the leak.

FIG. 3.1. Foam film to detect gas bubbles.

3.2.1.3. *Typical applications*

Bubble testing for leak location is one of the most widely used non-destructive tests because its simplicity permits its use by workers with minimal training. On an elementary scale, bubble tests can be used for testing connections on domestic propane systems, or for testing tire inner tubes in a soapy bath.

For small vessels, it is appropriate to pressurize the entire vessel, and coat all welds with a detecting medium. For larger vessels, and for welds in piping, it is possible to coat the inspected area with bubble solution, and then use a vacuum box to create the pressure differential. Active pressurized piping joints and connections in the vessel can be examined by coating individual or suspect welds when the vessel is operating at a pressure greater than the external pressure.

Heavier structures, such as those used in hydro power installations, can be examined using this method. In this case, a vacuum box is needed to create the pressure differential and the welds are examined in short sections, section length being related to the size of the vacuum box.

3.2.1.4. *Advantages*

The advantages of bubble leak testing relate to its simplicity, rapidity and economy. It is a fairly sensitive leak detection technique and enables the inspector to locate the exit points of leaks very accurately. Another advantage is that it readily detects very large leaks, yet provides rapid responses for small leaks.

It is not necessary to move a probe or sniffer over the surface being inspected. Often it permits the examination of the entire pressurized component to be inspected simultaneously. *Immersion testing* permits independent location of individual leaks. Leaks detected by this technique are real leaks, as opposed to the virtual leaks found in acoustic tests.

3.2.1.5. Limitations

Conditions that interfere with bubble testing are contamination of the test specimen surfaces, improper temperatures of test specimens, contaminated or foaming test liquids, improper viscosities of test liquids, excessive vacuum over surface of test liquid, and low surface tension of the test liquid which leads to clogging of leaks. Prior bubble testing in general can clog leaks or lower the sensitivity of subsequent leak testing by more sensitive methods.

For the immersion or dunk testing technique, the handling of the test item is important. Small components can be easily submerged, and very little pressure difference is sufficient, however larger heavy objects cannot be practically tested by this method.

3.2.2. Testing by means of pressure

3.2.2.1. Establishing operative conditions for the test of absolute pressure

Absolute pressure takes into account that measurements are usually made in ambient conditions that reflect atmospheric pressure. It there is necessary to correct for ambient pressure when establishing the zero pressure point for calculations. Differences between two pressures when measured under identical conditions are in absolute terms.

3.2.2.2. Pressurization of gases

Gases are pressurized by applying heat or external forces to decrease the volume occupied by a unit mass of gas. Following the ideal gas law, if external pressure is increased, the volume will decrease and the resisting pressure increase. If the volume is held constant and the gas is heated, it will want to expand. The resistance to this expansion results in an increased pressure of the gas in that specific container.

3.2.2.3. Effect of changes in temperature, vapour pressure and atmospheric pressure

As described then, if heat or external pressure are imposed on the system, the contained material will want to expand, and the contained pressure will increase. If the enabling pressure is atmospheric, then changing environmental altitude will result in a lower ambient pressure as one goes higher, and a lower pressure as one goes lower. The implication of this is that the parameters of the test may need to be changed.

3.2.2.4. Pressure decay technique

The pressure decay testing method measures the decrease in pressure in an object. The test object is initially inflated and then a reference pressure is established. After a designated amount of time, the pressure is monitored again, and the initial and final measurements are compared. The change in pressure is used to calculate the leak rate given the internal volume of the device. Pressure decay is able to detect minute changes in pressure. A drop in pressure signifies a leak; the greater the pressure drop, the larger the leak. This method is convenient in that it is easily automated and dry.

This technique can be used to test small parts at high speeds (see Fig. 3.2). A 0.3-inch diameter by 1.2-inch long medical filter can be tested to see if the filter is in place, if it is plugged and if it allows correct air flow. Test time from clamp to next clamp is 0.85 second at 15 psi. Also, a molded vacuum tube connection for the automotive industry (12 inches of 0.2 inch inner diameter tube with circular molded fitting) can be tested in a test time of

3.5 seconds, clamp-to-clamp at 15 to 30 psi, depending on part. Each test result can be made permanently recorded and traceable, if required.

A pressure drop system reacts to deviations from normally experienced pressure drops in the liquid ammonia pipeline. It is often based on a series of pressure drop measurements. When a deviation from the predetermined setting is detected from the relevant pipeline location, the corresponding isolation valves may be automatically closed. As this method tends to detect only big leaks, the pressure drop system is often combined with another leak detection method such as ammonia sensors or a mass balance system.

3.2.2.5. Determination of leak percentages by pressure drop

For compressor systems that have start/stop or load/unload controls, there is an easy way to estimate the amount of leakage in the system. This method involves starting the system when there are no demands on it (when all the air-operated, end-use equipment is turned off). A number of measurements are taken to determine the average time it takes to load and unload the compressor. The compressor will load and unload because the air leaks will cause the compressor to cycle on and off as the pressure drops from air escaping through the leaks.

Total leakage (percentage) can be calculated as follows:

$$\text{Leakage}\,(\%) = \frac{T}{(T + t)} \times 100 \qquad (3.1)$$

where T = on-load time (minutes)

t = off-load time (minutes)

Leakage can also be estimated in systems with other control strategies if there is a pressure gauge downstream of the receiver. This method requires an estimate of total system volume, including any downstream secondary air receivers, air mains, and piping (V, in cubic feet). The system is started and brought to the normal operating pressure (P_1). Measurements should then be taken as a function of the time (T) it takes for the system to drop to a lower pressure (P_2), which should be a point equal to about one-half the operating pressure.

Leakage can be calculated as follows:

$$\text{Leakage (cfm free air)} = \frac{V\,(P_1 - P_2)}{T} \times 14.7 \times 1.25 \qquad (3.2)$$

where: V is in cubic feet

P_1 and P_2 are in psi

T is time in minutes

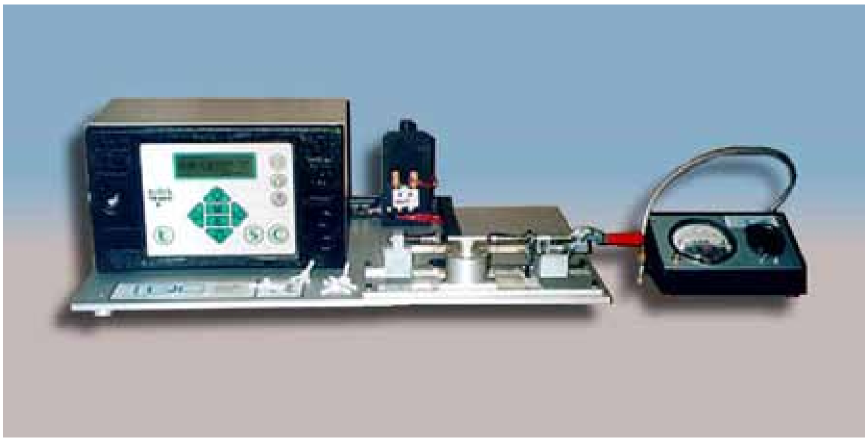


FIG. 3.2. Leak testing small medical tubing connection.

3.2.2.6. Positioning of sensors for temperature and dew point

Temperature and dew point influence measured pressure. Sensors for these two parameters need to be positioned as near to the pressure measurement sensor as practical, as both may vary throughout the system.

3.2.2.7. Filling in data sheets

As in all non-destructive test methods, completeness of records is a critical step. If automatic recording systems, strip chart or electronic data capture, are available, then there will be enough data available to complete the leak rate or pressure drop calculation. Nevertheless all parameters of the test should be recorded manually where practical, along with general environmental data such as ambient temperature. This should be organized prior to the test on a data sheet.

3.2.2.8. Advantages and limitations

The effectiveness of the pressure drop technique depends on the complexity of the system, the ease with which one can access the pressure envelope, and the ease with which the pressure can be controlled. In general, it is most effective for static testing.

3.2.3. Test by detection of halogens

Halogen leak detectors are used in the detector-probe mode (to 10^{-3} mbarl/s), requiring that the system be pressurized with a gas containing an organic halide, such as one of the Freons. The exterior of the system is then scanned with a sniffer probe sensitive to traces of the halogen-bearing gas. The principle is based on the increased positive ions (K or Na) emission because of sudden halide composition presence. The ion current is the measure of a leak size. Halogen detectors can be used also in an internal mode: the evacuated vessel is connected to the detecting instrument and is sprayed by Freon. In this manner, test sensitivity is up to 10^{-7} mbarl/s and can be used in rough, medium and high vacuum.

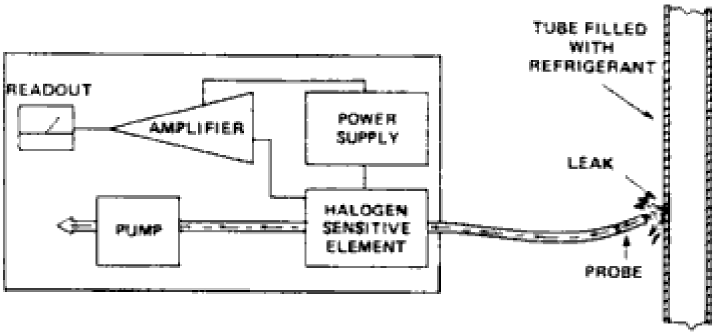


FIG. 3.3. Halogen leak detector.

3.2.3.1. Helium leak testing

(a) Test with helium spectrometer

Functioning principle and operating conditions for the leak test with helium spectrometer depends on the separation of helium from other gases in a vacuum. It is accomplished by ionizing a gas sample containing helium, pushing the sample through a magnetic field, and collecting the helium ions as they emerge. Since helium ions exit along a different path from all other ions, collection of helium is reasonably simple. The current produced by the helium ion flow is used to drive an ammeter. Often audio alarms, and visual display on leak detection system to give information and warnings about leak levels. Ionization, separation and collection takes place within a spectrometer tube, which is the heart of the system.

In the spectrometer tube, the heart of the helium mass spectrometer, the electrons produced by a hot filament enter an ionization chamber under vacuum, and collide with gas molecules, creating within the chamber ions quantitatively proportional to the pressure in the ion chamber. These ions are repelled out of the ion chamber, under vacuum, through the exit slit, by a repeller field. The combined electrostatic effect of the repeller, exit slit, focus plates, and ground slit collimates the ion beam so that it enters the magnetic field as a straight "ribbon" of ions.

The mass spectrometer method involves pressurizing the test object with a helium mixture and placing it in a snug-fitting vacuum chamber. The air is then evacuated from the chamber, creating a pressure gradient between the internal volume of the part and the vacuum. The helium molecules move out of the part through any porosity, holes and cracks. A mass spectrometer then samples the air inside the chamber and finds individual atoms of helium (see fig. 3.4).

The initial cost of a snug-fitting chamber is high, requiring precise machining and extremely tight seals, limiting the practical part size. A basic operation limitation is that a large leak will saturate the vacuum container with helium. This requires several hours of flushing to lower the helium background to a workable level. A pre-test can be employed to weed out the gross leakers. Many air conditioner condensers (radiators) are quite large, but they still must not leak for 8 to 10 years. For these applications, a wand testing system has been developed which, while not as accurate as placing the part in a vacuum chamber, is superior to any other kind of test, and substantially less expensive than the vacuum chamber system.

Portable dry helium leak detectors are now widely used for large systems, as typically shown in fig. 3.5 for a pharmaceutical industry. A sniffer wand is used to collect the helium and gas mixture that is then pulled into a chamber for spectrometric analysis.

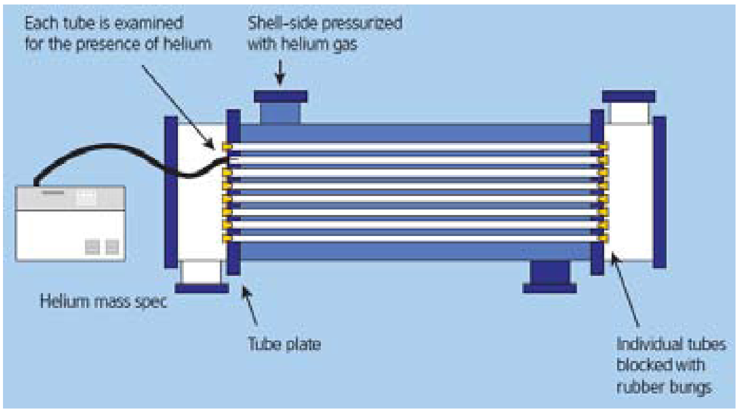


FIG. 3.4. Offline leak detection in heat exchanger using the helium mass spectrometer technique.

(b) Pressure and vacuum technology

Helium is present in only small amounts (5 ppm) in the ambient air. This results in low background noise and makes helium a very attractive gas for leak detection applications. In addition, helium is readily available on a worldwide basis, is not toxic or flammable and is an inert gas. Helium can be easily obtained in cylinders of various sizes and it only needs to be of welding-grade purity.

(c) Sensitivity of the test

This is the most sensitive test presently available. These testers are capable of detecting a leak of R600a refrigerant as small as 0.0028 ounce per year. In use, helium is usually a disposable item adding to cost, although recovery systems are now available. Electronic parts often are tested by placing them in a chamber and pressurizing with helium, and then placed in the vacuum chamber of the mass spectrometer to see if helium is drawn out. This method also will find porosity.

FIG. 3.5. Portable He leak tester being used in pharmaceutical industry.

(d) Helium tracers

Helium is used as a tracer because it penetrates small leaks rapidly. Helium has also the property of being non-toxic, chemically inert, inexpensive to produce, and present in the atmosphere only in minute quantities (5 ppm). Typically a helium leak detector will be used to measure leaks in the range of 10^{-6} to 10^{-13} mbar-L/s.

A flow of 10^{-6} mbar-L/s is slightly less than 1 ml per minute at Standard conditions for temperature and pressure (STP).

(A flow of 10^{-14} mbar-L/s is slightly less than 3 ml per century at STP.)

3.2.4. Advanced techniques

3.2.4.1. Radioactive tracers: Applicability, sensitivity and principle of test

Radioactive materials used as tracers offer the possibility of on-line measurements, providing information in the shortest possible time. Gamma radiation emitted by the radiotracers penetrates the vessel's walls and provides information about very small leaks even when direct access to the vessel is not possible. The emission of radiation is a specific property of the radioisotope, not affected by interference from other materials in the system; thus radiotracers have strong resistance against severe process conditions. Because the characteristics of the radiation differ from one radioisotope to another, multiple radiotracers may be employed and measured simultaneously if needed to locate the leaks. The success of radiotracer applications for leak detection rests upon high detection sensitivity for extremely small concentrations; for instance, some radiotracers may be detected in quantities as small as 10^{-17} grams. The amounts of radiotracer used are virtually insignificant. For example, 1 Ci (37 Bq) of 131I weighs 8 μg, while 1 Ci of 82Br weighs only 0.9 μg. That is why, when injected, they do not disturb the fluid dynamics inside the vessel under investigation and do not interfere with the product quality. The radiotracer technique is very sensitive; it enables the measurement of leak flows up to 10^{-10} mbar-L/s.

Radiotracers are the most sensitive tools largely used for on-line leak detection. The success of radiotracer applications for leak detection comes from the extremely high detection sensitivity for extremely small concentrations.

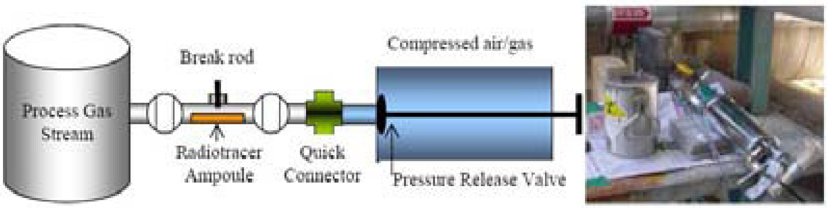


FIG. 3.6. A gaseous radiotracer injector.

3.2.4.2. Krypton-85 gas

The Krypton 85 Leak Testing technique is a highly sensitive technique used to measure fine and gross leak rates in high reliability devices. It is the preferred method to characterize small leak rates in critical military components. The technique was developed in the 1950's and is still in use today for evaluating military hybrids, commercial sensors, medical implants, silicon based MEMS packaging applications and many others. The device is placed into a specialized test chamber and pressurized with a gas mixture of air and small amounts of Krypton 85 gas, as shown in fig. 3.6. The mixture will then enter the package cavity if a leak is present. The advantages of Krypton 85 over other methods include extremely fast test times, lower overall testing cost, lower leak rate detection ($<10^{-12}$ mbar-L/sec), minimal absorption to glasses, leak site(s) identification and the ability to test in ambient conditions.

Like all radiotracer techniques, Krypton 85 tests are non-intrusive. They are economical when compared in terms of material cost. They are relatively easy to use.

3.2.4.3. Liquid penetrants and chemical tracers

(a) Applicability, sensitivity and characteristics of techniques

The liquid penetrant method of non-destructive testing is one of the simplest to apply using readily available and dependable materials. The basic principal is that a low viscosity liquid will be drawn into a tight opening by the principle of capillary action. The tighter the opening, the greater will be the penetration. Standard PT procedures call for applying the dye to the surface, leaving it a given period of time to allow it to enter into the opening, then cleaning off all surface traces of the penetrant as discussed in section 1.12. Once the surface is cleaned, a developer is applied to draw the penetrant back out to the surface. A brightly coloured dye is added to the penetrant material to make the retrieved penetrant extremely visible. When applied to a through crack (or leak), the same principles work. The dye is drawn into the breach, but for leak detection, the opposite side of the pressure envelope is examined with the use of a developer. A more sensitive technique uses fluorescent dye to enable detection of extremely small defects and use of an ultraviolet light to examine the opposite surface.

The process can be used on any system to which there is access to both sides of the pressure envelope. No pressure differential is necessary. Another variation is to add fluorescent or coloured dye to the contents of a liquid system as a tracer, and to examine for leaks from any accessible surface.

(b) Penetrant materials

To perform well, a penetrant must possess a number of important characteristics. It must spread easily over the surface of the material being inspected to provide complete and even coverage. It should be easily drawn into surface breaking defects by capillary action. While the penetrant must remain in the defect during the removal step, it should also be easy to remove from the surface. The penetrant should remain fluid so it can be drawn back to the surface of the part through the drying and developing steps, be highly visible or fluoresce brightly to produce easy to see indications. In addition to its ease of use, the penetrant must not have residual halogens, P and S that are harmful to the material being tested or the inspector.

(c) Advantages and disadvantages

Although this test is very time consuming, it requires no capital equipment, a relatively small amount of consumable material. It is easily applied and the results are visual. It is the most reliable method of finding cracks and pinholes, where even the smallest possible pinhole will be detected. On the disadvantage side, one needs access to both sides of the envelope. It may require extensive cleaning before and after the test.

3.2.4.4. Ammonia gas leak test

Escaping ammonia can be detected by ammonia sensors. Ammonia sensors are used in various locations in ammonia plants (e.g. on the compressor platform, in the synthesis area and in the refrigeration section). However, they can also be placed in loading and tank areas, and around an ammonia pipeline where they can prove a useful tool for the detection of a leak from a pipeline. There are basically three commonly used types of ammonia sensors:

(a) The electrochemical type

It is used for sensing concentrations up to 1000 ppm. As it can accurately analyse low concentrations relevant for the protection of personnel (10-100 ppmv ammonia), it is widely used in the industry. However, the instrument has to be every 6 months and the life time is typically limited to 3 years. The investment cost is low.

(b) The solid-state type

It is used for sensing concentrations up to 1-2 volume percent. This type of sensor is less accurate in the low concentration range. Calibration frequency is once per year, and its lifetime is 5-10 years. The weakness of the solid state type is its insensitivity to chemicals other than ammonia.

(c) The infrared type

It is also used for concentrations up to 1-2 volume percent. This type is less accurate in the low concentration range as well. Calibration frequency is once every 6-12 months. The big advantage of this system is that it can detect ammonia vapours over a long distance. While electrochemical and the solid state analysers analyse a gas sample, the infrared detector scans the environment for the presence of ammonia over a distance of typically 10-100 metres.

3.2.4.5. Carbon dioxide and hydrogen tracer gas

A variety of tracer gases are available, the ones most common being carbon dioxide (CO_2), hydrogen (H_2) and helium (He). The test method consists in loading the product with trace gas and then searching for leakage of that gas from the device or pack. Trace gas loading can be performed by low pressure flushing into a device or component. Alternatively, the finished test items can be ‘soaked’ in an atmosphere of trace gas prior to testing. Sub-assemblies can be sealed in an atmosphere enriched with the trace gas. Once the gas is loaded, specific detectors are used outside the test piece to ‘sniff’ for leakage.

The measurement techniques vary greatly according to which gas is utilised. CO_2 is detected by infrared absorption, H_2 by ion selective semiconductors and He by mass spectroscopy. Carbon dioxide is commonly used in the food industry. It has relatively higher natural abundance. CO_2 is ideal when moisture ingress to a pack is of concern rather than microbial contamination. Both hydrogen and helium are excellent for testing medical devices and packs. They both allow testing with extreme sensitivity and dissipate rapidly to allow repeat or complex testing. The detection systems for He are somewhat more cumbersome and costly than those for H_2.

Trace gas testing is not influenced by product volume or temperature. There are no toxicity or regularity concerns for the gases mentioned here, at the concentrations used.

3.2.4.6. *Chemical fumes leak detector*

Chemical fumes may be detectable by a change in ambient air concentration causing irritation, odour, or coughing. The object of the chemical leak detector is to identify the presence of the fume, to locate the source and to estimate the size of the leak. Fumes can be part of the contained gas, or can be generated when the leaking substance reacts with ambient air.

3.2.5. *Ultrasonic leak testing*

3.2.5.1. *Principles, sensitivity, characteristics and applicability of the test*

Ultrasonic gas leak detectors use acoustic sensors to detect changes in the background noise of a machine's environment. Since most gas leaks occur in the ultrasonic range of 25 kHz to 10 MHz, the sensors are able to easily distinguish these frequencies from background noise which occurs in the audible range of 20 Hz to 20 kHz. The ultrasonic gas leak detector then produces an alarm when there is an ultrasonic deviation from the normal condition of background noise. Despite the fact that ultrasonic gas leak detectors do not measure gas concentration, the device is still able to determine the leak rate of an escaping gas. By measuring its ultrasonic sound level, the detector is able to determine the leak rate, which depends on the gas pressure and size of the leak. The bigger the leak, the larger its ultrasonic sound level will be. Ultrasonic gas detectors are mainly used for outdoor environments where weather conditions can easily dissipate escaping gas before allowing it to reach gas leak detectors that require contact with the gas in order to detect it and sound an alarm. These detectors are commonly found on offshore and onshore oil or gas platforms, gas compressor and metering stations, gas turbine power plants, and other facilities that house a lot of outdoor pipeline.

3.2.5.2. *Advantages and limitations*

Acoustic detectors can be used in areas where the escaping gas is easily dissipated. They permit remote and telemetric monitoring real time monitoring. The major disadvantage is the sensitivity to background noise with overlapping frequency of leaks.

FIG. 3.7. Portable acoustic leak detector for field use.

3.2.6. Acoustic emission leak testing

3.2.6.1. Fundamental principles of acoustic emission leak testing

Acoustic ultrasonic leak detectors are sensitive to airborne sound and inaudible sound waves due to escaping gas. Acoustic emission techniques, on the other hand, detect high frequency sounds that travel within the envelope itself. The acoustic emission technique relies on the fact that escaping gas or liquid through a small breach creates a high frequency sound wave that travels through the enveloping system via acoustic leak path. It is the capture and recording of these waves that make up the acoustic emission technique.

3.2.6.2. Applicability, sensitivity and characteristics of test

The acoustic emission technique is best used where there is a direct sound path between the suspected leak location and the location of the sensor. Acoustic emission sensors are small piezoelectric transducers, similar in construction to those used in ultrasonic testing. The received signal is highly amplified and transmitted to the monitor where the number of events, the event rate and changes in the event rate are observed.

Acoustic emission tests are susceptible to background noise (false positives) due to equipment rotation, friction, or other operating sources. On the other hand, using several transducers and by triangulation, it is possible to very accurately pinpoint the location of source of the emission, i.e. the leak. Acoustic emission testing is considered to be considerably more sensitive than airborne acoustic testing, but does require access to the surface of the pressure envelope.

3.2.6.3. Methods of acoustic emission testing

To standardize the method of leak detection by using the cross-correlation technique in order to detect and locate the leaks themselves requires the use of sensing devices placed on existing pipeline fittings plus conditioning, acquisition and signal analysis instrumentation in order to detect and locate the leaks. The method can be applied to the testing of underground supply and distribution pipelines of steel, ductile iron, cast iron, asbestos cement, polyethylene and PVC.

Cast iron, steel or asbestos cement pipe sections of a maximum length of 250 meters can be inspected by using non-intrusive sensing devices (accelerometers). The maximum controllable length of plastic pipes such as PVC or (high and low density) polyethylene is about 50 metres when accelerometers are used.

Acoustic emission monitoring can be carried out while a system is operating searching for leaks of the contained fluid, or by imposing an artificial test load in the vessel (pressurizing).

3.2.6.4. Advantages and limitations

The acoustic emission technique is relatively simple, and relies on using the pressure envelope itself to transmit the high frequency sound waves associated with fluid flow through a small orifice. The major disadvantage is that it is not easy to quantify a leak based on the noise it is emitting. A growing leak is essential to generate acoustic emmissions for pick up and detection. Another disadvantage is the sensitivity to background noise generated by nearby operating machinery.

3.2.7. Vacuum box leak testing techniques

3.2.7.1. Applicability, sensitivity and principle of test

A variation of the bubble technique uses a vacuum box to apply a vacuum which creates a pressure differential across an interface. The box, from which air is extracted and the vacuum produced by a small pump, is designed to fit over (with a reasonable seal and a glass top) a specific length, e.g. 500 mm of weld. The liquid indicator is coated on the weld and the vacuum generated. A leak results in a string of bubbles observable through the glass top of the vacuum box.

3.2.7.2. Advantages and limitations

The vacuum box is recognized in many codes of construction as being a tool that the fabricator's personnel can use. It is relatively simple to operate, is sensitive, and is constructed from common materials. Major limitation is that it cannot quantify the leaks.

3.2.8. Halide torch testing

3.2.8.1. Principles

The use of a halide leak detector (Fig. 3.8) is the most effective method to detect leaks in a refrigerant system using halogen refrigerants. This consists of a torch burner, a copper reactor plate, and a rubber exploring hose.

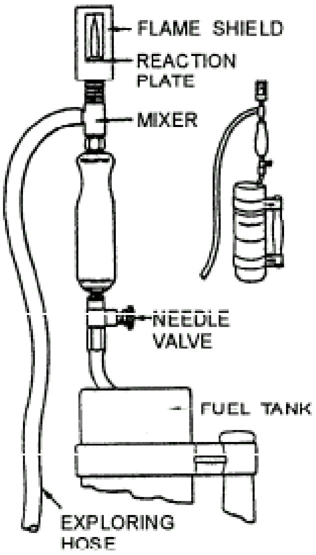


FIG. 3.8. Halide torch leak detector.

Detectors use acetylene gas, alcohol, or propane as a fuel. A pump supplies the pressure to the detector. If a pump-pressure type of alcohol-burning detector is used, it is critical that the air pumped into the fuel tank be pure.

An atmosphere suspected of containing a halogen vapour is drawn through the rubber exploring hose into the torch burner of the detector. Here the air passes over the copper reactor plate, which is heated to incandescence. If there is a minute trace of a halogen refrigerant present, the color of the torch flame changes from blue (neutral) to green as the halogen refrigerant contacts the reactor plate. The shade of green depends upon the amount of halogen refrigerant. A pale green color shows a small concentration of halogens and darker green shows a heavier concentration. Too much of a halogen refrigerant causes the flame to burn with a vivid purple color. Extreme concentrations of a halogen refrigerant may extinguish the flame by crowding out the oxygen available from the air.

The exploring hose is used to survey possible leakage points on the system.

3.2.8.2. Features of technique

The halide torch technique is relatively sensitive, but it is limited to being used in refrigeration systems.

The technique applies only to those systems which use halogen gas as a working fluid.

One of the disadvantages is that it requires an open flame which may not always be possible. Not all refrigerants contain halides.

4. EQUIPMENT AND ACCESSORIES

4.1. General considerations

For each of the leak testing techniques, specialized equipment is required, and it has been described within the chapters on test techniques and applications. This chapter describes the equipment and accessories which are general to all techniques, with a focus on the pumps which are used to achieve pressure differentials and the accessories which permit the measurement of pressures, vacuums and related changes.

4.2. Halogen diode detector

A halogen-diode detector uses a special sensing element that responds to halogen compound gases, such as bromine, iodine, fluorine, or chlorine. These compounds are used as pressurized tracer gases inside a vessel, triggering a probe in the detector device whenever gas begins to leak out. There are multiple types of halogen-diode detectors, but each is composed of a sensing element and a control unit. The sensing element, or probe, functions according to the principles of ion emission. Positive-ion emissions rise along with increases in halogen compound gas, and the ion current is converted into an electrical signal to indicate leaks. When locating leaks, the probe is moved over the area of joints or seams in an enclosure, touching the surface of any metal container. When it passes over a leak, the probe draws in the tracer gas and emits an audible visual signal. It is important not to pass the detector too quickly over the vessel’s surface, as this may cause smaller leaks to go undetected.

4.3. Helium mass spectrometer

A mass spectrometer is a device that sorts and filters various types of charged particles. As gas enters an analyzer, a filament releases a stream of electrons that converts the gas particles into charged ions that are accelerated to a rapid speed. Under a constant magnetic field, ions that share the same mass move along a specific trajectory toward a collector, which accumulates only the targeted molecules. Specialized devices, such as helium mass spectrometers, can be configured to remain sensitive only to a particular range of atomic mass, allowing other molecules to pass through the detector without triggering the collector. Mass spectrometers can only operate within a vacuum, making them effective for leak detection in vacuum systems, but can be adapted for pressurized tracer gas systems through the addition of a probe or an enclosure for collecting leakage. However, a mass spectrometer’s sensitivity and minimum leak detection rate tend to decrease when the device is applied to a pressure system.

4.4. Accessories

Besides the specialized equipment used in each leak testing technique, there are some common elements. It is necessary to create a pressure differential, either by pressurizing one side of the pressure envelope, or by evacuating one side. There is a wide variety of pumps that can be used for creating this differential.

Critical accessories also include the instruments that permit the measurement of pressure, and again there is a wide variety of such instruments, the choice of which is usually a compromise between cost and required sensitivity.

4.4.1. Vacuum pumps

4.4.1.1. Classification and selection of vacuum pumps

Pumps can be broadly categorized according to three techniques:

(a) *Positive displacement pumps* use a mechanism to repeatedly expand a cavity, allow gases to flow in from the chamber, seal off the cavity, and exhaust it to the atmosphere.

(b) *Momentum transfer pumps*, also called molecular pumps, use high speed jets of dense fluid or high speed rotating blades to knock gas molecules out of the chamber.

(c) *Entrapment pumps* capture gases in a solid or adsorbed state. This includes cryopumps, getters, and ion pumps.

4.4.1.2. Applications

Positive displacement pumps are the most effective for low vacuums. Momentum transfer pumps in conjunction with one or two positive displacement pumps are the most common configuration used to achieve high vacuums. In this configuration the positive displacement pump serves two purposes. First it obtains a rough vacuum in the vessel being evacuated before the momentum transfer pump can be used to obtain the high vacuum, as momentum transfer pumps cannot start pumping at atmospheric pressures. Second the positive displacement pump backs up the momentum transfer pump by evacuating to low vacuum the accumulation of displaced molecules in the high vacuum pump. Entrapment pumps can be added to reach ultrahigh vacuums, but they require periodic regeneration of the surfaces that trap air molecules or ions. Due to this requirement their available operational time can be unacceptably short in low and high vacuums, thus limiting their use to ultrahigh vacuums. Pumps also differ in details like manufacturing tolerances, sealing material, pressure, flow, admission or no admission of oil vapor, service intervals, reliability, tolerance to dust, tolerance to chemicals, tolerance to liquids and vibration.

4.4.1.3. Working principle and estimation of pump size

Pumping speed refers to the volume flow rate of a pump at its inlet, often measured in volume per unit of time. Momentum transfer and entrapment pumps are more effective on some gases than others, so the pumping rate can be different for each of the gases being pumped, and the average volume flow rate of the pump will vary depending on the chemical composition of the gases remaining in the chamber.

Throughput refers to the pumping speed multiplied by the gas pressure at the inlet, and is measured in units of pressure•volume/unit time. At a constant temperature, throughput is proportional to the number of molecules being pumped per unit time, and therefore to the mass flow rate of the pump. When discussing a leak in the system or back-streaming through the pump, throughput refers to the volume leak rate multiplied by the pressure at the vacuum side of the leak, so the leak throughput can be compared to the pump throughput.

Positive displacement and momentum transfer pumps have a constant volume flow rate, (pumping speed) but as the chamber's pressure drops, this volume contains less and less mass. So although the pumping speed remains constant, the throughput and mass flow rate drop exponentially. Meanwhile, the leakage, evaporation, sublimation and backstreaming rates continue to produce a constant throughput into the system.

The manual water pump draws water up from a well by creating a vacuum that water rushes in to fill. In a sense, it acts to evacuate the well, although the high leakage rate of dirt prevents a high quality vacuum from being maintained for any length of time.

4.4.1.4. Mechanism of a scroll pump

Fluids cannot be pulled, so it is technically impossible to create a vacuum by suction. Suction is the movement of fluids into a vacuum under the effect of a higher external pressure, but the vacuum has to be created first. The easiest way to create an artificial vacuum is to expand the volume of a container. For example, the diaphragm muscle expands the chest cavity, which causes the volume of the lungs to increase. This expansion reduces the pressure and creates a partial vacuum, which is soon filled by air pushed in by atmospheric pressure

To continue evacuating a chamber indefinitely without requiring infinite growth, a compartment of the vacuum can be repeatedly closed off, exhausted, and expanded again. This is the principle behind positive displacement pumps, like the manual water pump for example. Inside the pump, a mechanism expands a small sealed cavity to create a deep vacuum. Because of the pressure differential, some fluid from the chamber (or the well, in our example) is pushed into the pump's small cavity. The pump's cavity is then sealed from the chamber, opened to the atmosphere, and squeezed back to a minute size.

More sophisticated systems are used for most industrial applications, but the basic principle of cyclic volume removal is the same. A few widely used pump systems are:

- Rotary vane pump, the most common
- Diaphragm pump, zero oil contamination
- Liquid ring pump
- Piston pump, cheapest
- Scroll pump, highest speed dry pump
- Screw pump (10 Pa)
- Wankel pump
- External vane pump
- Roots blower, also called a booster pump, has highest pumping speeds but low compression ratio
- Multistage Roots pump that combine several stages providing high pumping speed with better compression ratio
- Toepler pump
- Lobe pump

The base pressure of a rubber- and plastic-sealed piston pump system is typically 1 to 50 kPa, while a scroll pump might reach 10 Pa (when new) and a rotary vane oil pump with a clean and empty metallic chamber can easily achieve 0.1 Pa.

(a) Momentum transfer pumps

In a momentum transfer pump, gas molecules are accelerated from the vacuum side to the exhaust side (which is usually maintained at a reduced pressure by a positive displacement pump). Momentum transfer pumping is only possible below pressures of about 0.1 kPa. Matter flows differently at different pressures based on the laws of fluid dynamics. At atmospheric pressure and mild vacuums, molecules interact with each other and push on their neighboring molecules in what is known as viscous flow. When the distance between the molecules increases, the molecules interact with the walls of the chamber more often than the other molecules, and molecular pumping becomes more effective than positive displacement pumping. This regime is generally called high vacuum.

FIG. 4.1. A cutaway view of a turbomolecular high vacuum pump.

Molecular pumps sweep out a larger area than mechanical pumps, and do so more frequently, making them capable of much higher pumping speeds. They do this at the expense of the seal between the vacuum and their exhaust. Since there is no seal, a small pressure at the exhaust can easily cause backstreaming through the pump; this is called stall. In high vacuum, however, pressure gradients have little effect on fluid flows, and molecular pumps can attain their full potential.

The two main types of molecular pumps are (i) diffusion pump and (ii) turbo-molecular pump. Both types of pumps blow out gas molecules that diffuse into the pump by imparting momentum to the gas molecules. Diffusion pumps blow out gas molecules with jets of oil or mercury, while turbo-molecular pumps use high speed fans to push the gas. Both of these pumps will stall and fail to pump if exhausted directly to atmospheric pressure, so they must be exhausted to a lower grade vacuum created by a mechanical pump.

As with positive displacement pumps, the base pressure will be reached when leakage, out-gassing, and back-streaming equal the pump speed, but now minimizing leakage and out-gassing to a level comparable to back-streaming becomes much more difficult.

(b) Liquid storage traps

Entrapment pumps may be cryopumps, which use cold temperatures to condense gases to a solid or adsorbed state; they may be chemical pumps, which react with gases to produce a solid residue; or ionization pumps, which use strong electrical fields to ionize gases and propel the ions into a solid substrate. A cryomodule uses cryopumping. Four types of entrapment pump are:

- Ion pump
- Cryopump
- Sorption pump
- Non-evaporative getter

Vacuum pumps are combined with chambers and operational procedures into a wide variety of vacuum systems. Sometimes more than one pump will be used (in series or in parallel) in a single application. A partial vacuum, or rough vacuum, can be created using a positive displacement pump that transports a gas load from an inlet port to an outlet (exhaust) port. Because of their mechanical limitations, such pumps can only achieve a low vacuum. To achieve a higher vacuum, other techniques must then be used, typically in series (usually following an initial fast pump down with a positive displacement pump). Some examples might be use of an oil sealed rotary vane pump (the most common positive displacement pump) backing a diffusion pump, or a dry scroll pump backing a turbomolecular pump. There are other combinations depending on the level of vacuum being sought.

Achieving high vacuum is difficult because all the materials exposed to the vacuum must be carefully evaluated for their outgassing and vapor pressure properties. For example, oils, and greases, and rubber, or plastic gaskets used as seals for the vacuum chamber must not boil when exposed to the vacuum. Often, all of the surfaces exposed to the vacuum must be baked at high temperature to drive off adsorbed gases.

Outgassing can also be reduced simply by desiccation prior to vacuum pumping. High vacuum systems generally require metal chambers with metal gasket seals such as Klein flanges or ISO flanges, rather than the rubber gaskets more common in low vacuum chamber seals. The system must be clean and free of organic matter to minimize outgassing. All materials, solid or liquid, have a small vapour pressure, and their outgassing becomes important when the vacuum pressure falls below this vapour pressure. As a result, many materials that work well in low vacuums, such as epoxy, will become a source of outgassing at higher vacuums. With these standard precautions, vacuums of 1 mPa are easily achieved with an assortment of molecular pumps. With careful design and operation, 1 µPa is possible.

Several types of pumps may be used in sequence or in parallel. In a typical pumpdown sequence, a positive displacement pump would be used to remove most of the gas from a chamber, starting from atmosphere (760 Torr, 101 kPa) to 25 Torr (3 kPa). Then a sorption pump would be used to bring the pressure down to 10^{-4} Torr (10 mPa). A cryopump or turbomolecular pump would be used to bring the pressure further down to 10^{-8} Torr (1 µPa). An additional ion pump can be started below 10^{-6} Torr to remove gases which are not adequately handled by a cryopump or turbo pump, such as helium or hydrogen.

Ultra high vacuum generally requires custom-built equipment, strict operational procedures, and a fair amount of trial-and-error. Ultra-high vacuum systems are usually made of stainless steel with metal-gasketed conflat flanges. The system is usually baked, preferably under vacuum, to temporarily raise the vapour pressure of all outgassing materials in the system and boil them off. If necessary, this outgassing of the system can also be performed at room temperature, but this takes much more time. Once the bulk of the outgassing materials are boiled off and evacuated, the system may be cooled to lower vapour pressures to minimize residual outgassing during actual operation. Some systems are cooled well below room temperature by liquid nitrogen to shut down residual outgassing and simultaneously cryopump the system.

In ultra-high vacuum systems, some very odd leakage paths and outgassing sources must be considered. The water absorption of aluminum and palladium becomes an unacceptable source of outgassing, and even the absorptivity of hard metals such as stainless steel or titanium is also important. Some oils and greases will boil off in extreme vacuums. The porosity of the metallic chamber walls may have to be considered, and the grain direction of the metallic flanges should be parallel to the flange face.

The impact of molecular size must be considered. Smaller molecules can leak in more easily and are more easily absorbed by certain materials, and molecular pumps are less effective at pumping gases with lower molecular weights. A system may be able to evacuate nitrogen (the main component of air) to the desired vacuum, but the chamber could still be full of residual atmospheric hydrogen and helium. Vessels lined with a highly gas-permeable material such as palladium (which is a high-capacity hydrogen sponge) create special outgassing problems.

4.4.2. Vacuum gauges

For measurement of pressure and vacuum several techniques are available. The instruments used to measure pressure are called pressure gauges or vacuum gauges and they include a manometer, usually limited to measuring pressures near to atmospheric or a vacuum gauge, used to measure both high and low vacuum.

Pressure is an absolute quantity however pressure measurements are made relative to a vacuum or to some reference as i) absolute pressure which referenced against a perfect vacuum and it is equal to gauge pressure plus atmospheric pressure, ii) differential pressure is the pressure difference between any two points and iii) gauge pressure which is referenced against ambient air pressure and it is equal to absolute pressure minus atmospheric pressure with negative sign usually omitted. Differential pressure is commonly used in industrial process systems. These gauges have two inlet ports and perform the mathematical operation of subtraction through mechanical means.

4.4.3. Static and dynamic pressure

Static pressure is uniform in all directions while dynamic pressure is not. An instrument facing the flow direction measures the sum of the static and dynamic pressures. Static pressure is useful for determining the net loads on pipe walls and dynamic pressure is used to measure flow rates and air speed through measurement of differential pressure in two perpendicular flow directions.

The primate instruments for pressure measurement are the liquid column (a vertical tube filled with mercury) manometer and the U-Tube. Hydrostatic gauges (such as the mercury column manometer) compare pressure to the hydrostatic force per unit area at the base of a column of fluid and are independent of the type of gas or fluid being measured and can be designed to have a linear calibration. However, they have poor dynamic response. Piston-type gauges or dead weight tester counterbalance the pressure of a fluid with a solid weight or a spring. Although any fluid can be used, mercury is preferred for its high density (13.534 g/cm3) and low vapour pressure. Similarly, water is used for low pressure differences well above the vapour pressure of water. A few popular pressure measuring instruments include McLeod gauge, Aneroid, Bourdon, Diaphragm and Bellows. Recently, several new techniques have been developed based on electromagnetic and other properties that are indirectly affected by the pressure. They include phenomenon such as piezoresistive, capacitive, magnetic, eddy current, piezoelectric, fibre optic, potentiometric (resistive mechanism), resonance etc.

5. CODES, STANDARDS, PROCEDURE AND GUIDELINES

5.1. Standards applicable to leak testing

5.1.1. General guidance regarding method selection and calibration

These standards are examples of standards which are widely used for the selection of the appropriate leak testing technique and for calibration. They should be referred prior to selecting any leak testing method.

While the standards listed are those available at the time of writing, one should always consult the latest edition of the referenced standard. This list is meant to demonstrate the scope of standards which are available, however there may be other standards, national and international, that apply to a specific leak testing task or to a specific type of product.

ASTM E432 – 91(2004) Standard Guide for Selection of a Leak Testing Method.

ASTM E479 – 91(2006) Standard Guide for Preparation of a Leak Testing Specification.

BS EN 1330-4 (2010) Non-destructive testing Terminology. Terms used in leak tightness testing.

BS EN 1779 (1999) Non-destructive testing: Leak testing; Criteria for method and technique selection.

BS EN 13192 (2002) Non-destructive testing: Leak testing; Calibration of reference leaks for gases.

BS EN 13625 (2002) Non-destructive testing: Leak test; Guide to the selection of instrumentation for the measurement of gas leakage.

5.1.2. Standards detailing test methods

The following standards have been selected from the literature to demonstrate the level of documentation that is available for application to specific leak testing techniques. The list may not be complete, and it should be recognized that the field of leak testing is a dynamic field with continual discovery of new applications. Similarly standards are continually being revised to ensure that the documentation keeps pace with industrial applications—the standard numbers and titles may change with revision.

ASTM E427 – 95(2006) Standard Practice for Testing for Leaks Using the Halogen Leak Detector (Alkali-Ion Diode).

ASTM E493 – 06 Standard Test Methods for Leaks Using the Mass Spectrometer Leak Detector in the Inside-Out Testing Mode.

ASTM E498 – 95(2006) Standard Test Methods for Leaks Using the Mass Spectrometer Leak Detector or Residual Gas Analyzer in the Tracer Probe Mode.

ASTM E499 – 95(2006) Standard Test Methods for Leaks Using the Mass Spectrometer Leak Detector in the Detector Probe Mode.

ASTM E515 – 05 Standard Test Method for Leaks Using Bubble Emission Techniques.

ASTM E908 – 98(2004), Standard Practice for Calibrating Gaseous Reference Leaks.

ASTM E1002 – 05, Standard Test Method for Leaks Using Ultrasonics.

ASTM E1003 – 05, Standard Test Method for Hydrostatic Leak Testing.

ASTM E1066 – 95(2006) Standard Test Method for Ammonia Colorimetric Leak Testing.

ASTM E1211 – 07 Standard Practice for Leak Detection and Location Using Surface-Mounted Acoustic Emission Sensors.

ASTM E1603 – 99(2006) Standard Test Methods for Leakage Measurement Using the Mass Spectrometer Leak Detector or Residual Gas Analyzer in the Hood Mode.

BS EN 1518 (1998) Non-destructive testing – Leak testing – Characterization of mass spectrometer leak detectors.

BS EN 1593 (1999) Non-destructive testing – Leak testing – Bubble emission techniques.

BS EN 1779 (1999) Leak tightness by indication or measurement of gas leakage.

BS EN 13184 (2001) Non-destructive testing – Leak testing – Pressure change method.

BS EN 13185 (2001) Non-destructive testing. Leak testing. Tracer gas method.

5.1.3. Standards related to specific product forms

In addition to the many standards that relate to the testing techniques and their applications, it should be recognized that the manufacturers and users of specific equipment may include in their standards some requirements for leak testing. Some typical such product standards are listed in this section. There has been no attempt to list all such standards and it is incumbent on the user to be familiar with the technology related to the specific product being examined.

ISO 27895 (2009) Vacuum technology - Valves – Leak test.

BS EN 12298 (1998) Biotechnology - Equipment - Guidance on testing procedures for leak tightness

ASTM A1047 – 05(2009) Standard Test Method for Pneumatic Leak Testing of Tubing.

ASTM D4991 – 07 Standard Test Method for Leakage Testing of Empty Rigid Containers by Vacuum Method.

ASTM F2338 – 09 Standard Test Method for Nondestructive Detection of Leaks in Packages by Vacuum Decay Method.

ASTM F2786 – 10 Standard Practice for Field Leak Testing of Polyethylene (PE) Pressure Piping Systems Using Gaseous Media under Pressure (Pneumatic Leak Testing).

5.1.4. Materials for the test

Test materials are covered in the individual procedural or recommended practice standards. For liquid penetrant testing, standard coloured or fluorescent dyes are used. For bubble testing, there are a range of commercial solutions available, but the important criteria is the ability for escaping gas to form bubbles.

Specialized helium, halogen and radioactive tracers use available, safe and economical materials.

One of the critical conditions is that the tracer or other leak testing working materials must not react in any way with the working fluid in the component being tested. The test materials should not leave traces after the test that can react with the working fluids.

5.1.5. ASME code

The ASME Boiler and Pressure Vessel Code is comprised of several sections related specifically to pressure equipment. Section V of the Code lists non-destructive test methods and in this Leak Testing is included. Equally important are the provisions within the product codes, such as Section I for Boilers, and Section VIII Division 1 for Pressure Vessels, providing guidance for when and where to apply leak testing .

Section I calls for hydrostatic testing as an acceptance test for new installations in Paragraph PG-99, as follows:

5.1.5.1. PG-99 hydrostatic test

Hydrostatic testing of the completed boiler unit shall be conducted in accordance with the following requirements:

After a boiler has been completed (see PG-104), it shall be subjected to pressure tests using water at not less than ambient temperature, but in no case less than 70°F (20°C). Where required test pressures are specified in this paragraph, whether minimum or maximum pressures, they apply to the highest point of the boiler system. When the boiler is completed in the Manufacturer’s shop without boiler external piping, subsequent hydrostatic testing of the boiler external piping shall be the responsibility of any holder of a valid “S,” “A,” or “PP” stamp. The pressure relief valves need not be included in the hydrostatic test. The tests shall be made in two stages in the following sequence:

5.1.5.2. PG-99.1

Hydrostatic pressure tests shall be applied by raising the pressure gradually to not less than 11⁄2 times the maximum allowable working pressure as shown on the data report to be stamped on the boiler. No part of the boiler shall be subjected to a general membrane stress greater than 90% of its yield strength (0.2% offset) at test temperature. The primary membrane stress to which boiler components are subjected during hydrostatic test shall be taken into account when designing the components. Close visual inspection for leakage is not required during this stage.”

Section VIII of the ASME Boiler and Pressure Vessel Code covers hydrostatic testing of new pressure vessels and components in paragraph UG-130 (d) (2):

5.1.5.3. UG-136(d)(2) hydrostatic pressure test

(a) Hydrostatic testing shall be performed on the pressure containing parts of the shell of each valve at a pressure at least 1.5 times the design pressure of the parts. The valve shell is defined as parts, such as the body, bonnet, and cap, which isolate primary or secondary pressure from atmosphere.

Parts meeting the following criteria shall be exempt from hydrostatic testing:

(1) the applied stress under hydrostatic test conditions does not exceed 50% of the allowable stress; and
(2) the part is not cast or welded.

(b) Testing may be performed pneumatically at a pressure of 1.25 times the design pressure of the part. Pneumatic testing can be hazardous; it is therefore recommended that special precautions be taken when conducting a pneumatic test.

(c) Testing may be done in the component or assembled condition.

(d) These tests shall be conducted after all machining and welding operations on the parts have been completed.

(e) There shall be no visible sign of leakage.

These particular instructions are common to all of the ASME product codes; ASME relies on the ability of the manufactured component or device to hold pressure—the visual observation for leaking coupled with observation of pressure drop has served well for many years.

5.2. Test specifications and procedures

5.2.1. Definition of testing and instructions, considering field of application, equipment and technique

Leak testing techniques are based on widely differing technologies. It follows that each technique has its own set of rules and instructions, its own dedicated equipment and its own safety rules. The selection of the correct technique can only be made with a good knowledge of the application and the possible test parameters, i.e. static or dynamic, additive, tracer or working fluid, and detection technique, particularly for those techniques which require chemical analysis.

5.2.2. Interpretation and evaluation

Interpretation must be based on knowledge of the working system and its performance characteristics, as well as the testing technique, and how it is affected by the presence of a leak.

5.2.3. Formulation of instructions for the test

Instructions for any test are prepared by or on behalf of a Level 3 expert. Generally these will be based on a published standard, on product information provided by the manufacturer, or on performance requirements detailed in the specification. Instructions or performance standards that are unachievable serve no one.

5.2.4. Contents of codes, standards, specifications and guidelines

Documented test instructions may be in the form of codes (referenced in legislation), standards (industry consensus), purchaser’s specifications or guidelines. It is the latter category that provide the most challenge for the service provider – he must not only prove that the test is appropriate and that the acceptance criteria are achievable, but that the results are a true indication of the integrity of the system tested.

5.3. National standards for leak testing and testing personnel

5.3.1. Quality control of the test and procedure for its administration

The qualification of personnel for leak testing is covered in ISO 9712:2005 and BS EN 73:2008. These standards provide guidance for third party certification of personnel at three levels in any NDT method, and specifically include leak testing.

Most national standards for personnel qualifications are based on one of the two international documents listed above.

5.3.2. Quality assurance requirements

General quality assurance requirements are detailed in Chapter 1 of this book.

6. SAFETY ASPECTS

6.1. Problems of industrial safety in the use of chemical and inflammable products

6.1.1. Applicable safety standards

Materials used in leak testing may be radioactive or reactive. Where such materials are used, the appropriate safety standards and plant practices shall apply.

6.1.2. Drafting of safety instructions for the personnel involved

Safety is the concern of every worker, with the supervisor bearing special responsibility to ensure that the worker has been properly instructed or trained. The role of safety instructions is to communicate those precautions which are common sense, those which are passed down by the manufacturer, and those which might arise with the specific application, to the worker.

6.1.3. Safety factors applicable to the test

Aside from any hazards which might arise from the materials being used in the test, the technician must be constantly aware of the function of the object under test. The consequences of a failure in service emphasize the importance of the test. For pressure tests, particularly pneumatic tests, the requirement to overpressure creates a hazard in itself.

Investigating leaks in an operating system can be hazardous. If the system is known to be leaking, there is a possibility that the leak is growing, and full failure could result. If the working contents are explosive, combustible or toxic, leaks must be approached with a great deal of caution.

6.2. Control of hazards from toxic and radioactive liquids, vapours and particles of flammable liquids and vapours

Hazards can be associated with the working fluids in the systems being tested or with the testing fluids. Some specific precautions for handling chemicals are listed below.

6.2.1. Chemical handling

Use bottle carriers to transport chemicals. Close caps securely. Pour all chemicals carefully. Add acid to water, not water to acid.

6.2.2. Labels

Be sure all labels are securely attached and legible. Keep chemicals in their original containers if possible. Label all secondary containers to avoid unknown chemicals and/or inadvertent reaction. Date all chemicals, which may become unstable over time or are peroxidizable.

6.2.3. Shelves

Do not store chemicals on hard-to-reach shelves. Labels on stored chemicals should be able to be read easily. Shelves should be made of a chemically resistant material and should have a 2-inch lip or side rails.

6.2.4. Incompatible chemicals

Incompatible chemicals should not be stored together. For each chemical, the hazardous nature must be considered individually and in relation to other chemicals in the area.

6.2.5. Excessive storage

Avoid stockpiling chemicals. Purchase only what is needed. Use older stock first. Discard chemicals that are no longer needed or that have expired.

6.2.6. Fume hoods

In general, fume hoods should not be used for storage of chemicals, unless the chemicals are part of the experiment being conducted in the fume hood at that time. The exception is storage in a fume hood, which is specifically designed for that storage, and where experimental procedures are not carried out.

6.2.7. Hazardous waste storage and disposal

Regulations require that hazardous wastes be accumulated and stored in properly managed containers on sufficiently impervious surfaces (free of cracks, gaps, etc.).

6.2.8. Storage

Hazardous waste in laboratories must be stored in satellite accumulation areas.

6.2.9. Disposal

Once a satellite accumulation area container is filled, it must be dated and transferred to a main accumulation area or shipped off-site. Disposal of hazardous wastes and chemicals in laboratory sinks is prohibited by regulation.

6.2.10. Labeling

Containers that accumulate and store hazardous waste must be labeled with the following information:

- The words "Hazardous Waste"
- The waste type in words (Spent non-halogenated solvents, waste oil, etc.);
- The associated hazard in words (i.e. ignitable, toxic, etc.); and
- The date upon which the container became filled.

Containers must be labeled and situated so that labels are clearly visible.

6.2.11. Closure

Containers must be closed at all times, unless waste is being added or removed. Open-top funnels may not be left in open containers.

6.2.12. Condition

Containers must be in good condition. There may not be severe rusting, dents or other conditions that could cause leaks, etc.

6.2.13. Compatibility

Containers must be compatible with hazardous waste stored within them. When in doubt, use the original shipping container.

6.2.14. Inspections

Containers must be inspected weekly by laboratory personnel to ensure that they are properly labeled, in good condition and meet the criteria described above.

6.2.15. Hazardous waste minimization

Laws may require generators of hazardous waste to implement measures to limit and reduce the volume and toxicity of hazardous waste. Laboratory waste minimization techniques include:

- Process/equipment adjustment or modification;
- Toxic material substitution;
- Waste segregation and separation; and
- Recycling

Where possible, microchemistry will reduce waste volume and has the added benefit of minimizing health and safety concerns. The exercise of prudence in ordering new chemicals will also ensure that excess chemical does not become subject to disposal has hazardous waste.

6.3. Safety precautions with compressed gas cylinders

Use and storage of any compressed gas under high pressure can be extremely dangerous if proper gas handling procedures are not observed. Moreover, chemical characteristics of specialty gases themselves can pose serious health hazards if containment is not tightly controlled. Paying close attention to a compressed gas product’s technical and safety information is invaluable for maintaining a safe, productive working environment and for ensuring reliable, efficient use of compressed specialty gases for any application.

All cylinders containing gases must be labeled, packaged and shipped according to local and national requirements as well as industry standards. Transportation label diamonds, regardless of colour, indicate hazardous materials. Personnel handling any compressed gas should be familiar with the potential hazards before using the gas. In addition to the chemical hazards of compressed gases, hazards accompanying high pressure or low temperature may also be present due to the physical state of the gas (i.e. liquefied or nonliquified).

It is also recommended that personnel who handle compressed gases engage in pre-job discussion with their supervisor or another knowledgeable coworker before beginning any task. The job should be outlined job step by step. Potential emergencies and the safe and proper measures necessary to avoid these emergencies should be discussed.

Some categories of industrial gases are described in the following paragraphs, however the reader is strongly cautioned to refer to the MSDS sheets provided with the product he is using.

6.3.1. Corrosive

Gases that corrode material or tissue with which they come in contact, or do so in the presence of water, are classified as corrosive. They can also be reactive and toxic and/or flammable or an oxidizer. Most are hazardous in low concentrations over long periods of time. It is essential that equipment used for handling corrosive gases be constructed of proper materials. Use check valves and traps in a system where there is a possibility that water or other inorganic materials can be sucked back into the cylinder. Due to the probability of irritation and damage to the lungs, mucus membranes and eye tissues from contact, the threshold limit values of the gas should be rigidly observed. Proper protective clothing and equipment must be used to minimize exposure to corrosive materials. A full body shower and eye wash station should be in the area. Personnel must be familiar with the work area. Aisles should always be clear and unobstructed in the event that the gas makes contact with the eyes and vision is disrupted.

6.3.2. Flammable

Gases that, when mixed with air at atmospheric temperature and pressure, form a flammable mixture at 13% or less by volume, or have a flammable range in air of greater than 12% by volume regardless of the lower flammable limit, are classified as flammable. They can be high-pressure, toxic, reactive and displace oxygen in air. A change in temperature, pressure or oxidant concentration may vary the flammability range considerably. All possible sources of ignition must be eliminated through proper design of facilities and the restriction of smoking and open flames. Use a vent line made of stainless steel, purge with an inert gas and use a flash arrester. It is important to have (and know how to use) a fire extinguisher in the area where flammable gases are used and stored, as well as a hand-held flammable gas detector to determine if flammable gases are building up. This gas detector can also be used as a leak detector on the lines of the equipment being used. Always remember that the source of flammable gas must be closed or shut-off before attempting to put out a fire involving flammable gases.

6.3.3. Inert

Gases that do not react with other materials at ordinary temperature and pressure are classified as inert. They are colourless and odourless, as well as nonflammable and nontoxic. The primary hazard of these gases is pressure. These gases are often stored at pressures exceeding 2,000 psi (138 bar). Also, they can displace the amount of oxygen necessary to support life when released in a confined place. Use of adequate ventilation and monitoring of the oxygen content in confined places will minimize the danger of asphyxiation. Always wear safety glasses and safety gloves when working with the lines to avoid absorption of the gas through the skin.

6.3.4. Oxidant

Gases that do not burn but will support combustion are classified as oxidants. They can be high-pressure, toxic and reactive, and can displace breathing oxygen from air (except O_2 itself). All possible sources of ignition must be eliminated when handling oxygen and other oxidants as they react rapidly and violently. Do not store combustible materials with oxidants.

Do not allow oil, grease or other readily combustible materials to come in contact with the cylinder or equipment used for oxidant services. Use only equipment that is intended for this type of service. Use only a regulator that has been clearly prepared for use with this type of service - this regulator should be labeled "Cleaned for O_2 Services."

6.3.5. Cryogenic

Gases with a boiling point below -130°F (-90°C) at atmospheric temperature are considered cryogenic gases. They are extremely cold and can produce intense burns (similar to heat burns) and tissue necrosis may be even more severe. They can be non-flammable, flammable or oxidizing. Cryogenic liquids can build up intense pressures. At cryogenic temperatures, system components may become brittle and crack. Never block a line filled with cryogenic liquid as a slight increase in temperature can cause tremendous and dangerous build-up of pressure and cause the line to burst. The system should also be designed with a safety relief valve and, depending upon the gas, a vent line. To protect from injury, always wear gauntlet gloves to cover hands and arms, and a cryogenic apron to protect the front of the body. Wear pants over the shoes to prevent liquids from getting trapped inside your shoes. Wear safety glasses and a face shield as cryogenic liquids tend to bounce upward when spilled.

6.3.6. Toxic or poison

Gases that may produce lethal or other harmful effects on humans are classified as toxic or poison. They can be high pressure, reactive, nonflammable or flammable, and/or oxidizing in addition to their toxicity. The degree of toxicity and the effects will vary depending on the gas; however, death will occur when breathed in sufficient quantities. The permissible exposure levels must be strictly adhered to.

Never work alone with toxic gases - a backup safety person is essential! Inspect the entire assembly or system that will contain the gas and thoroughly test it for leaks with an inert gas before use. Purge all lines with an inert gas before opening the cylinder valve or breaking connections.

Use toxic gases in a well-ventilated area. For safety purposes and to minimize exposure, it is important to have gas detectors. It is preferable that the breathing apparatus be stored in a safe area immediately adjacent to the work area, so that in the event of an emergency, a person can go directly into the area and close the door and safely put on the apparatus. Full body showers, eye washes, fire alarms and firefighting equipment should be in the area of use and readily accessible. Refer to your local building code for storage and use requirements for toxic gases. Keep your inventory of toxic or poison gases to a minimum. When a project is completed, return leftover cylinders to your gas supplier.

Some useful definitions related to industrial gases follow:

6.3.7. Compressed

Non-flammable material or mixture that is contained under pressure exceeding 41 psia (3 bar) at 70°F (21°C) or any flammable or poisonous material that is a gas at 70°F (21°C) and 14.7 psia (1 bar) or greater. Most compressed gases will not exceed 2,000 to 2,640 psig (138 to 182 bar) though some go up to 6,000 psig (414 bar).

6.3.8. Non-liquefied compressed

Chemical or material other than gas in solution that under the charged pressure is entirely gaseous at a temperature of 70°F (21°C).

6.3.9. Liquefied compressed

Chemical or material that under the charged pressure is partially liquid at a temperature of 70°F (21°C).

6.3.10. Compressed gas in solution

Non-liquefied compressed gas that is dissolved in a solvent.

6.4. Safety precautions in pressure and vacuum testing

The testing of systems using extreme vacuums can result in collapse of the pressure envelope. If this is a tank or vessel, then there could be damage to the test object.

Where the test system is testing using pressurization above its normal working level, it follows that the tester should be prepared for the consequences of failure. This means that there may need to be protective barriers or screens, but all such precautions will be specifically dedicated to the risk involved in the test.

6.5. Preparation of pressurized systems for safe leak testing, rise in temperature dangers

The technician must be conscious at all times of the potential for a rise in temperature to significantly increase pressure. Since most test techniques do not involve temperature increases, this is of most concern while conducting dynamic tests. Particular care should be taken with cryogenic gases since at very low temperatures, a slight change in temperature can result in an extremely rapid and severe increase in pressure. If the line is blocked, the container could fail.

A hydrostatic test is a way in which leaks can be found in pressure vessels such as pipelines and plumbing. The test involves placing water, which is often dyed for visibility, in the pipe or vessel at the required pressure to ensure that it will not leak or be damaged. It is the most common method employed for testing pipes and vessels. Using this test helps maintain safety standards and durability of a vessel over time. Newly manufactured pieces are initially qualified using the hydrostatic test. They are then continually re-qualified at regular intervals using the proof pressure test which is also called the modified hydrostatic test. Hydrostatic testing is also a way in which a gas pressure vessel, such as a gas cylinder or a boiler, is checked for leaks or flaws. Testing is very important because such containers can explode if they fail when containing compressed gas.

Hydrostatic tests are conducted under the constraints of either the industry's or the customer's specifications. The vessel is filled with a nearly incompressible liquid - usually water or oil - and examined for leaks or permanent changes in shape. Red or fluorescent dyes are usually added to the water to make leaks easier to see. The test pressure is always considerably higher than the operating pressure to give a margin for safety. This margin of safety is typically 150% or 5/3 of the design pressure, depending on the regulations that apply. For example, if a cylinder was rated to DOT-2015 PSI (approximately 139 bar), it would be tested at around

3360 PSI (approximately 232 bar). Water is commonly used because it is almost incompressible (compressible only by weight, not air pressure), so will only expand by a very small amount should the vessel split. If high pressure gas were used, then the gas would expand to perhaps several hundred times its compressed volume in an explosion, with the attendant risk of damage or injury. This is the risk which the testing is intended to mitigate.

Small pressure vessels are normally tested using a water jacket test. The vessel is visually examined for defects and then placed in a container filled with water, and in which the change in volume of the vessel can be measured by monitoring the water level. For best accuracy, a digital scale is used to measure the smallest amounts of change. The vessel is then pressurized for a specified period, usually 30 or more seconds, and then depressurized again. The water level in the jacket is then examined. The level will be greater if the vessel being tested has been distorted by the pressure change and did not return to its original volume, or some of the pressurized water inside has leaked out. In both cases, this will normally signify that the vessel has failed the test. If the Rejection Elastic Expansion is more than 10%, or not up to DOT or customer standards, the cylinder fails, and then goes through a condemning process marking the cylinder as unsafe. This measures the overall leakage of a system instead of locating the leaks and additives can be added to the water to reduce resistivity and increase the sensitivity of the test. The hydrostatic test fluid can also clog small holes (1×10^{-6} std cm^3/s or smaller) as a result of the increase in pressure. This is another reason why water is commonly used.

All the information the tester needs is stamped onto the cylinder. This includes the DOT information, serial number, manufacturer, and manufacture date. Other information is stamped as needed such as the REE or how much the manufacturer specifies the cylinder should expand before it is considered unsafe. All this information is usually taken down and stored on a computer prior to the testing process. All this information is necessary for keeping track of when the cylinder has been or needs to be hydrotested.

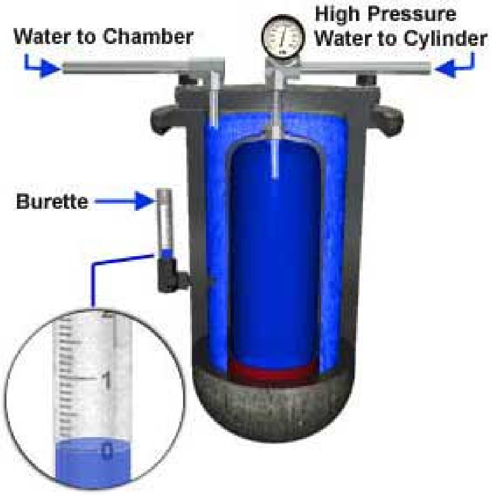


FIG. 6.1. Water jacket test.

A simpler test, that is still considered a hydrostatic test but can be performed by anyone who has a garden hose, is to pressurize the vessel by filling it with water and to physically examine the outside for leaks. The pressure level achieved in this sort of test does not come close to the pressure level that would be used in a professional testing facility.

6.6. Industrial safety standards, hydrotesting of pipe, pipelines and vessels

Hydrotesting of pipe, pipelines and vessels is done to ensure safe operation at design pressures, to expose possible leaks and to serve as a final validation of structural integrity. ASME B31.3 section 345 (2010) requires hydrotesting to ensure tightness and strength.

For buried high pressure pipelines, testing for strength is done by pressurizing them to 125% of their maximum operating pressure, in other words, 80% of specified minimum yield stress or hoop stress. During the testing, it is essential to ensure that excessive plastic deformation does not occur. On the other hand, BS PD 8010-3 (2004) requires testing to 150% of the design pressure. This should not be less than the maximum operating pressure plus surge and other incidental effects that might occur during normal operation. Most countries have strict legislation that requires pipelines and pressure vessels to be periodically tested, typically every two years using visual inspection for high pressure gas cylinders and five or ten years for low pressure systems.

6.7. Danger in presence of hydrogen

Hydrogen poses unique challenges due to its ease of leaking, low-energy ignition, wide range of combustible fuel-air mixtures, buoyancy, and its ability to embrittle metals that must be addressed to ensure safe operation. Hydrogen can be explosive under specific concentration, temperature and pressure conditions. Special precautions are needed for testing, handling and plant personnel safety. Liquid hydrogen poses additional challenges due to its increased density and extremely low temperatures. Hydrogen-air mixtures can ignite with very low energy input, for reference, an invisible spark can cause ignition. The minimum energy required for spark ignition at atmospheric pressure is approximately 0.02 millijoules. The flammability limits based on the volume percent of hydrogen in air at 1 atm (101 kPa) are 4.0 and 75.0 while they are 4.0 and 94.0 for hydrogen in oxygen. The explosive limits (upper and lower limits of percentage composition of a gas mixture explodes when ignited) of hydrogen in air are 18.3 to 59 percent by volume. Hydrogen collects under roofs and overhangs, where it forms an explosion hazard and this calls for good ventilation. Hydrogen pipes should be located above other pipes to prevent explosion hazards. Hydrogen leaks can support combustion at very low flow rates, as low as 4 micrograms/s. Flames in and around pipes or structures can create turbulence that causes a deflagration or detonation. Further, hydrogen diffuses extensively and is particularly subject to leakage with high leak rate because of its low viscosity and low molecular weight (leakage is inversely proportional to viscosity). The leak rate is 50 times that of water, and 10 times that of liquid nitrogen. Hydrogen sensors allow for rapid detection of hydrogen leaks. As in natural gas, an odorant can be added to hydrogen sources to enable leaks to be detected by smell. It is difficult to see hydrogen flames with the naked eye. However, they are readily seen by UV or infrared detectors.

6.7.1. Leakage, diffusion, and buoyancy

These hazards result from the difficulty in containing hydrogen. Hydrogen diffuses extensively, and when a liquid spill or large gas release occurs, a combustible mixture can form over a considerable distance from the spill location.

Hydrogen, in both the liquid and gaseous states, is particularly subject to leakage because of its low viscosity and low molecular weight (leakage is inversely proportional to viscosity). Because of its low viscosity alone, the leakage rate of liquid hydrogen is roughly 100 times that of JP-4 fuel, 50 times that of water, and 10 times that of liquid nitrogen.

Hydrogen leaks can support combustion at very low flow rates, as low as 4 micrograms/s.

Condensed and solidified atmospheric air, or trace air accumulated in manufacturing, contaminates liquid hydrogen, thereby forming an unstable mixture. This mixture may detonate with effects similar to those produced by trinitrotoluene (TNT) and other highly explosive materials.

Liquid Hydrogen requires complex storage technology such as the special thermally insulated containers and requires special handling common to all cryogenic substances. This is similar to, but more severe than liquid oxygen. Even with thermally insulated containers it is difficult to keep such a low temperature, and the hydrogen will gradually leak away (typically it will evaporate at a rate of 1% per day).

Hydrogen collects under roofs and overhangs, where it forms an explosion hazard; any building that contains a potential source of hydrogen should have good ventilation, strong ignition suppression systems for all electric devices, and preferably be designed to have a roof that can be safely blown away from the rest of the structure in an explosion. It also enters pipes and can follow them to their destinations. Hydrogen pipes should be located above other pipes to prevent this occurrence. Hydrogen sensors allow for rapid detection of hydrogen leaks to ensure that the hydrogen can be vented and the source of the leak tracked down. As in natural gas, an odorant can be added to hydrogen sources to enable leaks to be detected by smell. While hydrogen flames can be hard to see with the naked eye, they show up readily on UV/IR flame detectors.

6.8. Sparking and combustion

Working with fuel gases including hydrogen in potential low concentrations requires especial prudence in the use of hand tools and electrical equipment. The worker should always be conscious of the potential for ignition and combustion. The clash of steel tools could result in a spark, electrical equipment could short and cause an arc, and dry clothing could result in static electricity which could also be an ignitor for the right mixture of fuel and oxidant.

In bubble testing, simple soap or detergent solutions in water are effective and economical indicators. If working on a line or vessel that contains, did contain or could contain oxygen, the worker needs to be aware that some detergents contain hydrocarbons and hence the danger of providing a fuel in the presence of pure oxygen could have disastrous results.

6.9. Psychological factors and safety programme

No worker should endanger his health or his physical well-being in the course of his duties. It follows that any industrial activity should be conducted safely and with due respect to the environment. Generally there are laws and rules of good practice that govern every workplace. Inspectors often are only temporary visitors to the workplace. Although most service sites now provide site specific safety training as a condition of working on that site, the inspector still finds the occasional site where he has to apply his own common sense and the rules of his employer.

Every employee (and supervisor and manager) must be aware of their individual responsibility for their own safety. Safe work practices are documented for all activities including testing, and the worker must be aware of these practices.

Even if a formal safety programme is not required by law, it follows that the leak tester’s employer should, just as a matter of good practice and risk management, have his own programme.

7. APPLICATIONS

A number of conventional NDT methods can be applied effectively to the detection of leaks, and thus can be considered techniques in the context of leak testing. Specific methods that can be used this way are liquid penetrant testing (PT) and acoustic emission testing (AET). Reference should be made to Chapter 1, where an overview of the use of these methods is presented.

7.1. System reliability through leak testing

The use of the “leak before break” design concept relies on a detectable leak being the first indication of a flaw. To the extent this concept is used, the detection of leaks as soon as they occur is critical.

Loss of contents can result in many serious consequences. A toxic gas or liquid may take lives. Even a nontoxic contaminant may spoil the environment. Leakage might result in loss of lubricant and thus machinery failure. In the packaging industry, a leak might result in product spoilage. Of course, there is always the economic loss associated with a product loss, as well as costs associated with clean up.

7.2. Leak testing related to material flaws

Through cracks result in leakage, and through cracks may be precursors of more extensive cracking or fracture. In particular, pin holes and tiny internal breaches are detectable using leak detection techniques.

7.3. Desired degree of leak tightness

Product specifications often recognize that perfect leak tightness is impossible, and thus specify a maximum leak rate. For many aerospace applications, for example, components and systems are typically required to have a leak rate of less than $5 \cdot 10^{-6}$ standard cubic centimeters of gas at a pressure of one atmosphere ($5 \cdot 10^{-6}$ mbar-L^2/sec).

7.4. Helium leak testing

Before a leak test examination is performed, it is necessary to determine if the examination is to ascertain whether leaks are present or not, overall leak detection, or if the examination is to determine the location of a leak, localising leak detection. In some cases, an examination for overall leak detection is performed first, and if leaks are detected, the localising method is applied for pinpointing of the leak. This is however not always required nor possible.

Secondly, it is necessary to determine the leak rate which can be tolerated, as no object is 100% tight. This is the requirements of tightness of the object. If, for example, the object has to be watertight, a leak rate below 10^{-4} mbar l/s will be sufficient. If the object, for example, is to be used in the chemical industry the requirements can be a leak rate below 10^{-6} mbar l / s.

In leak testing, a pressure difference between the outer and the inner side of the object to be examined is produced. Subsequently the amount of gas or liquid which is passing through a leak is measured. In the helium leak test (see fig. 7.1), helium is used as a search gas. In principle, two methods are applied for leak testing and location of leaks, the "Vacuum method" and the "Overpressure method".

FIG. 7.1. Helium leak test.

In the "Vacuum method", the object to be examined for leaks is evacuated and sprayed from the outside with Helium. The gas enters through any leaks present in the object and is detected by a sensor connected to the leak test instrument.

In the "Overpressure method", the object to be examined for leaks is filled with the search gas, Helium, under slight overpressure. The search gas escapes through any leaks present to the outside and is detected by a detector probe. This detector probe is in most cases called a "sniffer" acting as a gas sampling probe.

For both methods specially developed leak detectors are available.

The object under test should, if possible, be tested according to its final mode of use, i.e. if it is used under vacuum, the vacuum method should be applied, if it is finally pressurised, the overpressure method should be adopted.

Examples of testing with the two methods are illustrated below. The Vacuum method is illustrated with the Hood Test and the Tracer Probe Test and the Overpressure method with the Hood test, the Bombing test and the Detector Probe or Sniffer test.

7.4.1. Vacuum method - Hood test

The Hood Test is an overall leak test. The evacuated test object is covered with a plastic hood. The space between the test object and the hood is filled with Helium from the search gas reservoir so the total outer surface of the test object is exposed to the Helium search gas, as shown in fig. 7.2. The helium enters through all leaks present at the evacuated test object and thus the detector connected to it. The detector then indicates the total leak rate.

The hood test can be used for examination of small vessels.

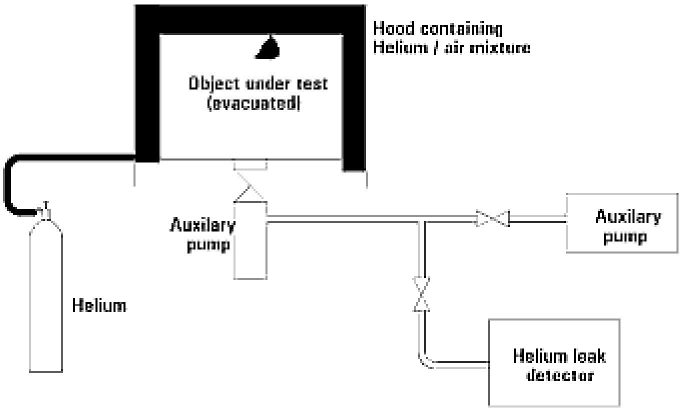


FIG. 7.2. Set up for Hood test.

7.4.2. Vacuum method - Tracer probe test

For the tracer probe test, the same set-up as used for the hood test is applied, but without the hood. A spray gun is used to spray a fine jet of helium search gas at areas suspected of leaking, as shown in fig. 7.3. Again the helium enters through leaks to the evacuated test object and the detector connected to it. The detector indicates if a leak is present at the area to which the helium search gas is exposed.

The tracer probe test can be used on seals, flange connections, and weld seams.

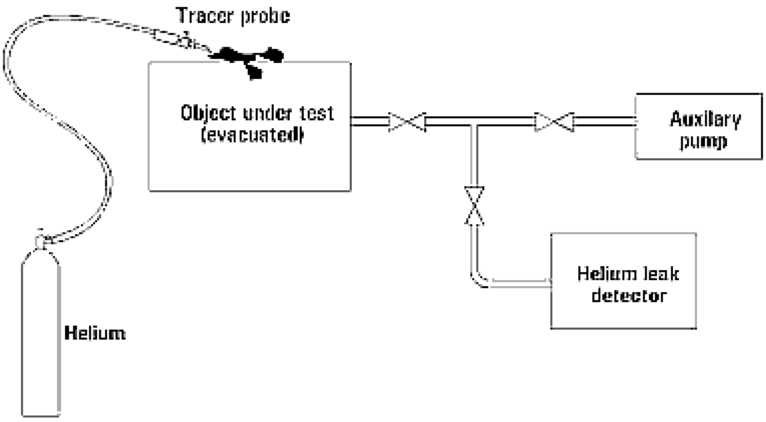


FIG. 7.3. Helium leak test, vacuum method, tracer probe test.

7.4.3. Overpressure method - Hood test

Like the vacuum hood test, the overpressure hood test is an overall leak test. A test set-up similar to the vacuum test is used. A vacuum chamber is used for the hood, which can be evacuated by a auxiliary pump and to which the leak detector is connected, as fig. 7.4 illustrates. The helium search gas which is escaping through leaks in the test object is indicated by the leak detector.

The use of a helium leak detector allows detection of extremely small leaks and is suitable for automatic leak detection in industrial equipment.

The hood test can be used for examination of vessels and heat exchangers.

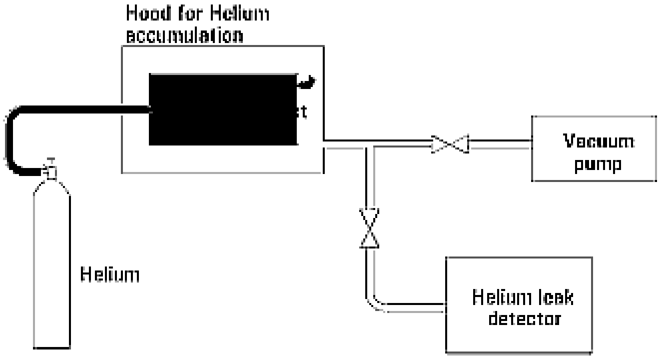


FIG. 7.4. Helium leak test, overpressure method, Hood test.

7.4.4. Overpressure method - Bombing test

The bombing test is a pressure/vacuum method of leak detection used for testing of hermetically sealed components containing a cavity which can be gas-filled or evacuated. The object to be tested is placed in a pressure chamber exposed to the helium search gas. During an exposure time of up to several hours at a high helium pressure, the helium will penetrate through any leaks present in the test object. This is the part referred to as the “bombing”. After the pressurisation or bombing, the objects are tested for helium emission in a vacuum vessel, following the same procedure as in the hood test. This test permits detection of the smallest leak rates and is especially used for objects which cannot be gas-filled by other means.

The bombing test can be used for examination of transistors and vacuum packed medications.

7.5. Applications of halogen leak detection

A halogen-diode detector uses a special sensing element that responds to halogen compound gases, such as bromine, iodine, fluorine, or chlorine. These compounds are used as pressurized tracer gases inside a vessel, triggering a probe in the detector device whenever gas begins to leak out. There are multiple types of halogen-diode detectors, but each is composed of a sensing element and a control unit. The sensing element, or probe, functions according to the principles of ion emission. Positive-ion emissions rise along with increases in halogen compound gas, and the ion current is converted into an electrical signal to indicate leaks. When locating leaks, the probe is moved over the area of joints or seams in an enclosure, touching the surface of any metal container. When it passes over a leak, the probe draws in the tracer gas and emits an audible visual signal. It is important not to pass the detector too quickly over the vessel’s surface, as this may cause smaller leaks to go undetected.

Halogen leak detection is widely applied to detecting leaks in refrigeration systems, as the working gases often contain halogens.

7.6. Applications of bubble leak detection

Product and food packaging is tested for leaks using the visual vacuum bubble leak testing technique for product and food packaging that contains some headspace gas. This may also be referred to as bubble emission testing when packaging is immersed under water under atmospheric conditions.

The bubble emission test is used to determine package integrity. Issues such as packaging material compatibility, sealing machine setup and seal reliability are crucial for high altitude trucking and airfreight shipments. Package integrity is also crucial to consumer safety since heat sealed packages are designed to provide a contamination free and sterile environment to the product.

Leak testing by bubble emission can be a destructive testing method and just like with dye penetrant leak testing, manufacturers should expect to waste a certain amount of package material and products. Leak testing by bubble emission involves submerging the package underwater and looking for leaks. With the proper equipment, vacuum can also be used to reduce the external pressure on the sealed package, giving sufficient internal pressure to allow air or gas to leak out from a defect creating a stream of bubbles.

Vacuum bubble emission testing is performed by filling a test vacuum chamber with water so that the package is submerged by water. The chamber lid is then closed and vacuum is applied. Vacuum is slowly increased so the package expands. The package is observed for a steady progression of bubbles from the flexible container indicating a leak. Once the vacuum is released the package is also inspected for the presence of test fluid inside the specimen. Flexible packing with little or no head space cannot be reliably evaluated with this test method. Parameters such as the vacuum level during test and the testing time will vary based on the various types of packaging methods and requirements.

7.7. Applications of vacuum box leak detection

Vacuum Box Testing is a practical technique of testing in comparison to the quantitative measures used to examine objects. Vacuum box testing can be used to test objects on which a pressure differential can be created across the area to be examined. The common application areas of vacuum box testing include piping systems, pressure vessels, and storage tanks.

There are various types of boxes or frames used in Vacuum Box Testing depending upon the application area. Vacuum box inspection can be carried out on lap welds, butt welds and fillet welds. These vacuum boxes are used to examine a small and specific portion of the welded area to produce accurate results. The vacuum boxes used in vacuum box testing are fabricated of thick, clear Perspex with a closed cell foam seal along the bottom edge.

Before proceeding with the vacuum box testing, a vacuum gauge and hose coupling are fitted in the box. Then a soapy solution is put on the line of welding in the testing object. After that the vacuum box is placed over the testing object and a vacuity is created inside the box. Now, the object is observed, if there any drop in the vacuum or bubble formation on the surface then it shows that there is leak in the weld and the object is defected or faulty.

Vacuum box testing is a very popular leak testing technique that is widely used to test various objects against defects, flaws, leaks, or other imperfections. It is very efficient and effective way of testing various welded objects for any kind of leaks or defects. There are basically two main types of vacuum box systems used for performing vacuum testing:

(a) High Pressure Models that are mainly used for inspection of above ground storage tanks that have been in service.

(b) Low Pressure Models used for weld integrity checks on new tank builds where gross defects are the main concern.

7.8. Applications of further and advanced techniques

7.8.1. Radioactive tracers

The use of radioactive tracers in the detection of leaks in pressure vessels and pipelines is well documented.[2] In any closed system, while on-line, the introduction of a small amount of radioactive tracer coupled with strategically located sensors for online detection, or a portable detector to manually examine a specific installation, provides early and accurate identification and localization of leaks.

For on-line applications, where small amounts of tracer can be introduced with no impact on the process itself, radiotracers offer a very sensitive tool with limited expense.

7.8.1.1. Radiotracer techniques for leak detection in underground pipelines

Some conventional NDT techniques such as gas detection, acoustic emission, and infrared waves have been developed for underground pipeline leakage detection. Leak location of a long underground pipeline, however, with these techniques is an extremely difficult task, as their sensitivity and ability for on-line leak location do not meet stringent field conditions.

Radiotracer techniques are very useful in the detection of leaks in underground pipelines because of their high sensitivity and accuracy in comparison with conventional NDT techniques. An appropriate radiotracer is injected into a pipeline and a certain pressure is applied to the pipeline to cause the radiotracer to follow any existing leak paths. The leaked tracer may migrate towards the ground surface in case of gaseous radiotracer or be absorbed into the soil or thermal insulation around the leak point in case of liquid radiotracer. The location of a leak is discovered by surveying the radioactivity from the leaked radiotracer.

The detection of the leaked radiotracer is performed from the ground surface, when the thickness of the soil above the pipeline is small enough (the gamma radiation of the radiotracer or the gaseous radiotracer itself can penetrate to the ground surface). In case of deeply buried pipelines the detection of leaked radiotracer is performed from the inside of the pipeline using a pipeline PIG (pipeline inspection gauge) equipped with one or more radiation detectors and a data logging system.

Three methods are used generally to detect and locate leaks in buried pipelines: tracer patch migration method, velocity drop method, and radiotracer – detector PIG method.

7.8.1.2. Radiotracer patch migration technique

This technique is known also as the *radiotracer pulse migration method*. The section of a pipeline to be inspected is filled with a fluid and is isolated by closing the valves. A small amount of radiotracer is introduced as single pulse at an injection point located in the middle section of the pipeline. A preset pressure is applied to the pipeline through the injection point using a pressure pump. The movement of the radiotracer is monitored by two radiation

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[2] IAEA Training Course Series No. 38, Leak detection in heat exchangers and underground pipelines using radiotracers, Vienna (2009) gives a detailed description for this application.

detectors installed at a few meters away from the injection point to both sides as shown in Fig. 7.5.

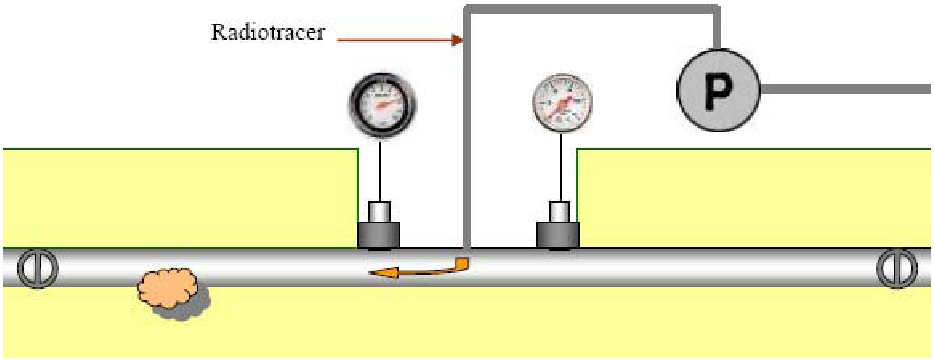

FIG. 7.5. Radiotracer patch migration technique.

The radiotracer patch moves along with the fluid and migrates towards the location of the leak. Rough estimation of the leak flow rate is also possible by measuring the velocity of the tracer patch movement. The search for the exact location of the leak can continue only at that side to which the radiotracer is moving. A modification of this method is to inject a radiotracer from one end and monitor its migration towards the leak using many detectors installed along the pipe. The pipeline dimensions affect the velocity of the radiotracer movement along its way from the injection point to the leak point. The chance to find small leaks in large diameter pipelines is rather scarce because the radiotracer concentration decreases under the influence of diffusion and dilution with respect to time. For larger leaks, this technique works quite well. The radiotracer patch migration technique can be employed in some circumstances for both shallow and deeply buried pipelines. For shallow buried pipelines, the detection is normally performed by moving a detector on the ground surface along the pipeline, while for deeply buried pipelines, the radiotracer patch inside the pipeline is monitored using radiation detectors lodged into pits dug at regular intervals along the ground surface projection of the pipeline (Fig. 7.6). Dug pits are few tens of centimetre depth, sufficient to shelter the detection probe as much as possible near the pipeline.

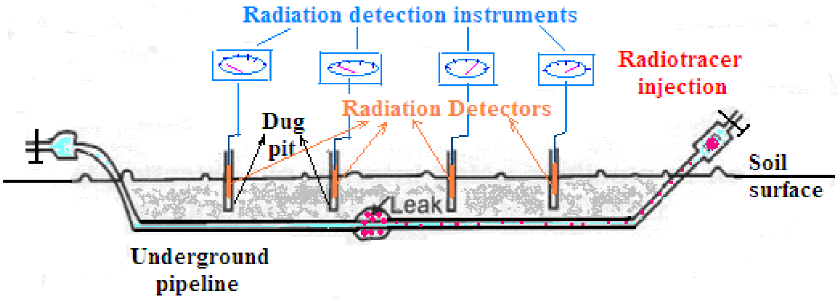

FIG. 7.6. Radiotracer patch migration method using dug pits for radiation detection.

7.8.1.3. *Radiotracer leak detection in an underground cooling water pipeline at a thermal power station – a case study*

Cooling water was being pumped from the water pump to the condensers of a thermal powerplant by a 400 meter long buried pipeline (Fig. 7.7). Two pumps feed water to the pipeline which is made of mild steel having internal diameter of 2240 mm with 12 mm wall thickness. The total volumetric flow rate in the pipeline is 29043 m^3/hour. This pipeline is buried about 2 meters deep under the soil surface up to the plant building entry point. Inside the plant building, the pipe is buried under a one meter thick reinforced concrete floor. Under the concrete floor, there is further 0.5 to 1.0 meter of soil cover over the pipeline. At the distribution point, inside the building, three pipes (labelled as Pipe #1, Pipe #2 and Pipe #3, shown in Fig.7.7.) were teeing-off vertically upwards from the main pipeline. Each teeing-off pipe has a metal sleeve around it separating the pipe from the concrete floor. There is a gap (3–5 cm wide) between the teeing-off pipe and the metal sleeve. Leakage water is flowing out from the gap between pipe and sleeve around all three teeing-off pipes. The first teeing-off pipe supplies water to various services and has a volume flow rate of 1543 m^3/hour. The second and third pipes supplies water to condensers with a volume flow rate of 13750 m^3/hour each. Furthermore, there is a pit (~ 5 x 5 × 5 cm) between Pipe # 2 and 3 (just adjacent to Pipe #3 as shown in Fig. 7.7.

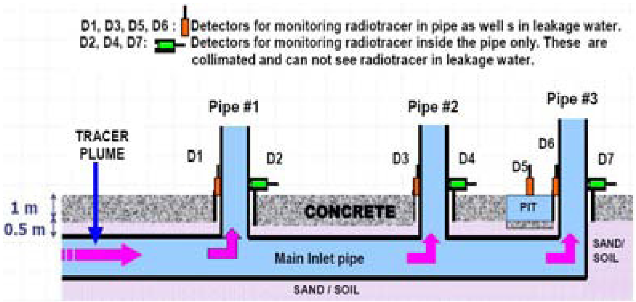

FIG. 7.7. Layout of 'teeing-off' pipes and leakage monitoring plan.

A number of plant installations are present in the near vicinity of the leakage point and it is not economical to dig out the floor without knowing the exact position of leakage. Apparently, leakage water was coming out around all three teeing-off pipes and in first instance it looked like the leakage was at teeing-off joints. Much more water appeared to be leaking from Pipe # 1 compared to Pipes #2 and #3. A small amount of water was also leaking from the pit. Because there is one-meter thick reinforced concrete floor overlying the pipeline and all around inside the building area, any leakage in the portion of the pipeline which is inside the building can only come out on the floor from the three metal sleeves around Pipe # 1, 2, 3 and the pit dug in floor near Pipe #3. Any leakage in the area outside the plant building has little chance to appear inside the building because of soil nature and natural drainage conditions. Therefore, leakage may be anywhere in the pipeline after it enters the building. The objective of the radiotracer study was to identify all leakage points so that an appropriate repair plan could be prepared.

A radiotracer pulse migration procedure was used to investigate this problem. An activity of ~50 mCi of 131 I in the form of NaI solution was injected at the pump inlet in the sump pit close to the suction point. A glass vial containing liquid radiotracer was crushed inside the water using a specially designed vial crushing mechanism. Radiotracer injection was monitored at pump outlet using a collimated sodium iodide (NaI) detector of 2"× 2" crystal.

The volume flow rate of cooling water inside the pipeline was 29043 m^3/hour at a pressure of 2 kg/cm^2 and linear speed of around 2 m/s. Therefore, radiotracer flowing inside the pipeline will travel relatively quickly along with the cooling water, but, when water leaks out, its speed and pressure become lower.

Two radiation detectors were installed side by side at the exit point of leakage water at each teeing-off pipe to detect radiotracer flowing inside the pipeline and radiotracer present in leakage water. There is an appreciable time-lag between the arrival, at detectors, of radiotracer flowing inside the pipe and radiotracer present in leakage water. Logically, radiotracer flowing inside the pipeline should arrive at the detection point earlier than the radiotracer present in leakage water. Similarly, radiotracer present in leakage water should appear earlier at those radiation detectors that are relatively closer to the leakage point. Seven detectors (NaI, 2" × 2") were installed around the suspected leakage points for monitoring of radiotracer present in water flowing inside the pipelines as well as in potential leakage water. Detectors D1, D3 and D6 were installed adjacent to pipe #1, pipe #2 and pipe #3 respectively.

These detectors were not collimated and were immersed inside the leakage water coming out from the sleeves of the respective pipes. The purpose of these detectors was to monitor radiotracer present in the leakage water outside the pipes but they could also see the radiotracer passing inside the pipes because they are installed just near the pipes.

Fig. 7.8 shows the experimental response curves recorded by 7 detectors. Detectors D2, D4 and D7 were collimated with lead shielding and were installed horizontally against pipe #1, #2 and #3 respectively. The purpose of these detectors was to monitor radiotracer passing inside the pipes only, i.e., they were made blind to the tracer in leakage water. Detector D5 was uncollimated and installed in the pit water. It could see radiotracer inside adjacent pipe #3 as well as radiotracer present in leakage water.

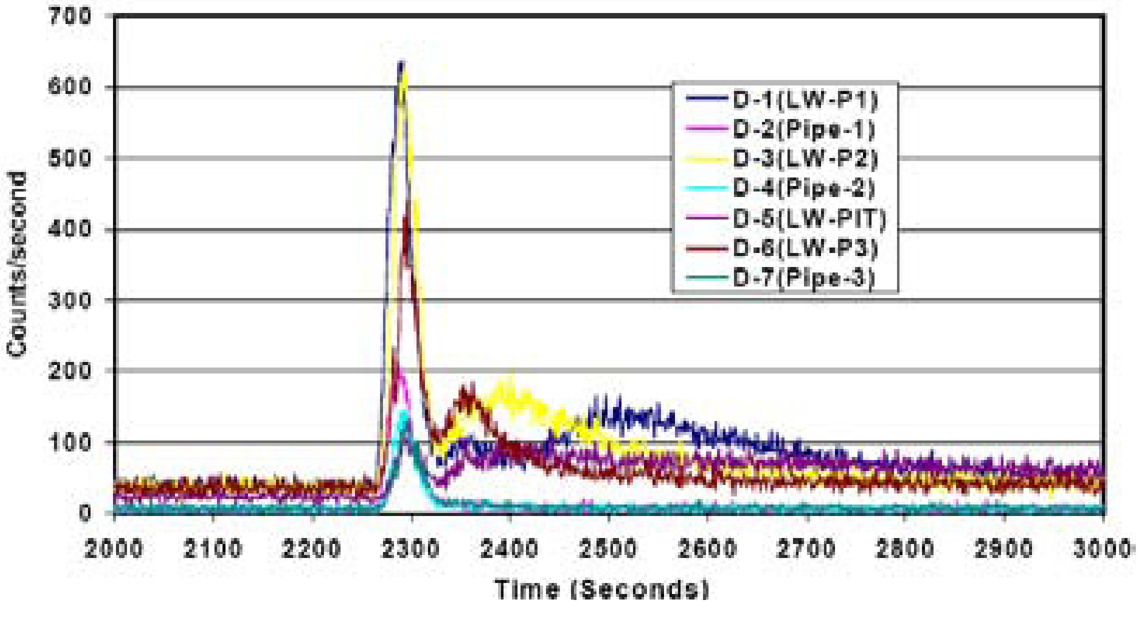

FIG. 7.8. Radiotracer responses registered by seven detectors.

The leakage water from pipe #1, #2, #3 and pit was isolated, on the floor, separated so that leakage for one point did not mix from leakage from any other point until it leaves the area of the radiation detectors and is discharged into the drain.

The summary of radiotracer arrival and peak timings at seven detectors is given in Table 7.1. The comparison between the relative timings of leakage peaks helps determine the leakage points.

TABLE 7.1. RADIOTRACER ARRIVAL AND PEAK TIMINGS FROM DIFFERENT DETECTORS

	D-1	D-2	D-3	D-4	D-5	D-6	D-7
Detector	(LW-P1)	(P1)	(LW-P2)	(P2)	(Pit)	(LW-P3)	(P3)
Tracer arrival time (sec)	2266	2266	2269	2269	2272	2272	2272
Peak 1 (signal from pipe)	2291	2287	2292	2293	2292	2296	2298
Peak 2 (leakage)	2349	-	2399	-	2289	2262	-
Peak 3 (leakage)	2497	-	-	-	-	-	-

The arrival of radiotracer at detectors D1and D2 is recorded at the same time i.e., at 2266 seconds. Detector D1 has recorded three peaks; peak 1 is due to tracer flowing inside the pipe #1 while peak 2 and peak 3 are due to leakage. Detectors D2, D4 and D7 have recorded only one peak because they are seeing radiotracer flowing inside pipe #1 only and are blind to radiotracer present in leakage water. The arrival of radiotracer at detectors D3 and D4 is recorded at the same time i.e., at 2269 seconds (3 seconds after radiotracer arrival inside pipe #1). Detector D3 has recorded two peaks, peak 1 is due to tracer flowing inside pipe #2 and peak 2 is due to leakage. Arrival of radiotracer at detector D5 is recorded at 2272 seconds. This detector has recorded two peaks. Peak 1 is recorded at 2292 seconds and it is due to radiotracer inside pipe #3, while peak 2 recorded at 2389 seconds is due to leakage. The arrival of radiotracer at detectors D6 and D7 is recorded at the same time i.e., at 2272 seconds (3 seconds after radiotracer arrival at pipe #2). Detector D6 has recorded two peaks. Peak 1 is due to tracer flowing inside pipe #3 and peak 2 is due to leakage water. Radiotracer responses of un-collimated detectors D1, D3, D5 and D6, which were monitoring radiotracer flowing inside the pipes as well as from leakage water, are presented in Fig. 67. Radiotracer arrival at detectors D1, D3 and D6 is recorded exactly at the same time as it is recorded at collimated detectors D2, D4 and D7 respectively. Detector D5 also recorded the same arrival time as that of Detector D6 and D7. Peak 1 of all the four detectors represents the radiotracer passing through the pipes while peak 2 of all detectors and peak 3 of detector D1 represent the leakage water.

The leakage peak first appears at detector D1 (installed at pipe #1) at 2349 s which indicates leakage near pipe #1. It then appears at detector D6 (installed at pipe #3) at 2362 s indicating leakage near pipe #3. The leakage water near pipe #3 travels backwards in the soil along the outer surface of the pipeline and reaches detector D5 (installed in pit water) at 2389 s. The same leakage water travels further backwards and reaches detector D3 (installed at pipe #2) at 2399 s. This leakage water travels further more towards pipe #1 and reaches detector D1 (installed at pipe #1) at 2497 s. The major leaks are in pipe #1 and pipe #3.

7.8.2. Liquid penetrant and chemical tracers

Flaws which extend completely through thin-wall metal containers — tanks, tubing, and vessels — are readily detected by the dye penetrant process. The procedure differs from the standard process: dye penetrant is applied to one side while developer is applied to the opposite side; there is no dye penetrant removal step.

Dye penetrant leak test procedures are often used for inspection of tank walls. During leak testing, the inside of the tank is coated with dye penetrant. The other side is covered with developer. The dye penetrant migrates through the flaw, and when it reaches the opposite side, reveals the flaw as a red mark on a white background.

Flaw passages must be free of contaminants — water, solvents, or oils. Moisture from air pressure tests conceivably can interfere with through penetration. The dye penetrant leak test should be used prior to other tests, such as hydrostatic and ultrasonic, to minimise the possibility of flaw passage contamination.

An extended dye penetrant dwell time is usually necessary. Dye penetrant leak testing has limitations and, typically, the process is restricted to wall thicknesses of 1/4 inch or less. The rate of through penetration depends in part on the shape of the capillary passage with a narrow tube providing the best passage. Porosity retards dye penetrant movement. If wall thickness is near maximum and if poor capillary action is anticipated, the dwell time should be extended. Thirty minutes is suggested. A second application of dye penetrant during the 30 minute dwell may also prove advantageous.

Fluorescent dye penetrants can also be used where enhanced visibility is desired. Microelectronic component manufacturers develop components designed to withstand the effect of time and environment. Whether the component is hermetic or not, protecting the active area inside the device is critical.

In this application, the technique consists of submerging the device into a fluorescent dye fluid which has the viscous properties to fill very fine cracks. Leak rates as low as $5 \cdot 10^{-8}$ mbar-L/sec Helium have been effectively measured. After curing, the impregnated device is encapsulated in a transparent resin for cross-sectioning. A microscope inspection of cross-sections under ultraviolet light reveals the leak pathways.

Another application is to incorporate a small amount of fluorescent penetrant inside a pressurized system, taking care to ensure that the penetrant is compatible with the system fluid, then to examine the accessible side with an ultraviolet light. This is an extremely sensitive technique for finding pinholes in welds. Fig. 7.9 shows an inspector examining a heat exchanger wall for leakage. Another application is to detect and locate leak points in an automobile radiator. The method is inexpensive yet accurate.

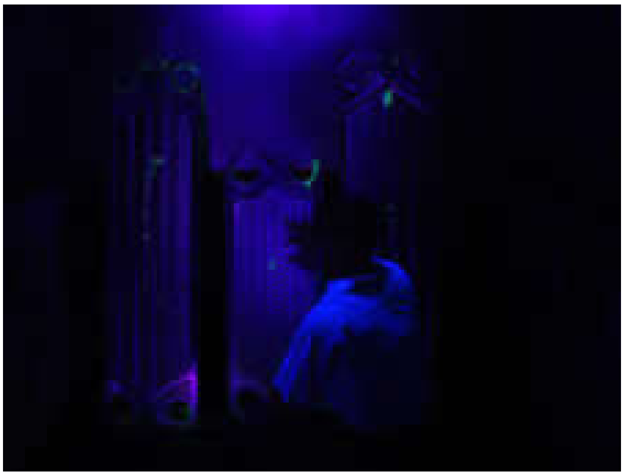

FIG. 7.9. Inspecting a heat exchanger wall with ultraviolet light looking for fluorescent dye leakage.

7.8.3. Acoustic leak testing

There are many applications where acoustic techniques have been applied to detect and locate small leaks in large systems. Whether the high frequency sound waves are conducted through the air (ultrasonic leak detection) or through the structure (acoustic emission leak testing), the principle is the same.

One area where these techniques have been used successfully is in the checking for leakage in water pipelines. Leaks in water pipelines cause unnecessary waste of limited resources, and thus justify the expense of leakage prevention and detection. The experience of water distribution companies shows that the reduction of leakage and the preservation of a low leakage level can be achieved with a strategy that requires a loss analysis followed by leak detection and location survey.

Effective techniques of leak detection by acoustic emission have been developed and applied in several water systems.

The water systems in Brescia, Italy, for example, incorporate around 2,200 km are constructed mainly of ductile iron and cast iron pipes. Over 120 boreholes and 30 spring sources supply the networks delivering to users a total of 47 million mc a year.

Since 1988, ASM BRESCIA S.p.A. has been engaged in an active programme of leakage reduction employing various methods of leakage monitoring and detection, including amongst others, leak detection and location using leak noise correlators and area surveys using acoustic loggers (Aqualogs). This commitment to leakage reduction has resulted in a reduced level of leakage achieved in many of the managed water networks.

In order to reduce pumping and hence operating costs to a minimum, an intensive leakage location program was initiated in the late 1980's, with the aim of systematically checking the network at regular intervals using correlators. As successful as this approach proved to be in locating the leaks, it provided no guarantee that the reduction in leakage would be sustained. What was needed was a permanent leakage control system.

ASM decided to divide the network into a number of small zones called districts that has proved by experience in different parts of the world, to be the most efficient method of controlling leakage. Then, permanently closing the boundary valves and installing flow meters on the few supplying mains, one can continuously monitor the level of leakage. If an increase is registered in the night-time consumption, a team is sent in to locate the leaks. In this way, leakage is under permanent control, but intervention occurs only at the optimum moment.

The modern leak noise correlator is now the most effective and widely used system for leak detection and location. For this reason, the leak inspection on water pipelines using the cross-correlation method were standardised in 1991 by a work group of the CNR (Italian National Research Council). The code of practice highlights those elements necessary for carrying out the leak detection survey in order to improve the quality and standardize the activity. This document can be used by the Water Distribution Companies as well as by Service Companies as a useful reference.

The technique is based on the analysis of casual continuous acoustic noise generated by the water escaping from the pipeline and carried out by using the cross-correlation technique. The target is to standardize the method of leak detection by using the cross-correlation technique in order to detect and locate the leaks themselves yet not their amount. The method of testing requires the use of sensing devices placed on existing pipelines fittings as well as conditioning, acquisition and signal analysis instrumentation in order to detect and locate the leaks.

The method described applies to the control of underground supply and distribution water pipelines of steel, ductile iron, cast iron, asbestos cement, polyethylene and PVC. Cast iron, steel or asbestos cement pipe sections of a maximum length of 250 meters can be controlled by using non-intrusive sensing devices (accelerometers) and up to 600 meters by intrusive sensing devices (hydrophones). The maximum controllable length of plastic pipes such as PVC or (high and low density) polyethylene is 50 metres only, when accelerometers are used, and 120 meters when hydrophones are used.

The method of testing requires the use of non intrusive sensing devices (accelerometers) or intrusive devices (hydrophones) placed on existing pipeline fittings as well as conditioning, acquisition and signal analysis instrumentation in order to detect and locate leaks. The location of the leaking point in the pipe is obtained knowing: the distance between the sensors that span the leak, the propagation velocity of the leak sound in the pipeline and the time delay, measured by the cross-correlation function (see Fig. 7.10) that the leak sound takes to reach the two sensors.

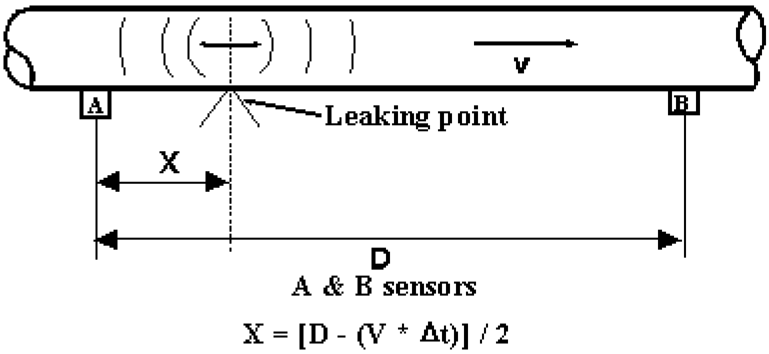

FIG. 7.10. Method of leak location.

Where

- X = distance of the point of leak from the reference sensing device;
- D = distance between the two sensing devices;
- V = propagation wave speed;
- Δt = time delay obtained from the peak position of the cross-correlation function.

Fig. 7.10 shows how the position of the leaking point may be obtained using time delay and Fig. 7.11 shows an example of the cross-correlation function.

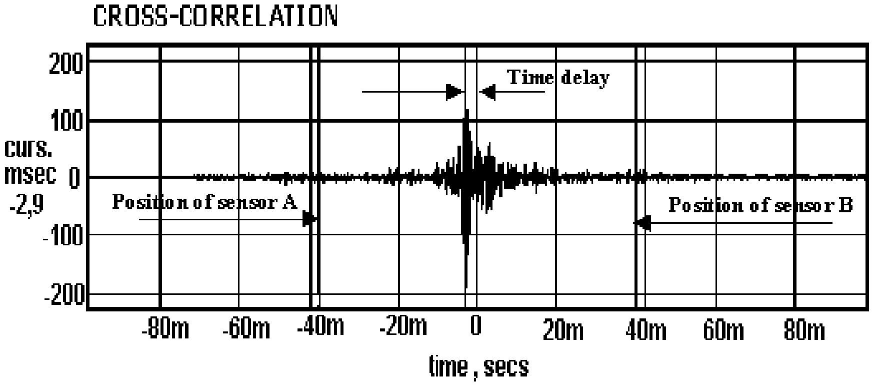

FIG. 7.11. Cross-correlation function plot.

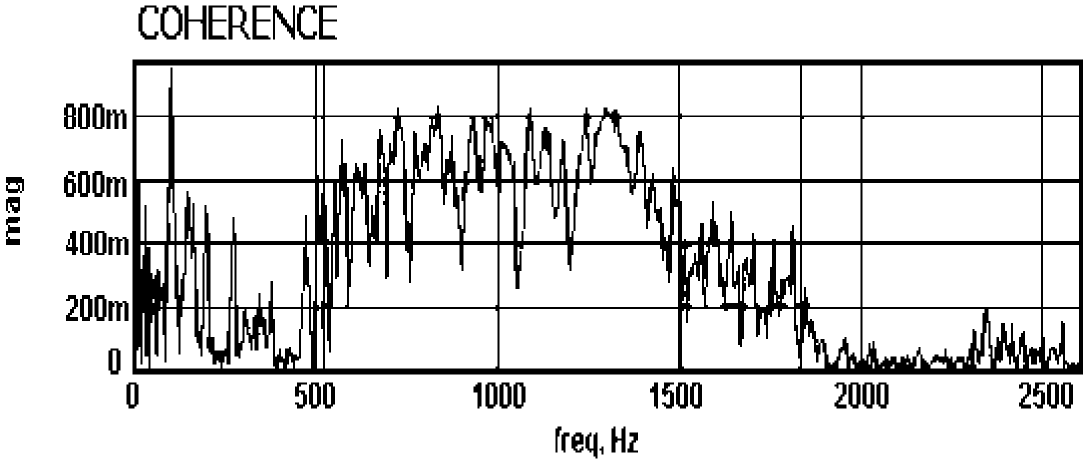

FIG. 7.12. Coherence function plot.

The diagram in Fig. 7.12 shows that the position of the leak, in relation to the two sensing devices, is determined by detecting the maximum of the cross-correlation function related to the time delay of the signals.

The coherence function allows establishing the reliability rating of the measure carried out. It expresses the dependence of the signals, detected at the two measurement points A and B, from a common leak noise source. The coherence is normally represented between zero and one, therefore, the nearer the coherence is to one the closer is the link between the two detected signals.

The results obtained over a sample of 4820 km of water distribution network in different Italian cities that have been surveyed using the cross-correlation technique in the last ten years are now outlined. During the systematic survey concerning the above mentioned networks — about half consisting of cast and ductile iron pipes and the other half of steel pipes and asbestos cement pipes (only 33 km of plastic pipes have been inspected) — a total of 3450 water leakages have been detected. Out of the detected leaks, 3312 (96%) have been located exactly and have undergone repair. Some of the remaining 174 leaks have been located during the repair excavation at distances greater than 3–4 meters. The location errors are essentially due to the uncertainty of the used distance between sensors.

In the last few years other acoustic techniques have been developed to optimise water leakage management in identifying leakage areas prior to directing leak detection operators to pinpoint the leak. Systems have been developed for acoustic noise monitoring and recording that can be permanently or time limited installed at hydrants, valves or house connections. These “noise loggers” record typical noises in the network during low consumption hours at night and identify areas of potential leakage for further investigation. The ultimate advance consists in transmission of leak presence from the noise loggers to a receiver module, which may be hand carried or vehicle-mounted.

The noise logger is installed at fittings using a simple magnetic coupling, and is battery powered with no maintenance requirement, and no problems for being immersed in water.

The separation distance between loggers depends mainly on the pipe material, with plastic pipes requiring closer spacing than metallic. Each unit is intelligent and adapts itself to the environment. If no leak is present, a radio signal is transmitted to indicate normal background conditions. However, as soon as a leak is detected, the unit enters an alarm state and transmits a radio signal to indicate a “leak condition”. Signals are received by a module that can be mounted in a patrolling vehicle, or can be easily hand-held. This receiving module analyses and "homes in" on signals to identify the location of units indicating a "leak condition", and thus the approximate position of a likely leak.

The reading of an area meter could easily include the monitoring of the loggers within it, so that new leaks are localised at exactly the same time as increases in the night flow are noticed. This should mean a prescribed leakage level can be easily maintained, because the detection time is greatly reduced. This innovative technology offers the possibility of continuous, permanent monitoring for leakage for the entire distribution system or just for those parts that are known problem areas.

In the last fifteen years the use of acoustic techniques has shown that leaks can be accurately identified and localised much faster than with any conventional method. These experiences in leakage detection and location have proved that the application of acoustic techniques gives the water industry the most effective tools for conserving precious water resources.

In particular, the use of cross-correlation technique to detect and locate the leaks on underground pipelines has gained larger and larger approval within the water industry, because it offers a more accurate location of the leak, less dependence from operator interpretation and it can be used in very noisy conditions. The obtainable benefits due to the application of the considered technique are dependent on the care and manner in which it is applied and the results are as good as the operators strictly observe the guideline. With the application of the “noise loggers” which record typical noises in the network during low consumption hours at night is now possible the permanent acoustic monitoring of the distribution network. This new technology will help to achieve further leakage reduction without increasing the costs for water leak detection.

7.8.4. Infrared gas analyzers

An infrared gas analyzer can detect gas compounds that have a clear absorption band in the infrared spectrum through a comparison with a standard sample of the same gas. Heat is applied to absorption containers holding the two gases, which are separated by a diaphragm linked to a metal plate in an electrical condenser. If the two gases are chemically identical, the diaphragm will not register any pressure differences under heating, but if the gas is mixed with a high-absorption tracer gas, the diaphragm will move in relation to the metal plate. This change is translated into electrical output recorded on a meter. A tracer gas with a high level of infrared absorption, such as nitrous oxide, tends to be effective for this method of detection.

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LIST OF ACRONYMS

AE	Acoustic emission
BCC	Body-centred cubic
DIR	Digital industrial radiography
ET	Eddy current testing
FCAW	Flux cored arc welding
FCC	Face-centred cubic
GMAW	Gas metal arc weld
GPR	Ground Penetrating Radar
GTAW	Gas tungsten arc welding
IR	Infrared
IRT	Infrared thermography
LIBS	Laser induced breakdown spectroscopy
LT	Leak testing
MT	Magnetic particle testing
NDE	Non-destructive evaluation
NDT	Non-destructive testing
PAW	Plasma arc welding
PCRT	Process compensated resonance testing
POD	Probability of detection
PT	Liquid penetrant testing
RBI	Risk-based inspection
RT	Radiographic testing method
RUS	Resonant ultrasound spectroscopy
SAW	Submerged arc welding
SMAW	Shielded metal arc welding
TNDT	Thermal non-destructive testing
TOFD	Time of flight diffraction
UT	Ultrasonic testing
VT	Visual testing

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