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Guidebook for the Fabrication of Non-Destructive Testing (NDT) Test Specimens

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FOREWORD

The International Atomic Energy Agency (IAEA) is promoting the industrial applications of radiation technology, which include non-destructive testing (NDT) under its various programmes such as individual country technical co-operation (TC) projects, regional projects and co-ordinated research projects (CRPs). The NDT technology is essentially needed for the improvement of the quality of industrial products, equipment and plants all over the world, especially in the developing Member States. An important feature of the NDT programme, notably in the East Asia and Pacific (RCA) region, has been the establishment in each of the Member States of a system for training and certification of NDT personnel based on the International Organization for Standardization standard ISO/FDIS 9712-1999, "Non-destructive Testing: Qualification and Certification of Personnel". The main focus is the creation of a core group of personnel who are trained and qualified to establish the training and certification process in their respective countries. An important requirement for such a process is to have appropriate training materials that include, among others, NDT test specimens having standard known dimensions and in-laid artificial defects simulating the real defects that can or may occur in industrial components.

NDT test specimens constitute a very important part of training and certification of NDT personnel and are important for carrying out actual inspection and testing, and for achieving international harmonization of NDT practices. Naturally, therefore, there is a need to pay greater attention to this subject. A number of seminars and workshops on NDT test specimens have been organized for this purpose during the past years under various RCA regional projects while a number of additional activities, such as regional training courses and seminars, are planned for the future.

It has always been felt that there is a strong need to have a proper guidebook addressing various issues and problems related to the fabrication of NDT test specimens. Such a book would be useful for conducting training courses on this theme in the future, thereby spreading the know-how for the fabrication of NDT test specimens and establishing and strengthening education, training and certification process in many Member States on a sustainable basis.

In view of the above, the IAEA organized an advisory group of experts to develop a Guidebook for the Fabrication of NDT Test Specimens. The experts consulted the ISO/FDIS 9712-1999 requirements for training and certification of personnel and the suitability of various types of NDT test specimens that are needed to meet such requirements.

A set of appropriate NDT test specimens, as well as the methodology and procedures for their fabrication, were established. These are presented in this guidebook. The experts recommended that these procedures be taken only as a guide, and can be expanded and perfected by the national certifying bodies of the Member States. It was felt that there is the need to compile similar procedures for the remaining types of test specimens but this could not be addressed due to limited time.

The IAEA wishes to express its appreciation to the governments and organizations who provided financial, technical and administrative support, and to the experts who contributed to the production of this Guidebook.

The IAEA officer responsible for this publication was A.A. Khan of the Division of Physical and Chemical Sciences.

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1. NON-DESTRUCTIVE TESTING: BASIC OVERVIEW OF COMMON METHODS

1.1. INTRODUCTION

It is fact that there are inherent flaws in materials due to crystal lattice imperfections and dislocations however microscopic they may be. Manufacturing processes such as welding, casting, forging, surface treatment, etc. may cause further flaws or defects. Materials are used under various conditions of stress, fatigue and corrosion, which may create additional defects or aggravate present ones. It has been established that most material failures occur because these defects reach dangerous proportions such that remaining parts of the materials could not withstand the stress they are subjected to, thus become ductile or brittle.

There is, therefore, a need to detect these flaws and evaluate them in terms of their nature, size and location. Further steps should be to assess (a) how severe and dangerous the flaws are in their present state, (b) whether they need to be removed by repairing the tested component, (c) if the component be scrapped, or (d) with known flaws, if the product can be allowed to go into service. These are done through inspection and testing.

One method of inspection is to subject the material or weld to destructive tests, which would provide information about the performance of that test object. The disadvantage of destructive testing is that, as the name implies, the test object is destroyed in the process. Therefore, testing methods have been developed to provide the information required of the test object without rendering it unfit for service.

These methods are referred to as non-destructive tests because they permit evaluation of the material or component without destroying it. Destructive testing of parts can be expensive and assumes that the untested parts are of the same quality as those tested. Non-destructive tests give indirect yet valid results and, by definition, leave the test object fit for its intended use.

There are a variety of NDT methods that can be used to evaluate the materials, components as well as completed welds. All NDT methods share several common elements.

These elements are:

- some source of probing energy or some type of probing medium
- discontinuity that must cause a change or alteration of the probing medium
- some means of detecting the change
- some means of indicating the change
- some means of observing and/or recording this indication so that an interpretation can be made.

The suitability of any NDT method for a given application will be determined by considering the above elements. The source of the probing energy or probing medium must be suitable for the test object and for detecting the defect or discontinuity sought. If present, a defect or discontinuity must then be capable of somehow modifying or changing the probing medium. Once changed, there must be some way of detecting these changes. These changes to the probing medium by the discontinuity must form some indication or otherwise be recorded. Finally, this indication must be reviewed in order for it to be interpreted and classified.

Various NDT methods have been developed, each one having advantages and limitations making it more or less appropriate for a given application. With the variety of NDT methods available, it is important to select the method that will provide the necessary results. A combination of different NDT tests may be applied to provide assurance that the material or component is fit for use.

1.2. COMMON NDT METHODS

While there are many different methods of NDT only the more common NDT methods used for the evaluation of materials and welds will be outlined here. These methods are the following:

(1) Visual inspection
(2) Liquid penetrant inspection
(3) Magnetic particle testing
(4) Radiographic inspection
(5) Ultrasonic testing
(6) Eddy current testing

1.2.1. Visual inspection

Visual inspection (VT) relies upon the detection of surface imperfections using the eye. Normally applied without the use of any additional equipment, VT can be improved by using aids such as a magnifying glass to improve its effectiveness and scope.

VT is considered to be the primary NDT method. Since it relies on an evaluation made using the eye, VT is generally considered to be the primary and oldest method of NDT. With its relative simplicity and because it does not require sophisticated apparatus, it is a very inexpensive method thus provides an advantage over other NDT methods. A further advantage of VT is that it is an ongoing inspection that can be applied at various stages of construction.

The primary limitation of VT is it is only capable of evaluating discontinuities, which can be seen on the surface of the material or part. Sometimes there may be some visual indication of a subsurface imperfection that may need an additional NDT method to provide verification of the subsurface discontinuity.

VT is most effective when it is performed at all stages of any new fabrication, and is the main method used during the inspection of pressure equipment.

If applied say after welding has been completed, it is possible that subsurface flaws may not be detected. Therefore, it is important to appreciate that VT will only be fully effective if it is applied throughout any fabrication or inspection. An effective VT programme if applied at the correct time will detect most defects or discontinuities that may later be found by some other costly and time consuming NDT method. The economics of VT can be seen in welding if we consider how much easier and inexpensive a welding problem can be corrected when found at the right time, i.e. as it occurs.

For example, a flaw, such as incomplete fusion at the weld root, can be repaired easily and quickly right after it is produced, saving on expense and time required repairing it after the weld has been completed and inspected using some other NDT technique.

VT will also give the technician instant information on the condition of pressure equipment regarding such things as corrosion, bulging, distortion, correct parts, failures, etc.

VT requires three basic conditions to be in place. These are:

— good vision, to be able to see what you are looking for
— good lighting, the correct type of light is important
— experience, to be able to recognize problems.

As mentioned previously, one of the advantages of VT is that there is little or no equipment required, which improves its economy or portability. Equipment, which may be employed to improve the accuracy, repeatability, reliability, and efficiency of VT, include various devices. Magnifying glasses may also be utilized for a more detailed look at some visual feature. However, care must be taken to avoid making erroneous decisions regarding the size or extent of some discontinuity when its image is magnified.

As mentioned before, the primary limitation of VT is that it will only detect surface discontinuities. It is also limited to the visual acuity and knowledge of the technician.

In order to preserve the test results, various methods can be employed. These include: drawing a sketch, describing the visual appearance using written words, or taking a photograph or video of the surface conditions noted. It is important to accurately record the location, extent, and type of any defect so that the owner, designer, principal and production personnel know what requires repair and where the repair is to be carried out.

1.2.1.1. Limitations

(a) Restricted to surface inspection
(b) Good eyesight required
(c) Good lighting required
(d) Person performing the inspection must know and be able to recognize what he/she is looking for.

1.2.1.2. Advantages

(a) Primary method of inspection
(b) On-going inspection
(c) Most economical inspection method
(d) Applicable at any stage of fabrication.

1.2.2. Liquid penetrant inspection

Liquid penetrant inspection (PT) reveals surface flaws by the “bleed-out” of a penetrating medium against a contrasting background. This is done by applying penetrant to the pre-cleaned surface and flaw of the item being inspected. The penetrant is applied to the surface and allowed to remain on the surface for a prescribed time (dwell time); the penetrant liquid will be drawn into any surface opening by capillary action. Following removal of excess penetrant an application of a developer reverses the capillary action and draws penetrant from the flaw. The resultant indications reveal the presence of the flaw so that it can be visually inspected and evaluated.

Within the categories of penetrant inspection are a family of tests, these relate to the type of penetrant used. There are also two ways in which penetrant materials are classified, typically the type of indication produced and the method of removal. Penetrant testing results are displayed in two ways, visible and fluorescent. The visible penetrant type produces a bold red line or strain indication against a white developer background when viewed under good white light conditions. The fluorescent penetrant produces a green, fluorescent indication when observed under an ultraviolet (black) light. Because the human eye can more readily perceive a fluorescent indication than a visible indication, the use of fluorescent penetrant inspection will result in a more sensitive test.

The second way in which penetrants are classified is the method by which the excess penetrant is removed from the test surface. The penetrants are either water washable, solvent removable or post-emulsifiable. Water washable penetrants contain an emulsifier that allows the penetrant to be rinsed off using low-pressure water spray; sometimes a water-dampened towel is used. Solvent removal penetrants require a solvent to remove the excess penetrant from the test surface. Post-emulsifiable penetrants are removed by adding an emulsifier after the penetrant dwell time. By combining the characteristics of these two classifications, six different types of penetrants can be used.

1.2.2.1. Types of penetrant

(1) Visible/water – washable
(2) Visible/solvent – removable
(3) Visible/post – emulsifiable
(4) Fluorescent/water – washable
(5) Fluorescent/solvent – removable
(6) Fluorescent/post – emulsifiable.

With any of these types, application and use is considered the same, except for post-emulsifiable penetrant that requires an emulsifier application step. With any of the methods, there are several steps to follow. It is important that each of the steps is performed carefully in its correct sequence; otherwise, the test results may not be reliable.

Liquid penetrant testing is used by all industries where there is concern about the surface condition of a material or welded joint. It is used extensively on non-magnetic materials, i.e. stainless steel and aluminium that cannot be evaluated using magnetic particle testing.

1.2.2.2. Limitations

(a) Access required for surface preparation and cleaning
(b) Surface condition must be satisfactory
(c) Non-relevant indications from irregular surfaces
(d) Will only detect surface flaws
(e) Flaw must be clean and not contaminated.

1.2.2.3. Advantages

(a) Economical
(b) Aid to VT
(c) Portable
(d) Can inspect a wide range of materials and components.

1.2.3. Magnetic particle testing

Magnetic particle testing (MT) is used to locate surface and slight subsurface discontinuities or defects in ferromagnetic materials. Such flaws present in a magnetized part will cause a magnetic field, i.e. flux, to leave the part. If magnetic particles are applied to this surface, they will be held in place by the flux leakage to give a visual indication.

While several different methods of magnetic particle tests can be used, they all rely on this same general principle. Therefore, any magnetic particle test will be conducted by creating a magnetic field in a part and applying the magnetic particles to the test surface.

To understand the principle of MT, it is necessary to have some basic knowledge of magnetism. Therefore, consider some of the important characteristics of magnetism in and around typical bar magnet.

First, there are magnetic lines of force, or magnetic flux lines, travelling from one end (or pole) of the magnet to the opposite end (pole). These poles are generally designated as the north and south. The magnetic flux lines form continuous loops that travel from one pole to the other. These lines generally remain parallel to one another and will not cross each other. Also, the force of these flux lines (and therefore the flux density of the resulting magnetic field) is greatest when they are fully contained within a ferromagnetic material. Although they will travel through air gaps, their intensity is reduced as the length of the air gap is increased.

If we now consider a horseshoe magnet, magnetic lines of force are travelling in continuous loops from one pole to the other. However, if a piece of steel or keeper is placed across the ends (poles) of the magnet, a continuous magnetic path for the lines of force is provided. While there is some flux leakage present at the slight air gaps between the ends of the magnet and the piece of steel, the magnetic field remains relatively strong because of the continuity of the path created by the keeper.

If a discontinuity or flaw is present in the steel bar (keeper) across the ends of the magnet in the vicinity of that flaw, a flux leakage field is created at the flaw surface because the magnetic field leaves the magnetic material and travels through air. If the steel bar is sprinkled with iron particles, such particles would be attracted and held in place by the flux leakage at the flaw. This will occur because the iron particles provide a continuous magnetic path for the lines of force just as the piece of steel across the ends of the magnet completed the magnetic circuit for the magnet.

Therefore, to perform MT, there must be a means of generating a magnetic field in the test specimen. Once the part has been magnetized, iron particles are applied to the surface. When discontinuities are present, these particles will be attracted and held in place to provide a visual indication of the flaw. In the examples discussed so far, permanent magnets.

However, use of a permanent magnet for MT is generally considered to be inferior to other methods of magnetic particle inspection.

Therefore, MT of pressure equipment is generally performed using a certain type of electromagnet. An electromagnet relies on the principle that there is a magnetic field associated with any electrical conductor.

Either alternating current (AC) or direct current (DC) can be used to induce a magnetic field. The magnetic field created by AC due to the "skin effect" is strongest at the surface of the test object. AC will also provide greater particle mobility on the surface of the part allowing them to move about freely to locate areas of flux leakage, even though the surface of the part may be irregular.

Direct current (DC) induces magnetic fields that have greater penetrating power and can be used to detect near surface discontinuities.

1.2.3.1. Limitations

(a) Materials or part being inspected must be ferromagnetic
(b) High currents can be used
(c) Will only detect surface and slightly subsurface flaws
(d) Material or part may need to be demagnetized
(e) Material or part must be clean and relatively smooth
(f) Equipment can be bulky and heavy
(g) Power supply generally required
(h) Coating may mask indications
(i) Material or part permeability may affect results.

1.2.3.2. Advantages

(a) Economical
(b) Aid to VT
(c) Can be fixed or portable equipment
(d) Instant repeatable results
(e) Effective inspection method
(f) Contrast or fluorescent consumables.

1.2.4. Radiographic inspection

Radiographic inspection or testing (RT) is a non-destructive inspection method based on using short wavelength electromagnetic radiation passing through the material. Materials with areas of reduced thickness or lower material density allow more, and therefore absorb less, radiation. The radiation, which reaches the film after passing through the material, forms a shadow image on a photographic film (radiograph).

Areas of low absorption (slag, porosity) appear as dark areas on the developed film (radiograph). Areas of high absorption (dense inclusions) appear as light areas on the developed film.

Lower energy radiation can be in the form of either gamma or X rays. Gamma rays are the result of the decay of radioactive isotope. A common radioactive source is Iridium 192. A gamma source is constantly emitting radiation and must be kept in a shielded storage container when not in use. These containers often employ lead or depleted uranium.

X rays are produced when electrons, travelling at high speed, collide with matter. The conversion of electrical energy to X radiation is achieved in an evacuated tube. A low current (mA) is passed through a filament to produce electrons. Application of a high potential (kV) voltage between the filament and a target accelerates electrons across this voltage differential. The action of an electron stream striking the target produces X rays; these are produced only while voltage is applied to the X ray tube. Whether using gamma or X ray sources, the test object, e.g. weld, is not radioactive following the inspection.

Subsurface discontinuities that are readily detected by this method are voids, e.g. rounded flaws, metallic and non-metallic inclusions, and favourably aligned incomplete fusion and cracks. Voids, such as porosity, produce dark areas on the film because they represent a significant loss of material density. Metallic inclusions produce light areas if they are denser than the test object.

For example, tungsten inclusions in aluminium welds, which can be produced when using gas tungsten arc welding (GTAW) techniques, appear as light areas on the film. Non-metallic inclusions, such as slag produce dark areas on the film. Cracks and incomplete fusion must be aligned such that the depth of discontinuities is nearly parallel to the radiation beam for detection. Surface discontinuities, which may also be detected using VT, include undercut, excessive reinforcement, incomplete fusion, and heavy penetration. Radiographic testing can be used to inspect all common engineering materials and is used extensively for the inspection of welds in pressure equipment.

Among the equipment required to perform radiographic testing is some source of radiation. This source can be either an X ray machine, which requires some electrical input, or a radioactive isotope that produces gamma radiation. The isotope offers increased portability. Either type requires film in a light-tight film cassette. Lead letters or lead tape is used to identify the test object. Because of the high density of lead and the local increased thickness, these letters form light areas on the developed film. Penetrameters or image quality indicator “IQIs” are used to verify sensitivity of the radiograph. These are made of known material and known diameters or thicknesses. Sensitivity of usually 2% or better is verified by the ability to detect a given difference in film density (usually between 2–3) of the wire diameter or shim thickness.

1.2.4.1. Limitations

(a) Equipment can be bulky and heavy.
(b) Radiation hazards.
(c) Testing area needs to be controlled access.
(d) Equipment relatively time consuming and expensive.
(e) Access may be required to both sides of object.
(f) May not detect critical flaws.
(g) Results require interpreting by experienced person.
(h) Gamma results inferior to X ray results.
(i) Gamma less sensitive than X ray, especially on thin materials.
(j) Not suitable for certain configurations, e.g. tee joint.

1.2.4.2. *Advantages*

(a) Volumetric inspection.
(b) Can detect surface and subsurface flaws.
(c) Permanent records.
(d) Good quality control method.

1.2.5. Ultrasonic testing

Ultrasonic testing (UT) is a non-destructive inspection method that uses high frequency sound waves (ultrasound) that are above the range of human hearing, to measure geometric and physical properties in materials. Ultrasound travels in different materials at different speeds (velocity). However, the speed of sound propagation in a given material is a constant. There are several ways that sound travels through a material. One type of sound wave, called longitudinal or compression travels about 330 metres per second in air and about 6400 metres per second in aluminium or in steel at approximately 5960 metres per second.

To perform UT, electrical energy is converted to mechanical energy, in the form of sound waves, by a transducer. The transducer accomplishes this energy conversion due to a phenomenon referred to as the piezoelectric effect. This occurs in several materials, both naturally-occurring and man-made. Quartz is a naturally occurring piezoelectric material. A piezoelectric material will produce a mechanical change in dimension when excited with an electronic pulse. Similarly, this same material will also produce an electric pulse when acted upon mechanically. An example of the common use of piezoelectric materials is found in the electronic lighters available for starting gas stoves, gas grills, cigarette lighters, etc. In these examples, the piezoelectric crystal is squeezed and released suddenly to result in the generation of an electric spark that jumps across a gap to ignite the gas.

To perform UT, the transducer is attached to an electronic ultrasonic set. Following a prescribed calibration procedure, the ultrasonic set will essentially be converted into a measuring device. The ultrasonic set will generate precise electronic pulses that are transmitted through a coaxial cable to the transducer that has been placed using a couplant in contact with the test object. These pulses are of very short duration and high frequency (typically 1 to 10 million cycles per second). This high frequency sound has the ability to be directed in which its shape is like the beam from a torch.

When excited by the electronic pulses, the transducer responds with mechanical vibration, which creates a sound wave that is transmitted through the material at whatever velocity is typical for that material. A similar phenomenon can be heard when a metal is struck with a hammer to provide a “ringing”. This ringing is simply a sonic (lower frequency) sound wave that travels through the material.

The sound wave will continue to travel through the material at a given velocity and does not return to the transducer unless it hits a reflector (a boundary between two different materials, or a flaw). If that reflector is favourably oriented, it will reflect the sound back to the transducer at the same velocity. When struck by this sound wave, the piezoelectric crystal will convert that energy into an electronic pulse which is amplified and displayed on a cathode ray tube (CRT) of the ultrasonic set as a visual indication to be interpreted by the operator.

By using “calibration” blocks of the correct material having specific dimensions and shapes as well as the various controls on the ultrasonic set, the time it takes for the sound wave to travel through the material can be related to the distance the sound has travelled. Consequently, the ultrasonic set allows the operator to control how long it takes for the sound to travel through the material to a reflector and back to the transducer to facilitate the accurate distance of how far the sound has travelled.

One of the primary benefits of UT is that it is considered to be a truly volumetric test. That is, it is capable of determining not only the length and location of a flaw, but it will also provide the operator with information as to the type of flaw found. Another major advantage of UT is that it only requires access to one side of the material being tested. This is a big advantage in the inspection of pressure equipment, tanks and piping systems.

Another important advantage is that UT will best detect those more critical planar discontinuities such as cracking and incomplete fusion. UT is most sensitive to discontinuities that lie perpendicular to the sound beam. Because a variety of beam angles can be used UT can detect laminations, incomplete fusion and cracks that are oriented such that detection with radiographic testing would not be possible. UT has deep penetration ability. Modern UT equipment is lightweight and often battery-powered making that method portable.

The major limitations of this test method are that it requires a highly skilled operator because interpretation can be difficult. Also, the test object surface must be fairly smooth and couplant is required for contact testing. Further limitations are that reference standards are required and that no permanent record of the CRT display is generally available. This test method is generally limited to the inspection of butt welds in materials that are thicker than 6 mm.

1.2.5.1. Limitations

(a) Test surface must be smooth.
(b) Couplant required.
(c) Expensive equipment.
(d) Reference standards required.
(e) Results require interpretation by experienced person.
(f) Inspection of welds over 6 mm thick.

1.2.5.2. Advantages

(a) Volumetric inspection.
(b) Access to only one side required.
(c) Inspects a variety of thicknesses and weld types.
(d) Portable equipment.
(e) Can detect surface and subsurface flaws.
(f) Can readily size flaws detected.
(g) Subject to orientation, can detect planar flaws reliability.
(h) Non-hazardous to personnel.
(i) Suitable for automation.

1.2.6. Eddy current testing

In eddy current testing (ET), a coil carrying an AC current is placed close to the specimen surface, or around the specimen. The current in the coil generates circulating eddy currents in the specimen close to the surface and these in turn affect the current in the coil by mutual induction. Flaws and material variations in the specimen affect the strength of the eddy currents. The presence of flaws, etc. is therefore measured by electrical changes in the exciting coil. Both voltage and phase changes can be measured, but some simpler instruments measure only the voltage changes.

The strength of the eddy currents produced depends on the:

- electrical conductivity of the specimen
- magnetic permeability (for a ferromagnetic specimen)
- stand-off distance between the specimen and coil
- AC frequency used in the exciting coil
- dimensions of the coil and specimen
- presence of flaws.

Much of the success of ET testing depends on separating the effects of these variables. Most eddy current instruments require calibration on a set of test specimens and the flaw sensitivity can be very high.

Equipment vary from simple portable meter-read-out instruments, to more complex oscilloscope read-out displaying both phase and voltage; recently the outputs have been digitized to produce fully automated computer programmed equipment with monitored outputs for high speed testing.

Applications vary from crack detection to rapid sorting of small components for either flaw, size variation, or material variation. Many applications are to bar, tube and wire testing. Metal sorting is also a common application of ET.

1.2.6.1. Limitations

(a) Requires highly skilled operator
(b) Applicable to conductive materials only
(c) Depth of penetration in limited
(d) Its application to ferromagnetic materials is difficult.

1.2.6.2. Advantages

(a) Gives instantaneous response
(b) Can be easily automated
(c) Versatile
(d) No contact between the probe and the test specimen is essential
Its equipment can be made portable.

2. TECHNOLOGY OF WELDING

2.1. GENERAL CONSIDERATIONS

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 that is of the same composition as the parts being joined may be added, in which case, 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. 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 that are commonly used for the welding of metals are described and their features are discussed in the following sections.

2.2. WELD DESIGNS 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.

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 and 2 and explained below:

(a) Flat position (1G) – the test plates are placed in an approximately horizontal plane and the weld metal deposited from the upper side, Fig. 2 (A).

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

(c) Vertical position (3G) – the test plates are placed in an approximately vertical plane with the welding groove approximately vertical, Fig. 2 (C).

(d) Overhead position (4G) – the test plates are placed in an approximately horizontal plane and the weld metal deposited from the underside, Fig. 2 (D).

(e) 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. 2 (A).

(f) Vertical (2G) – the pipe is placed with its axis in an approximately vertical position with the welding groove in an approximately horizontal plane (Fig. 2 (B)).

(g) 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. 2 (E).

(h) Inclined fixed (6G) – the pipe is inclined fixed ($45^{o}\pm5^{o}$) and not rotating during welding, Fig. 2 (F).

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

(a) 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. 2 (A).

(b) 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. 2 (B).

(c) Vertical position (3F)– each fillet weld is made vertically, Fig. 2 (C).

(d) 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. 2 (D).

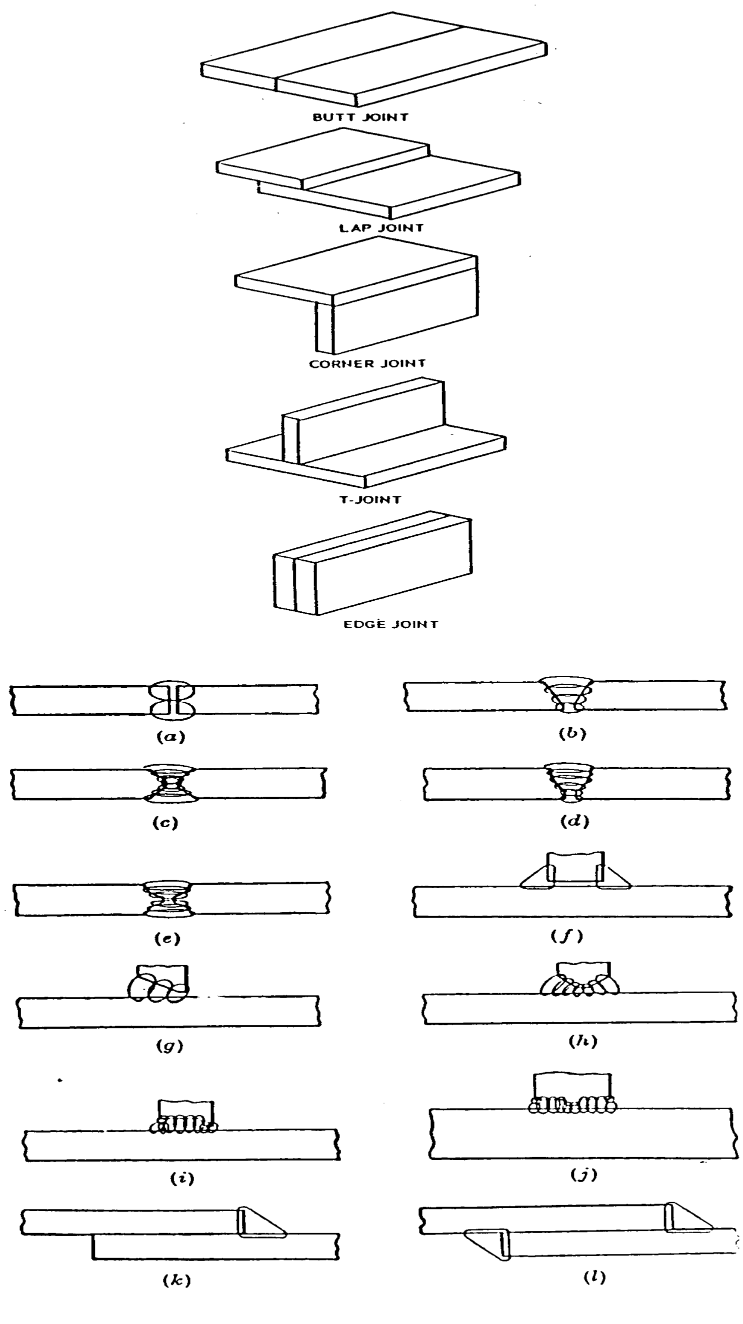
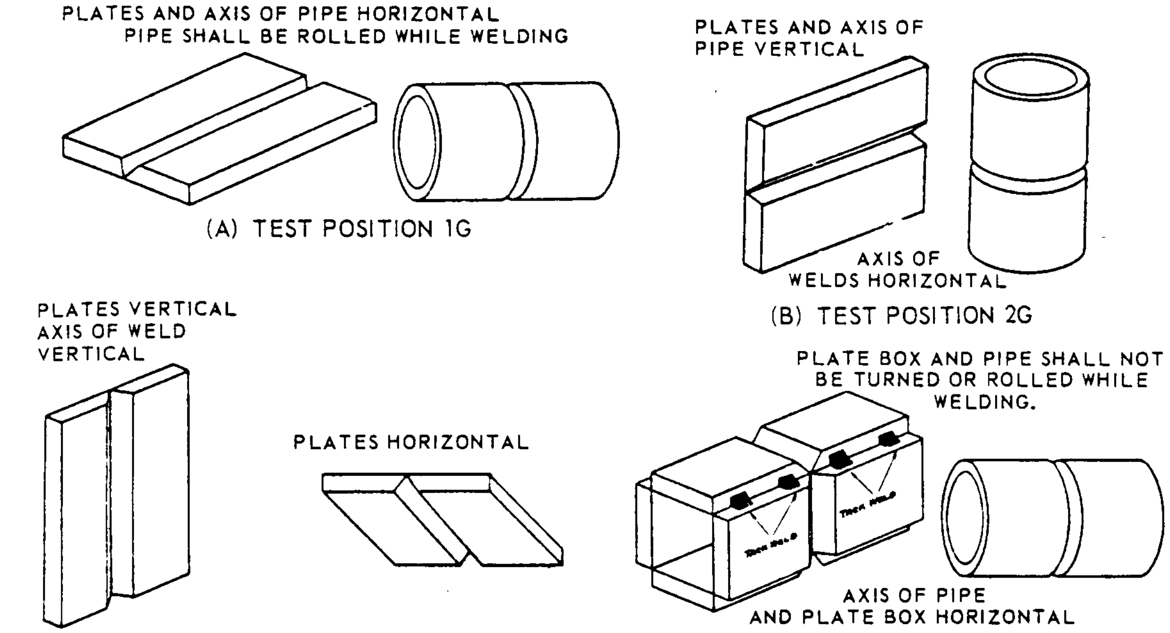
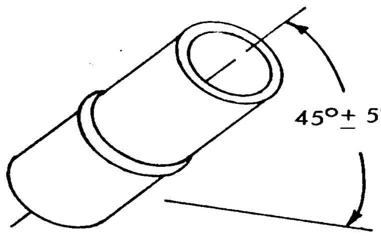


FIG. 1. Types of welding joints.

(a) square butt joint; (b) single-v butt joint; (c) double-v butt joint; (d) single-u butt joint; (e) double-u butt joint; (f) square-t joint; (g) single-bevel t-joint; (h) double-bevel t-joint; (i) single-u t-joint; (j) double-u t-joint; (k) single-bead lap joint; (l) double-bead lap joint.



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



(F) TEST POSITION 6G

FIG. 2. Positions of plates and pipes for groove weld.

2.3. WELDING PROCESSES — BASIC OVERVIEW OF COMMON METHODS

2.3.1. Manual metal arc welding

Manual metal arc welding (MMAW) is an electric arc welding process where the heat for welding is generated by an electric arc between a flux covered metal electrode and the work. The filler metal is deposited from the electrode and the electrode covering provides the shielding. Other names for this process include the North American term “Shielded metal arc welding” (SMAW), “stick welding” or “stick electrode welding”. A diagram of this process is shown below.

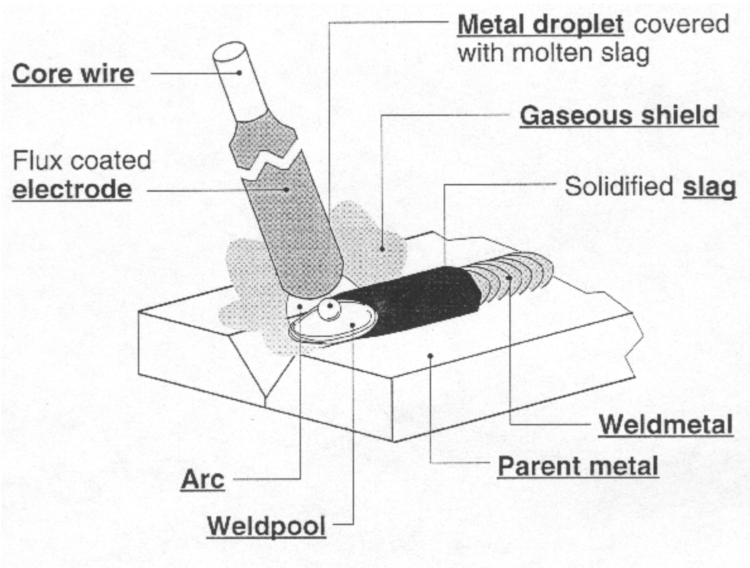


FIG. 3. Schematic diagram of MMAW.

SMAW process is a simple and versatile arc welding process. This process is used predominantly to weld ferrous metals and it can weld thickness above about 2 mm in all positions. The arc is under the control of the welder and is visible. The welding process leaves a slag on the surface of the weld bead that must be removed. The most popular use for this process is for the welding of structural steel including low alloy and other higher strength steels. This equipment is extremely rugged and simple. The process is flexible, as the welder only needs to take the electrode holder and worklead to the point of welding.

2.3.1.1. Equipment

The equipment for the SMAW process consists of a power source, welding cable, electrode holder, and work clamp or attachment.

2.3.1.2. Electrode

The electrodes for SMAW consist of a core wire with a flux coating. The usability characteristics of different types of electrodes are standardized and defined by the relevant standard organization or society. The identification system indicates the strength of the deposited weld metal, the welding positions that may be employed, the usability factor of the electrode, and in some cases, the deposited metal analysis. A classification number is printed on each electrode for identification purposes.

The specifications commonly encountered include:

— AWS A5.1, American Welding Society specifications — are also American National Standards
— ISO 2560, the international standard for MMAW electrodes.

The AWS classification system of mild steel and low alloy steel covered electrodes consists of the letter "E" and four or five digits. Sometimes a suffix is added to the classification for additional information. The letter "E" indicates an electrode. The first two or three digits indicate the minimum tensile strength. In the American system the digits stand for the tensile strength in ksi, e.g. there is 1000 psi in 1 ksi.

The third and fourth digits indicate the positions the electrode can be used, the type of current and the coating type. Sizes available are 1.6, 2.5, 3.2, 4.0, 4.8, 5.0 and 6.0 mm.

Electrode classification	Minimum tensile strength		Minimum yield strength	
X = a variable	MPa	ksi	MPa	ksi
E60XX or E43XX	425	60	345	48
E70XX or E48 XX	485	70	395	58
E80XX	550	80	460	
E90XX	620	90	530	
E100XX	690	100	600	
E110XX	760	110	655	
E120XX	825	120	740	

2.3.1.3. Advantages of MMAW

(a) MMAW is a widely accepted, versatile and well developed welding process.
(b) High quality welds are readily achieved on all steels in both the workshop and on-site.
(c) The equipment is relatively simple, inexpensive and portable.
(d) The shielding gas provided by the burning flux is less sensitive to wind and drafts when compared to a process with an external shielding gas.

2.3.1.4. Limitations

(a) Deposition rate can be lower than gas metal arc welding (GMAW), FCAW or SAW.
(b) The weld is covered by a layer of slag that must be removed.
(c) High skill level required for high quality welds.

2.3.2. Gas metal arc welding

GMAW is an electric arc welding process that fuses together the parts to be welded by heating them with an arc between a solid metal electrode and the work. Filler metal is obtained from melting of the electrode wire, which is fed continuously into the arc by the equipment. Shielding is obtained from an externally supplied gas or gas mixture. Some slang names for the process are MIG welding and CO_2 welding. A diagram of this process is shown below.

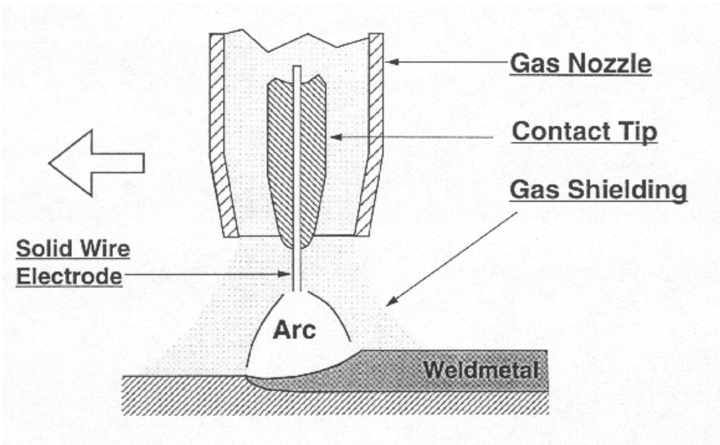


FIG. 4. Schematic diagram of GMAW.

The GMAW process is capable of welding most ferrous and non-ferrous metals from thin to thick section. It can be used in all positions to produce weld deposits with little or no spatter. Higher deposition rates, travel speeds and welder efficiencies, result in less welding time in production situations, as compared to SMAW.

2.3.2.1. Equipment for welding

The equipment for the GMAW process consists of a power source, controls, wire feeder, welding gun, welding cables and a gas shielding system. There are several items that are added to the basic equipment for automatic applications such as devices for providing movement and seam followers.

2.3.2.2. Metal transfer

The first type of metal transfer is commonly called short-circuiting. During short-circuiting transfer a metal droplet grows at the tip of the electrode wire. As the droplet grows, the wire moves closer to the puddle until it actually comes in contact with the puddle. At this point, a short-circuit is produced which causes the wire to resist heat and pinch off, producing a new arc. This cycle continues many times a second, depending on the amperage/voltage relationship.

Globular transfer is similar to short circuiting in that a droplet is formed at the end of the electrode wire. However, during the globular transfer the molten ball continues to grow until it is larger than the diameter of the electrode wire. Then the droplet detaches and crosses the arc to form the weld deposit. Because of this, the arc is less stable and more spatter is produced. Globular transfer is commonly used to weld the same metals as short-circuiting transfer, except in greater thickness.

Spray transfer is characterized by small droplets that rapidly transfer across the arc. During this metal transfer, the electrode tapers down to a point. The droplets are formed at the tip and pinched off due to electromagnetic forces. Spray transfer is normally used to weld non-ferrous metals in all positions. Argon, or a mixture of argon and helium, is used to shield the arc. Spray transfer can also be used to weld carbon steels, low alloy steels and some stainless steels, using a mixture of argon and of other gas. Spray transfer on steel is normally used to weld medium to heavy thickness of steel in the flat and horizontal position.

2.3.2.3. Electrode

The electrode wire for GMAW is solid and bare. Steel wires normally have a thin copper coating to improve electrical pick-up and protect the wire from oxidation. The electrode wire size is determined by its diameter. Various diameters as 0.6, 0.8, 1.0, 1.2, 1.3, 1.6, 2.4 mm, are available based on the metal transfer, welding position and application. The wire is contained on spools, coils and reels and packed in special containers for protection against deterioration and contamination.

The AWS classifies solid electrode wires, using a series of numbers and letters, similar to SMAW electrodes. For carbon and low alloy steels, the classification is based on the mechanical properties of the weld deposit and their chemical composition. For most other metals, the electrode wire is normally placed on the spool and/or the filler metal packaging.

A typical steel classification using the AWS system is ER70S-6 where:

— E indicates the filler wire is an electrode that may be used for GMAW.
— R indicates it may also be used as a filler rod for gas tungsten arc or plasma arc welding.
— The next two (or three) digits indicate the nominal tensile strength of the filler wire.
— The letter to the right of the digits indicates the type of filler metal. S stands for a solid wire and C stands for a metal cored wire that consists of a metal powder core in a metal sheath.
— The digit or letters and digit in the suffix indicates the special chemical composition of the filler.

2.3.2.4. Advantages of GMAW

(a) Deposition rate is high with spray transfer.
(b) Costs can be kept lower than with MMAW because there is less electrode waste (no electrode stubs), no slag removal and welder downtime due to changing electrodes is less compared to MMAW.
(c) Smoke and fumes are less than MMAW or FCAW.
(d) Obtains deeper penetration than MMAW.
(e) It is versatile (al position process for carbon, low alloy and stainless steels).

2.3.2.5. Disadvantages

(a) High capital cost of machinery, maintenance required on wire feed system.
(b) Accessibility to the welding joint is restrictive because of the size of the gun.
(c) Shielding gas is sensitive to wind and drafts.
(d) The length of the welding lead is restrictive.
(e) The equipment is not as portable as MMAW.

2.3.3. Flux cored arc welding

Flux cored arc welding (FCAW) is an electric arc welding process which fuses together the parts to be welded by heating them with an arc between a continuously fed flux filled electrode and the work. Shielding is obtained through decomposition of the flux within the tubular wire. Additionally shielding may or may not be obtained from an externally supplied gas or gas mixture.

Welding is normally limited to the flat and horizontal positions with large diameter wires. Smaller diameter wires are used in all positions. A layer of slags is left on the weld bead that needs to be removed after welding.

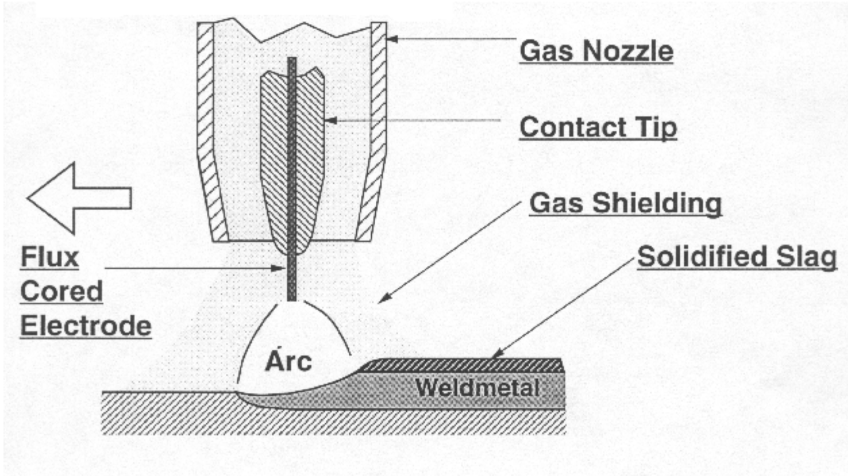


FIG. 5. Schematic diagram of FCAW.

2.3.3.1. Equipment

The equipment for FCAW is very similar to that used for GMAW.

2.3.3.2. Electrode

The electrode wire for FCAW is tubular and filled with flux. The flux provides shielding, deoxidization, arc stabilization and slag formation. Sometimes alloying elements can be added to the ingredients within the core. An external shielding may or may not be used with these wires, depending on the type. FCAW electrodes are available in a variety of sizes from 0.8, 0.9, 1.0, 1.2, 1.6, 1.8, 2.0, 2.4, 3.0, 4.0 mm the wire is contained on spools and coils or in drums.

The AWS classifies FCAW electrodes for carbon steels, using a series of letters and numbers. A typical classification in the AWS system is E70T-1 where:

- E indicates the filler wire is an electrode.
- The next digit indicates the nominal tensile strength of the filler wire in increments of 10,000 pounds per square inch.
- The next digit indicates the positions the wire can be used in
  - 0 – flat and horizontal positions
  - 1 – all positions
- The T indicates the wire is tubular.
- The last number indicates the usability and the performance characteristics of the electrode wire.

2.3.3.3. Advantages of FCAW

(a) Deposition rate is high with larger diameter wires, and for positional welding.
(b) Costs can be kept lower than with MMAW because there is less electrode waste (no electrode stubs), and welder downtime due to changing electrodes is less compared to MMAW.
(c) Deeper penetration is possible than with MMAW.
(d) FCAW has high operator appeal; process is easy to use and welds are of good appearance.

2.3.3.4. Disadvantages

(a) High capital cost of machinery, maintenance required on wire feed system.
(b) Accessibility to the welding joint is restrictive because of the size of the gun
(c) FCAW-gas shielded is sensitive to wind and drafts (self-shielded version has high draft tolerance)
(d) The available length of the welding lead can be restrictive
(e) The equipment is not as portable as MMAW
(f) Electrode is more expensive ($/kg) than GMAW
(g) Produces more smoke and fumes than GMAW
(h) Slag covering that must be removed.

2.3.4. Submerged arc welding

Submerged arc welding (SAW) is an arc welding process which fuses together the parts to be welded by heating them with an electric arc or arcs between a bare electrode or electrodes and the work. The arc is submerged under a blanket of granular flux. The filler metal is obtained from melting the solid electrode wire and sometimes from alloying elements in the flux. A slang name for the process is Sub-Arc.

The SAW process joins all the weldable steels. The process provides high deposition rates that make it excellent for medium and thick sections of plate and pipe. Also, the process produces deep penetration that means less edge preparation is required to obtain penetration. Full penetration welds are readily achieved on sections up to 12.00 mm thick without edge preparation.

The process is normally limited to the flat and horizontal fillet positions because of the flux used to shield the weld puddle. However, with special flux dams, the process can be used in the horizontal groove weld position.

Since the arc is hidden, only safety glasses are generally required by the welding operator. The process generally produces a smooth weld bead with no spatter. A layer of slag is left on the weld bead that is normally easy to remove.

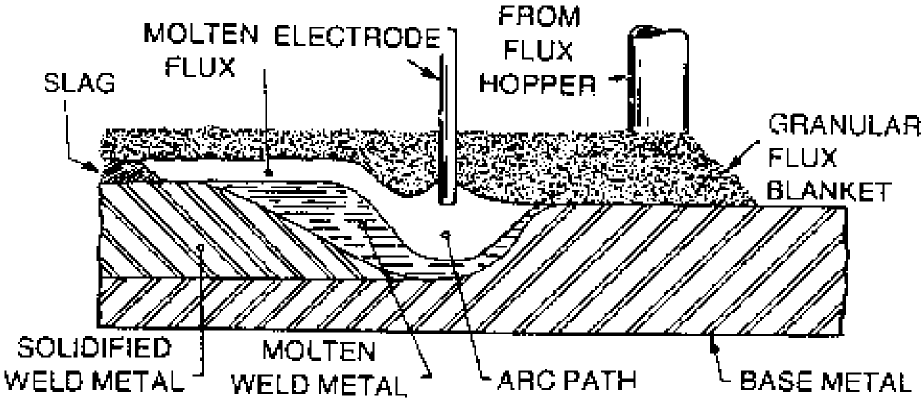


FIG. 6. Schematic diagram of SAW.

2.3.4.1. Equipment for welding

The major equipment components required for SAW are:

— welding machine (power source)
— wire feeding mechanism and control
— welding torch for automatic welding or the welding gun and cable assembly for semi-automatic welding
— flux hopper and flux feeding mechanism
— travel mechanism for automatic welding.

A flux recovery system is usually included in an automatic installation.

2.3.4.2. Electrode

The electrode wires used for SAW are usually solid and bare except for a thin, protective coating on the surface, usually copper. The electrode contains elements that help clean and scavenge the weld metal to produce a quality weld. Alloying elements may also be included in the composition and the type of flux must be matched to the requirements of the base metal in order to provide a quality weld. Electrode wires are available in sizes from 1.6 mm, 2.0 mm, 2.4 mm, 3.2 mm, 4.0 mm, 4.8 mm, 5.6 mm and 6.4 mm diameter. Wire is usually available in coils ranging from 23 kg to 455 kg.

There are several AWS classifications covering SAW electrodes. The classification for carbon steel electrodes is based on the chemical composition of the electrode wire as manufactured. In this classification system, designations for electrodes consist of the letter “E” (for electrode) and between 2 and 4 letters and digits following it. The letters and digits have specific meanings.

TABLE I. MANGANESE CONTENT OF AWS ELECTRODES

Letter	Class	% Mn (max)
L	Low Manganese	.60
M	Medium Manganese	1.40
H	High Manganese	2.25

(1) The first letter following letter E indicates the manganese content of the wire as shown in Table I below.

(2) One or two digits following the manganese class letter indicate an approximate carbon content for the electrode.

(3) Letter K following the digits is sometimes used. This letter indicates that the steel was manufactured from one that was silicon "killed". Silicon killed wire has a greater silicon content than the wire used for the other electrode wires. Silicon is a de-oxidizing agent that helps prevent porosity.

(4) Sometimes a suffix N is used to indicate that the wire is nuclear grade and can be used for nuclear welding applications. In an EM13K wire, E indicates electrode, M indicates medium manganese class, "13" indicates approximately .13% carbon and K indicates silicon "killed". The low alloy solid electrodes used for SAW are also classified according to the chemical composition of the wire, as manufactured. Exceptions to this are the composite electrode classifications that are based on the chemical composition of a fused sample. Low alloy steel electrodes sometimes have letter C following E in the classification indicating the electrode is a composite wire, which means it is a cored wire. The classifications for stainless steel and nickel and nickel alloy electrodes are the same as those used for GMAW, GTAW, and plasma arc welding.

2.3.4.3. Fluxes

Fluxes used in SAW consist of granular mineral compounds, some of which are fused together during welding to form a slag covering for the weld. Fluxes have several purposes:

(a) To protect the molten weld puddle from the atmosphere by forming a slag.
(b) To deposit weld metal with the desired chemical or mechanical properties, or both.
(c) To deposit a weld bead of the desired shape in the joint being welded.
(d) To deposit a weld bead which meets the above requirements at the lowest possible cost.

In addition to the above purposes, some fluxes contain additional de-oxidizers or alloying elements to be added to the molten weld puddle. Fluxes are packaged in drums or bags. Fluxes are produced by several different manufacturing methods. There are three different types of fluxes used. These are fused, bonded, and agglomerated. Fluxes were originally manufactured as fused and re-ground compounds, but now all three different types are common. The characteristics of these fluxes are, as follows.

1. Fused

— Homogeneous
— Particle size and composition and effected by recovery
— Slag removal difficult
— Does not absorb moisture
— Contain little or no dioxidizers and alloying elements
— Good at high travel speed applications.

2. Bonded

— Non-homogeneous
— Particle size and composition effected by recovery
— Slag removal easier
— Absorbs moisture
— De-oxidizers and alloying elements can be added
— Allows thicker flux blanket due to low density.

3. Agglomerated

— Similar to bonded
— Can contain a limited amount of deoxidizers and alloying elements.

SAW fluxes are classified, according to the relevant code or standard, by the mechanical properties of the weld deposit produced in combination with a specific type of electrode. The two mechanical properties used for flux classifications are tensile strength and impact strength. A flux classification can only be used in conjunction with a specific electrode wire. One flux can have more than one classification when used in conjunction with more than one electrode wire.

A flux classification begins with letter F, for flux, and is as followed by a two or three digit number (Table II). The first digit alloys have the minimum tensile strength in increments of 10,000 Ibs./sq. in or 690 MPa for carbon and low alloy steels. The digits used are shown below. The second, or third, digit indicates the minimum impact strength of the weld deposit at a specific temperature. For example, the AWI classification of F64 – EM12K, "F" designates flux, 6 indicates a minimum tensile strength in the weld deposit of 415 MPa or 60,000 psi, and 4 indicates a minimum impact strength in the weld deposit, all of these in conjunction with an EM12K electrode wire. A complete filter material classification must have a flux and electrode designation.

2.3.4.4. Advantages

(a) High deposition rate.
(b) Deep penetration welds of excellent appearance and profile.
(c) High utilization of electrode wire.
(d) Weld puddle is submerged, eliminating the need for protective clothing.
(e) No smoke or fume.

TABLE II. FLUX CLASSIFICATION OF AWS ELECTRODES FOR SUBMERGED ARC WELDING

AWS flux classification	Tensile strength ksi	Tensile strength MPa	Yield strength ksi	Yield strength MPa	Elongation in 5 mm %
F6X-EXXX	62 to 80	430-550	50	345	22
F7X-EXXX	70 to 95	485	60	415	22
F8X-EXX-X	80 to 1000	550-690	68	470	20
F9X-EXXX-X	90 to 110	620-760	78	540	17
F10X-EXXX-X	100-120	690-825	88	605	16
F11X-EXXX-X	110 to 130	760-895	98	675	15
F12X-EXXX-X	120 to 140	825-965	108	755	14

2.3.4.5. Disadvantages

(a) Limited welding positions (flat and horizontal)
(b) Weld puddle not visible
(c) Portability restricted.

2.3.5. Gas tungsten arc welding

GTAW is an arc welding process that fuses together the parts to be welded by heating them with an arc between a non-consumable tungsten electrode and the work. Filler metal may or may not be used with the process. Shielding is obtained from an inert gas or inert gas mixture. Slang names for the process are TIG welding, Argon-arc welding and Tungsten arc welding.

The GTAW process can be used to weld commercial metals, including steel, stainless steel, aluminium, magnesium, copper, nickel, titanium, and others. The process can be used on a wide range of metal thicknesses. However, due to the relatively low deposition rates associated with the process, thinner materials are most often welded. It is also popular for depositing the root and hot passes on pipe and tubing.

This process can be used in all welding positions to produce quality welds on almost all metals used in industry. Since the shielding gas is used, the weld is clearly visible to the welder, no spatter is produced, post weld cleaning is reduced, and slag is not trapped in the weld.

The GTAW process is normally applied using the manual method. The welder controls the torch with one hand and feeds the filler metal with the other. The semi-automatic method is also sometimes used in some applications. The filler metal is fed into the weld puddle by a wire feeder similar to that used in GMAW. The machine and automatic methods are sometimes used in New Zealand. With these systems, the welding operator monitors the welding operation and little welding skill is required.

In the manual method, a high degree of welding skill is required.

2.3.5.1. Equipment

The major components required for gas tungsten welding are:

— welding machine or power source
— GTAW torch, including the tungsten electrode
— shielding gas and controls
— filler rod, when required.

2.3.5.2. Shielding gas

A shielding gas prevents the weld puddle and tungsten electrode to oxidize during welding. The two most commonly used shielding gases with the GTAW process are argon and helium. The most common shielding gas is argon since it is less expensive. Argon produces a lower arc voltage than helium. This makes it especially useful for thin gauge materials where lower arc heat is necessary to prevent excessive penetration. Helium may be used on heavy welds where high heat input is required to produce deeper penetration.

Argon is heavier than air, causing it to remain in the arc area longer when the puddle is located below the gas nozzle.

2.3.5.3. Tungsten electrodes

The electrodes used with the GTAW process are made of tungsten alloys (Table III). Tungsten has the highest melting point of any metal, which is around 3400^{o}C and is considered non-consumable. When properly used, the electrode does not touch the molten weld puddle. If the tungsten electrode accidentally touches the weld puddle it becomes contaminated and must be cleaned immediately. If it is not cleaned, an erratic arc will result. The filler metal for GTAW is a solid wire. The filler metal size is determined by the diameter. Filler metals are available in a wide range of sizes in an approximate range from 1.6, 2.4, 3.2 mm. Filler metals are manufactured in straight cut lengths for manual welding and continuous spools for semi-automatic and automatic welding.

Filler metals for GTAW are classified using the same system for GMAW electrodes, such as ER70S-6. The only difference is that gas metal arc wires carry electric current and are considered electrodes (E), while gas tungsten welding wires normally do not carry current and are considered filler rods (R).

TABLE III. CLASSIFICATION OF AWS ELECTRODES FOR TUNGSTEN ARC WELDING

AWS classification	Tungsten % (min.) (by difference)	Thoria %	Zirconia %	Total of other elements (max.) %	Colour code
EWP	99.5	-	-	0.5	Green
EWTh-1	98.5	0.8-1.2	-	0.5	Yellow
EWTh-2	97.5	1.7-2.2	-	0.5	Red
EWTh-3	98.95	0.35-0.55	-	0.5	Blue
EWZr	99.2	-	0.15-0.40	0.5	Brown

2.3.5.4. Advantages

(a) Capable of welding thin material
(b) Controls heat input extremely well because the heat source and the filler material are separately controlled
(c) Welds can be made without adding filler material by fusing the base metals together
(d) Full penetration welds joined from one side only can be made
(e) Produces X ray quality welds
(f) Recommended for materials which form refractory oxides, like aluminium and magnesium
(g) Used for root runs.

2.3.5.5. Disadvantages

(a) Cost of equipment and shielding gas is high
(b) Deposition rate is slow
(c) A high degree of operator skill is required to produce quality welds
(d) Fit-up tolerances are restrictive.

3. WELD DEFECTS AND DISCONTINUITIES

3.1. GENERAL CONSIDERATIONS

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, etc. 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.

The weld defects and discontinuities are in general undesirable from the point of view of the industrial uses of the welded materials. But for purposes of proper training and qualification of NDT personnel it is necessary to have the test specimens with known flaws.

The ability to detect, identify and size flaws is fundamental to the qualification of NDT personnel. Therefore, the flaw characteristics and reliability of their detection, location and size will govern the NDT personnel's success or failure in the examination.

Manufacturers of NDT examination test specimens must have procedures to determine the flaw location, type and size during the fabrication of the test specimen in addition to any NDT inspection.

Such flaws in these specimens may be termed as 'intended flaws'. In the following chapters the reasons and methodology for the deliberate creation of such 'intended flaws' are described. The procedure for creating each type of individual flaw is also given.

This procedure provides criteria for the manufacture of examination test specimens that may be used for the hands-on practical examination according to recognized standards for the qualification of NDT personnel.

3.2. DEFINITIONS

Examination test specimens

Test specimens in this guide are NDT products designed with flaws to be used exclusively for the qualification of NDT personnel.

Intended flaws

An intended flaw whose size and location dimensions meet the requirements of clause 10.2 is intentionally produced within the test specimen.

Unintended flaws

A flaw that has been unintentionally produced during the manufacturing process. (Unintended flaws within the specified acceptance criteria may remain in the test specimen.)

Rejectable flaws

Flaws outside the specified criteria are called rejectable flaws.

End user

The organization, body or person that details the shape, design, material, dimensions, flaws and reporting criteria required of the test specimen.

3.3. QUALITY ASSURANCE

3.3.1. Quality assurance system

The manufacturer shall use a documented quality assurance system that demonstrates that the examination test specimens have been fabricated to the requirements of this guide. This should include fabrication records of the test specimens.

3.3.2. NDT flaw characteristics

The manufacturer shall demonstrate, by practical trials, their ability to accurately evaluate flaws from their appearance, indication or response.

3.3.3. Evidence/trials

The manufacturer shall demonstrate that the flaw dimensions given in this guide can be achieved and maintained. For planar flaws a macrosection should be used to determine height and width on at least two samples. For volumetric flaws, macrosections and radiography should be used to measure the flaw length, height and depth for at least two samples. Samples shall be witnessed and approved by a second or third party.

Trials for each flaw type and each welding technician shall be carried out to evaluate the dimensions whenever there is a change of the fabrication process or welding technician.

4. EXAMINATION TEST SPECIMEN REQUIREMENTS

4.1. GEOMETRIC CONDITIONS

Geometric conditions such as a counter bore, mismatch, etc. should not affect the detection, sizing and evaluation of the intended flaws.

4.2. SURFACE CONDITION AND APPEARANCE

The test specimen surface condition shall not interfere or influence the intended examination results.

4.3. DIMENSIONAL TOLERANCES

The nominal size for a given type of examination test specimen, regarding length, diameter and thickness should meet the following dimensions:

Test specimen length/width	± 10%
Test specimen diameter	± 10%
Test specimen thickness	± 10%

4.4. SELECTION OF RAW MATERIALS PRIOR TO THE FABRICATION OF TEST SPECIMENS

(1) Materials forming a permanent part of a qualification test specimen must not contain any flaws that will interfere with the examination of the test specimen. Refer to the acceptance criteria for unintended flaws (refer to clause 14).

(2) Materials, where requested, must meet the requirements of the end user.

(3) Materials used for the ultrasonic specimens shall not have a transfer correction exceeding 6 dB.

(4) All materials must be inspected and meet the requirements under Section 3.

4.5. WELDING REQUIREMENTS

4.5.1. General considerations

Test specimens must replicate the real component but it does not necessarily have to be welded/constructed to the same standard. A high standard of welding must be achieved to include intended flaws but avoid unintended flaws.

4.5.2. Approval of welding technicians

The manufacturer must be able to demonstrate that welding technicians can produce welds, which meet the acceptance criteria laid down in this guide. There is no requirement to have approved welding technicians. However, documented evidence of the welding technician's previous experience similar to the welding procedures and acceptance standard stated in this guide is recommended.

4.5.3. Welding procedures

The manufacturer must have documented welding procedures and be able to demonstrate that such procedures consistently produce welds which meet the acceptance criteria laid down in this guide. However there is no requirement to have formally approved welding procedures.

4.5.4. Weld repairs

It is not necessary to keep records of weld repairs, as long as such repairs have no effect on the use of the test specimen.

4.5.5. Post weld heat treatment

Post weld heat treatment should not be carried out. This is to avoid any unnecessary propagation of the intended flaws.

4.6. INSPECTION REQUIREMENTS

4.6.1. General considerations

NDT measurements are subjective and may vary depending on the equipment and techniques employed. They must not be used as the primary means of determining flaw size and location, but should be used to verify that the intended flaw has been embodied and to ensure that flaw propagation has not occurred. Wherever possible the physical dimensions of the flaw should be the controlling size. NDT must be employed to detect and evaluate unintended flaws in both parent material and welds, and warrant that intended flaws have the correct NDT characteristics.

4.6.2. Visual inspection

All completed examination test specimens shall be visually inspected to ensure that:

- the test specimen has a traceable identification number
- surface breaking flaws are not readily visible unless intended
- all flaw location manufacturing/inspection markings are removed
- the flaw implanting technique/procedure has not left any evidence of the flaw location
- the surface condition is suitable for the intended NDT inspection.

4.6.3. Non-destructive evaluation

4.6.3.1. NDT method employed

Only NDT methods should be used to evaluate flaw existence, size location, characteristics or existence of unintended flaws.

4.6.3.2. NDT personnel

NDT personnel verifying the test specimen shall hold a Level II or Level III certificate according to ISO 9712 or equivalent in the appropriate NDT method(s). The NDT personnel shall have full knowledge of the intended flaws in the test specimen being inspected.

4.6.3.3. Procedures

There is no requirement to have specific approved NDT procedures. The manufacturers shall have documented NDT procedures and be able to demonstrate that the procedures can detect, identify and evaluate the intended and unintended flaws.

4.6.3.4. Equipment

Equipment used for the evaluation of a test specimen shall be within calibration and/or verified for its intended performance.

5. FLAW CHARACTERISTICS

5.1. INTRODUCTION

It is acceptable to produce flaws using any process, providing the resulting flaw is distinguishable by its NDT characteristics.

NDT results are dependable upon the specific type of flaw in the test specimen. Therefore, locating the flaw is dependent upon its position and type in the test specimen along with its characteristics. For these reasons flaws embodied in the test specimen need to be representative of the type of flaw sought therein.

5.2. TOLERANCES FOR INTENDED FLAWS

The following tolerances shall be used:

Working tolerance

The acceptable difference between the required flaw and the final flaw dimensions. (If the flaw location is incorrect, but still meets the working tolerance it should be accepted.)

Reporting tolerance

The actual measured size of the flaw.

Datum

The mark on the test specimen where the position and size of the flaw is measured from.

Item	Working tolerance	Reporting tolerance
From datum point (X)	20mm	±3mm
From datum point (Y)	±5mm	±3mm
From surface /1 (Z)	±5mm	±2mm
Flaw Length (L)	±5mm	±3mm
Flaw Height /2 (H)	±3mm	±2mm
Tilt - if applicable	±10°	±5°
Skew - if applicable	±10°	±5°

/1 Embodied flaws
/2 Surface breaking flaws

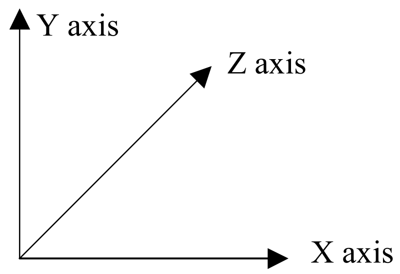


FIG. 7. Presentation of three dimensions of flaws.

5.3. FLAW SIZE/LOCATION MEASUREMENTS

Flaw size and location shall be measured where possible by physical means and verified using the same NDT method as the test specimen’s intended use.

6. OTHER IMPORTANT REQUIREMENTS

6.1. DOCUMENTATION

A written inspection report shall accompany each completed test specimen. This report shall include, as a minimum:

- Report number
- Date of test
- Description of test specimen description (dimensions, material, etc.)
- Unique identification number of test specimen
- NDT method and process
- Testing conditions and equipment (type and make) used
- Technician/inspector (name and qualifications)
- Inspection and acceptance specification
- Flaw type(s), size(s) and location(s) details shall be in tabular form and scale drawing(s).

6.2. SECURITY AND CONFIDENTIALITY

The security and confidentiality of test specimens are paramount to ensure the validity of personnel qualifications; therefore manufacturers shall meet the following requirements:

- A written confidentiality agreement must be in place to restrict employees, vendors or visitors (past or present) who have, or have had access to specimens disclosing flaw details.
- Manufacturers shall prove their independence from other vendors for whom the flaw details would affect the outcome of personnel qualifications.
- Manufacturers shall have a policy of not disclosing, transmitting or distributing documents, which contain flaw details to any third party unless authorized by the end user or purchaser.

6.3. GENERAL DESIGN CONSIDERATIONS AND FLAW CONTENT OF TEST SPECIMENS

Generally, test specimens should be of similar shape and configuration and contain flaws characteristic of those that may occur during manufacturing and in-service.

The physical size of a test specimen should enable the intended NDT method to locate, characterize and size the intended flaw and should be specified by the end user.

The number of areas or volumes to be tested shall be applicable to the personnel competence level, NDT method and to the industrial sector concerned.

Test specimens shall contain two or more reportable flaws, which should be separated.

6.4. ACCEPTANCE CRITERIA FOR UNINTENDED FLAWS IN TEST SPECIMENS

6.4.1. Rejectable flaws

Rejectable flaws shall be removed unless otherwise accepted by the end user.

6.4.2. Sensitivity settings, sizing techniques and flaw reporting criteria for ultrasonic test specimens

To ensure an accurate and standardized report format it is useful to apply the following recommendations:

- Sensitivity levels for compression and shear wave probes:
  Reference sensitivity: Distance Amplitude Curve (DAC) from a 1.5mm diameter side drilled hole of the same type and grade of material should be set with the maximum response at Full Screen Height (FSH).

- Search sensitivity reference +6 dB plus any transfer correction used
- Sizing flaws using shear wave probes:
  Flaw length 6 dB drop technique using centre of beam and for through wall depth 6 dB drop technique using centre of beam, and/or 20 dB drop technique. It is advised that a suitable plotting aid be used.

- Sizing flaws using compression wave probes:
  Flaw length 6dB drop technique using centre of beam. It is advised that a suitable plotting aid be used.

- All flaw indications with an amplitude greater than 25% DAC (–12 dB) shall be reported or as required by the end user.
- Regardless of amplitude reporting of isolated single point reflectors is not required.

TABLE IV. FLAW REPORTING CRITERIA

Flaw Category	Flaw Type	Reporting Criteria
Planar flaws	Cracks or laminar tears Lack of root fusion Lack of side-wall fusion Lack of inter-run fusion Lack of root penetration	Report on the requirements of the end user
Cavities (subsurface)	Isolated or individual pores Group porosity	
Cavities (surface breaking)	Isolated or individual pores Group porosity	
Solid inclusions	Isolated or individual inclusions Linear and parallel to weld axis	

6.5. INFORMATION TO BE SUPPLIED BY THE END USER TO THE MANUFACTURER

(a) Intended NDT method (PT, MT, UT, RT, VT, ET)
If the test specimen is required for a specific NDT method in addition to those stated above the NDT method should be specified.

(b) Type of test specimen
(plate, pipe, tee, nozzle, node)
(c) Weld joint geometry
(preparation details which includes angle, single V, double V, single bevel, double bevel, single J, double J, single U, double U, fillet)
(d) Material details. Unless specific material thickness and shapes of test specimens are required, selection and type should be from standard sizes and common forms.
(carbon steel, stainless steel, aluminium, thickness, pipe schedule)
(e) Type, number and dimensions of flaws
(f) Position of flaws
(surface breaking, subsurface [side-wall, weld body], root, tilt, skew)
(g) Welding process
(SMAW, GTAW, GMAW, SAW, FCAW, EBW)
(h) Documentation
(a drawing should be supplied)
(i) Reporting requirements
(intentional flaws, unintended flaws)
(j) Identification requirements
(numbering and/or lettering system, position).

6.6. INTER-CHANGEABILITY OF TEST SPECIMENS BETWEEN DIFFERENT NDT METHODS

Manufactured test specimens should be for a specific NDT method qualification. However, where a test specimen is suitable for other NDT method qualifications, they may be used.

7. MANUFACTURE OF TEST SPECIMENS

7.1. GENERAL CONSIDERATIONS

The flaw fabrication methods detailed below are not guaranteed; therefore, inspections should always be applied to verify that the required flaw has been created.

Test specimens following fabrication should be easy to handle and clean after use.

7.2. POROSITY

Molten weld metal has a considerable capacity for dissolving gases that 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 below (Fig. 8).

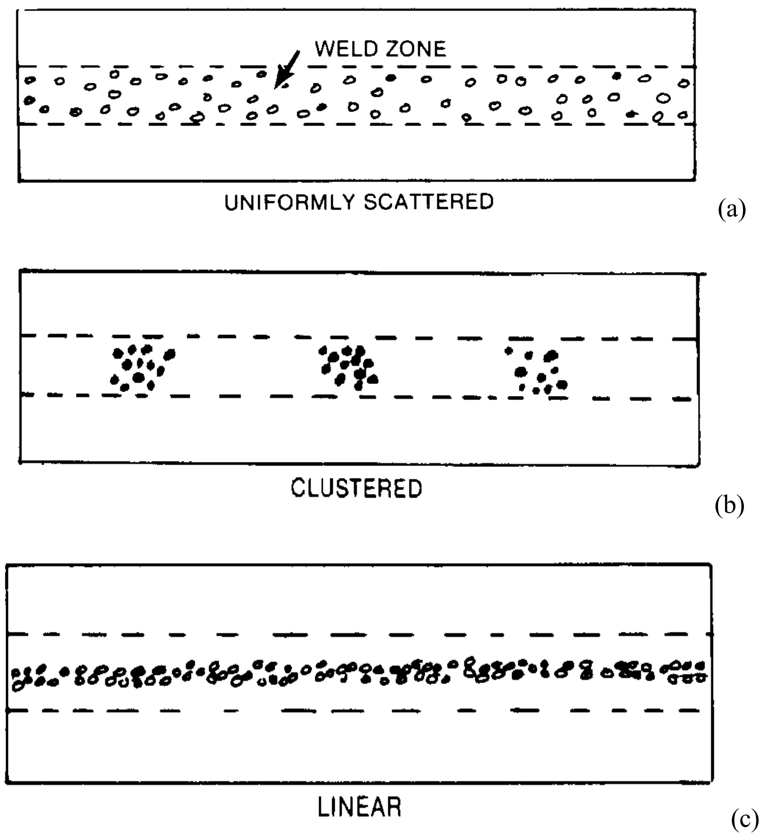


FIG. 8. Three types of weld porosity.

FIG. 9. Piping in weld.

7.3. 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 appears like a branch of a tree (Fig. 9). These can be caused by the use of wet welding electrodes.

Cavities

These may be created by removing the arc shield during welding, such as creating a long arc, interrupting the shield gas or a combination of both.

Wetting an area of the welding electrode and carrying out a typical weld run and ensuring that the wetted area of the weld electrode has been consumed may create fine cavities.

7.4. 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.

7.4.1. Surface breaking inclusions

These may be created by leaving areas of slag that are trapped in the surface of the weld. This can be created by not removing and leaving slag, in the area required, on the previous run prior to the final weld run.

7.4.2. Inclusions for RT

Weld between 25% and 75% of the material thickness, back-gouge the selected area to a length of the slag inclusion required, fill with slag and weld over. Touching the tungsten electrode into the weld pool may create a tungsten inclusion. For aluminium test specimens, copper particles may be introduced during the welding process.

7.4.3. Inclusions for UT

Weld between 10% and 90% of the material thickness, back-gouge the selected area to a length of the slag inclusion required, fill with slag and weld over.

7.5. 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 DC source. Tungsten inclusions can also be caused by 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.

Tungsten inclusions may be created by adding some pieces of tungsten metal to the molten weld metal during welding.

7.6. LACK OF FUSION

This is due to the lack of union in a weld between the weld metal and parent metal, 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 interrun 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.

(a) Choose the area where lack of fusion is required and apply a non-metallic coating such as a 900º C or higher temperature indicating crayon. Weld over this area as normal. Alternatively, this process may be used to create lack of fusion in the root area.

(b) Lack of root fusion may be created using MMAW by reducing, with a smooth file, the flux coating only on one side of the welding electrode and welding the area with this electrode where lack of root fusion is required. Ensure that the thinned area of the electrode is 180º to the weld face where lack of root fusion is required.

7.7. 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. 10). 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).

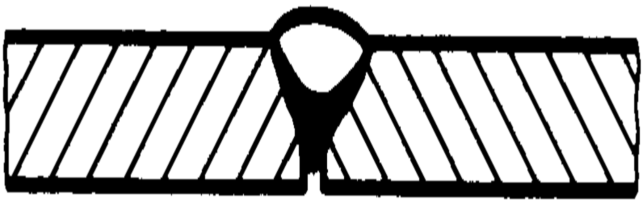


FIG. 10. Incomplete root penetration.

7.8. 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. 11).

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.

7.8.1. Transverse cracks

In the weld metal, transverse cracks are formed when the predominant contraction stresses are in the direction of the weld axis (No. 2 in Fig. 11). 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. 11) occur on the surface in or near the heat-affected zone. They are the result of 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.

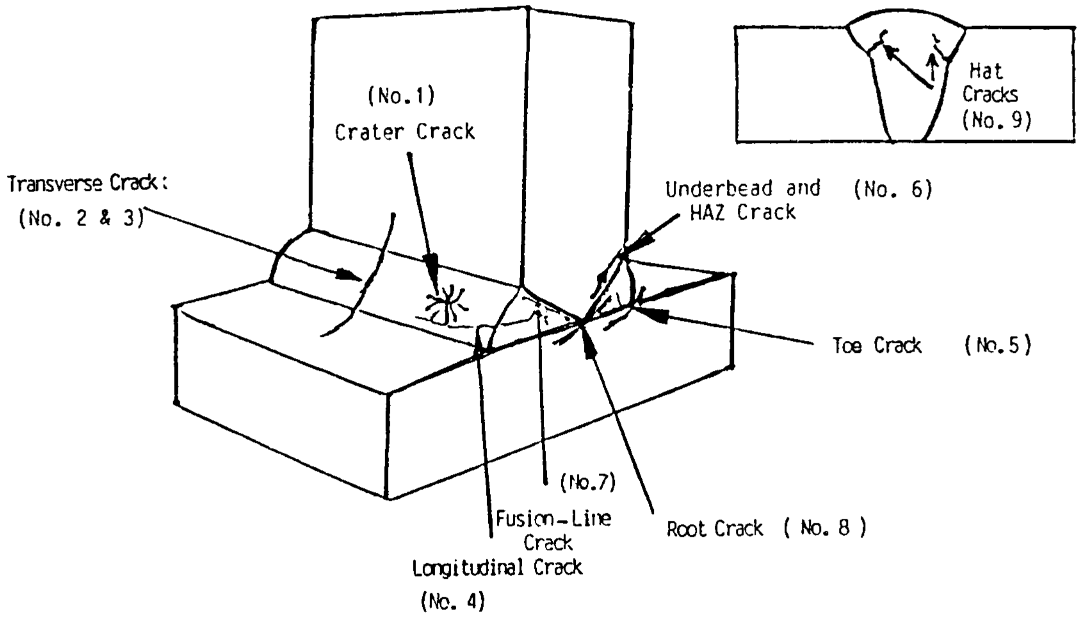


FIG. 11. Different types of cracks located in and around a welded joint.

7.8.2. 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. 11).

7.8.3. Longitudinal cracks

These cracks may exist in three forms, depending on their position in the weld (No. 4 in Fig. 11). 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 is generally 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.

(a) Prepare plate and gouge the first side surface to a depth of two thirds the material thickness. Weld up the gouge using an AWS E7016 or equivalent electrode, leaving in the final pass, a short unwelded area equal to the crack length required. Fill this area using an AWS E11016 electrode. Turn the plate over and back-gouge the second side to a depth of one third the material thickness and weld up this gouge. After welding the second side flatten the plate and check to see if a crack has occurred. To simulate heat-affected zone cracking, the intended crack should be in the weld toe adjacent to the parent material.

(b) For pipes, gouge or machine a groove to a depth to width ratio exceeding 2:1 around the full circumference of the pipe. Weld a short area of the crack length required using an AWS E11016 electrode. After cooling, inspect this area for cracking. If a crack has occurred, weld the remaining gouge or groove using an AWS E7016 or equivalent electrode.

(c) To simulate cracks in the weld root, prepare the two sections to be joined and run a short tack weld equal to the crack length required, using an AWS E11016 electrode. Restrain one section of the specimen in a vice or jig and move the unrestrained section in a backward and forward direction until fracture occurs. (This movement must be done in a controlled manner.) Place the two sections together ensuring the fracture surface profiles fit together, tack weld the sections together.

7.8.4. 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. 11). 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.

These can be produced by rapid withdrawal of the welding electrodes following a short weld run. (A crater pipe may also occur using this method).

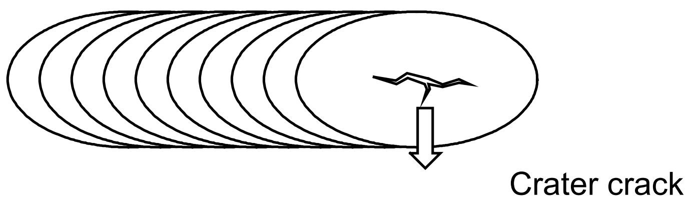


FIG. 12. Crater crack.

7.8.5. 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. 11). 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.

7.8.6. 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. 11).

Multidirectional cracks

During welding of the weld cap or root run, drop a 5–10 mm x 2 mm diameter piece of copper wire into the molten weld pool.

7.9. 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. 13).

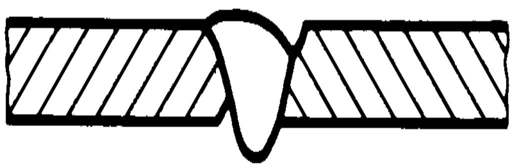


FIG. 13. Undercut.

(a) Fill the weld groove, leaving only one run adjacent to the parent material, to complete the welding.
(b) Weld the last run as normal but for the length of undercut required, increase the welding current by 20 – 30 amps and tilt the welding electrode at an angle greater than would normally be used.
(c) Complete the welding as normal.

7.10. CONCAVITY AT THE ROOT OR SURFACE OF THE WELD

A concave surface at the root of the weld can occur especially in pipe welding (without a cover pass on the root side). Root concavity is commonly produced by the FCAW process. In overhead welding this condition is a consequence of gravity that 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. 14).

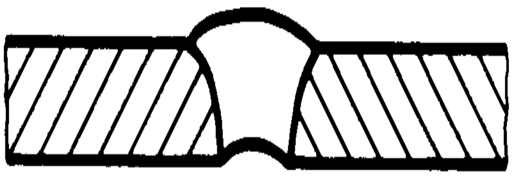


FIG. 14. Root concavity.

7.10.1. Root concavity

Prepare the test specimen and select the area where the root concavity is required. Weld the root keeping the deposited weld as small as practical. Weld the second bead (hot pass) ensuring that this pass produces a heavier weld bead. Alternatively, root concavity can also occur by increasing the purging pressure during welding of the root bead.

7.10.2. Surface concavity

Prepare the test specimen and select the area where the surface concavity is required. During welding increase the welding speed in this area, ensure that the deposited weld metal is reduced leaving the deposited weld cap concave to the surface of the material. Ensure that the deposited weld fuses at the toe of the parent material (Fig. 15).

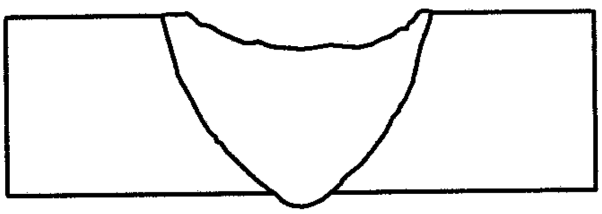


FIG. 15. Surface concavity.

7.11. EXCESSIVE PENETRATION

In welds, molten metal sometimes runs through the root of the weld groove producing an excessive reinforcement at the backside of the weld. In general this is not continuous but has an irregular shape with characteristic hanging drops of excess metal (Fig. 16).

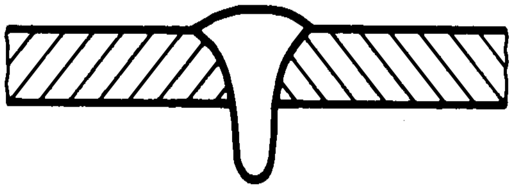


FIG. 16. Excessive penetration.

(a) Select an area in the weld root where excess penetration is required.
(b) Complete welding of the weld root leaving the area where excess penetration is required unwelded.
(c) Dress the ends of the weld runs adjacent to the unwelded area to form shallow craters.
(d) Increase the welding current 20 – 30 amps and, keeping the electrode vertical to the material surface, start from one end of the unwelded area towards one crater and then backweld to the other crater.

7.12. 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. 17). 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.

Welding in a vertical or horizontal position using a slower welding speed than normal may create overlap.

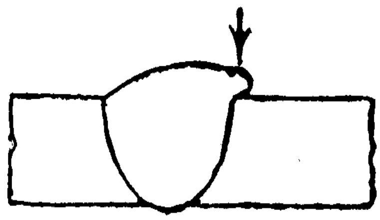


FIG. 17. Overlap.

7.13. 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

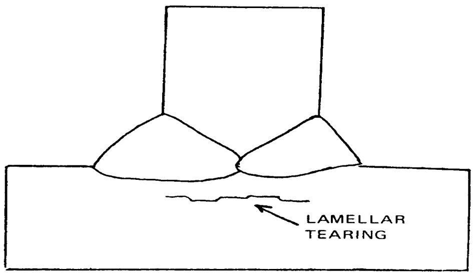


FIG. 18. Lamellar tearing.

in a separation taking 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 decohesion of non-metallic inclusions and 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. 18).

7.14. 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 (Fig. 19). It is caused by 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. 19. Burn-through.

(a) Prepare test specimen and select the area where burn-through is required.
(b) Start welding the root bead and, in the required area, pause until loss of the weld pool occurs before continuing welding.

7.15. 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.

(a) For a stainless steel test specimen, weld the root bead using a purging gas leaving the selected area un-welded.
(b) Remove the purge and complete the weld bead.

7.16. MISMATCH

Prepare the test specimen and select the area where mismatch is required. Deform the selected area to the extent required by mechanical means (Fig. 20).

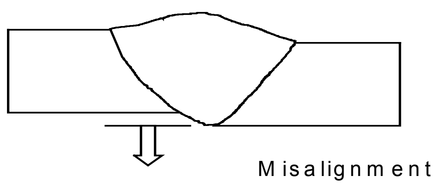


FIG. 20. Misalignment.

7.17. ARC-STRIKE

During welding of the test specimen, ground the live electrode on the parent material in the area selected for the arc-strike.

7.18. SPATTER

Mask an area where the spatter is required and apply anti spatter spray to the unmasked material surface. Remove the mask and weld using SMAW or GMAW with a higher current setting than normal and increased arc length prior to the last weld run. Complete the welding with normal settings. Alternatively, place a piece of metal over the weld groove and weld on this material as stated above (Fig. 21).

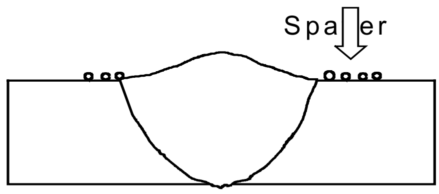


FIG. 21. Spatter.

7.19. IRREGULAR PROFILES

(a) Using a faster welding speed than normally used, may create insufficient throat of a fillet weld when a single pass is used. Where two weld passes are used, ensure there is insufficient throat in the weld toe between these two weld passes.

(b) Reducing the welding speed below than which is normally used may create excessive convexity.

(c) Holding the welding electrode at an angle biased towards one of the material surfaces can create unequal leg lengths in a fillet weld.

(d) Incompletely filled groove can be created by not completing the final weld pass, ensuring part of the weld preparation is still visible.

7.20. MISCELLANEOUS SURFACE IMPERFECTIONS

Hammer marks

Are created by striking the material on and adjacent to the weld using the pointed end of the chipping hammer.

Grinding marks

In the selected area where the defect is required, create short grinding marks using an angle grinder. The depth of the grinding marks should not be less than 1 mm.

7.21. LAMINATION

Produce a slot parallel to the surface of the material, less than 1mm wide, to the required dimensions using either a cutting wheel, electron discharge machine (EDM) or by other suitable means. The slot should be positioned mid-section in the material.

8. NDT METHOD-RELATED TEST SPECIMENS

8.1. TEST SPECIMENS FOR LIQUID PENETRANT TESTING

8.1.1. Design and material type(s) of test specimen

Type:	Plate, pipe and T joint welds
Minimum length:	100 mm weld length
Minimum diameter:	30 mm for pipe
Material:	Carbon steel, stainless steel, aluminium

8.1.2. Typical flaws

Types:	Cracks, lack of fusion, lack of penetration, inclusions, porosity
Location:	Flaws should be separated and open to the surface

The creation of such flaws in the test specimens has been described in Sections 7.2, 7.3, 7.4, 7.6, 7.7, and 7.8

8.2. TEST SPECIMENS FOR MAGNETIC PARTICLE TESTING

8.2.1. Typical design of test specimen

Type:	Plate, pipe and T joint welds
Minimum dimensions:	Length 300mm
Plate width	200 mm
Pipe diameter	50 mm
Thickness	5 mm
Material:	Carbon steel

8.2.2. Typical flaws

Types:	Cracks (transverse and longitudinal directions), lack of fusion, lack of penetration, inclusions
Location:	Each type of flaw should be separated, flaws should be open to the surface but near surface flaws may be used.

The creation of such flaws in the test specimens has been described in Sections 7.4, 7.6, and 7.8

8.3. TEST SPECIMENS FOR RADIOGRAPHIC TESTING

8.3.1. Typical design of test specimen

Type:	Plate and pipe welds
Minimum dimensions:	Length 300mm
Plate width:	100mm
Pipe diameter:	25mm (max. 300 mm)

Thickness:	1 mm
Material:	Carbon steel, stainless steel, aluminium

8.3.2. Typical flaws

Types:	Cracks, lack of fusion, lack of penetration, cavities, inclusions, excess penetration, undercut, concavity, burn-through, mismatch, arc-strike, oxidation, spatter
Location:	Each type of flaw should be separated, flaws may be surface or subsurface

Most of the flaws described in Sections 7.2, 7.3, 7.4, 7.5, 7.6, 7.7, 7.8, 7.9, 7.10, 7.11, 7.14, 7.15, 7.16, etc. are relevant for this method.

8.4. TEST SPECIMENS FOR ULTRASONIC TESTING

8.4.1. Typical design of test specimen

Type:	Plate, pipe and T joint welds, nozzles and nodes
Material:	Carbon steel unless otherwise specified by the end user.
Dimensions:	

(i)	Weld length	> 150mm
(ii)	Thickness	≥ 6 mm
(iii)	Size	
	Pipe diameter	min. 75mm; max. 300 mm
	T	90°
	Y	30° – 60°
	K	30° – 60°
	Nozzle:	shell section flat or diameter > 1m
	Pipe penetration diam.	> 75 mm (may be set on, set in, set through)
	Node: shell section diameter > 1m	
	pipe section diameter	> 150 mm
	pipe section angle	> 45°, < 60°

(iv) Groove angle: included angle, min 60°, max 70°, nodes as required by the end user
(v) Scanning width: 8 x material thickness on both sides of the weld (if specimen is prepared with weld cap)
(vi) Scanning width: 4 x material thickness on both sides of the weld (if specimen is prepared without weld cap)
(vii) Other weld preparations: as requested by the end user
(viii) Backing bars, strips, consumable inserts, etc. at the request of the end user.

Note: It is recommended that the scanning width is equal on both sides of the weld cap. However, the end user may request only one side of the weld to meet (v and vi) above.

8.4.2. Typical flaws

Types:	Cracks, lack of fusion, lack of penetration, cavities, inclusions, excess penetration, undercut, concavity, burn-through, mismatch, lamination
Location:	Each type of flaw should be separated, flaws may be surface or subsurface.

Most of the flaws described under various Sections are relevant for this method.

8.5. TEST SPECIMENS FOR VISUAL TESTING

8.5.1. Typical design of test specimen

Type:	Plate, pipe and fillet welds
Minimal Dimensions:	Length 150mm
Width:	100mm,
Pipe diameter:	25mm (max. 300 mm)
Thickness:	≥ 5 mm
Material:	Applicable materials

8.5.2. Typical flaws

Types:	Cracks, lack of fusion, lack of penetration, cavities, inclusions, excess penetration, undercut, concavity, burn-through, mismatch, arc-strike, oxidation, spatter, irregular profiles, miscellaneous surface imperfections
Location:	Flaws shall be separated and be on or open to the surface.

8.6. TEST SPECIMENS FOR EDDY CURRENT TESTING

For eddy current testing of welds it is possible to use the test specimen as described in Section 6 with the option of masking the surface with a thin layer of coating.

9. QUALITY CONTROL OF NDT TEST SPECIMENS

9.1. HANDLING, SHIPPING, STORAGE AND TRANSPORTATION

Following the fabrication of the test specimen, care should be taken to protect the surfaces from corrosion and damage. This can be achieved by applying a protective coating, bagging or wrapping. The protection method used must have no effect on the intended use of the specimen. Some of the suggested corrosion protection methods are listed in Table V.

TABLE V. SOME SUGGESTED CORROSION PROTECTION METHODS FOR TEST SPECIMENS

Protection method	Intended use of specimen
Plastic bags with silica gel	all methods
Vacuum packs	all methods
Coating with thin layer of paint	UT, ET, RT
Waxed paper	UT, ET, RT, MT
Anti-corrosion coatings	UT, RT
Thin, smooth electron plating	UT, RT

9.2. SECURITY

(a) Test specimens should be stored, transported and delivered separately from the reports.
(b) Test specimens shall be stored in a secure environment.
(c) Test specimens and reports shall be forwarded to a name-nominated person of the end user.

ABBREVIATIONS

AC	alternating current
AWS	American Welding Society
BCA	bifunctional chelating agent
CRT	cathode ray tube
DC	direct current
EDM	electron discharge machine
ET	eddy current testing
FCAW	flux cored arc welding
GMAW	gas metal arc welding
GTAW	gas tungsten arc welding
h	hour/hours
MMAW	manual metal arc welding
MT	magnetic particle testing
NDE	non-destructive evaluation
NDT	non-destructive testing
PT	penetrant testing or inspection
RT	radiographic testing or inspection
SAW	submerged arc welding
SMAW	shielded metal arc welding
UT	ultrasonic testing
VT	visual testing or inspection

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