Module 4

Design for Assembly
Lecture 3

Design for Welding-II
Instructional Objective

The following lecture will outline various defects associated with welding processes and possible remedial measures to avoid the welding defects. A brief exposure on the post-weld heat treatment and inspection methodologies for welding defects will also be discussed.

Basic Metallurgy of Fusion Welding

A typical fusion welded joint varies in metallurgical structure from the fusion zone to the base material with consequential variations in mechanical properties. This is because of the fact that fusion welding processes result in melting and solidification with very high temperature gradient within a small zone with the peak temperature at the center of the fusion zone. In general, a weld can be divided in four different zones as shown schematically in Figure 4.3.1.

![Figure 4.3.1 Schematic presentations of several zones in a fusion welded joint](image)

The **fusion zone (referred to as FZ)** can be characterized as a mixture of completely molten base metal (and filler metal if consumable electrodes are in use) with high degree of homogeneity where the mixing is primarily motivated by convection in the molten weld pool. The main driving forces for convective transport of heat and resulting mixing of molten metal in weld pool are: (1) buoyancy force, (2) surface tension gradient force, (3) electromagnetic force, (4) friction force. Similar to a casting process, the microstructure in the weld fusion zone is expected to change significantly due to remelting and solidification of metal at the temperature beyond the effective liquidus temperature.

The **weld interface**, which is also referred to as **mushy zone**, is a narrow zone consisting of partially melted base material which has not got an opportunity for mixing. This zone separates the **fusion zone** and **heat affected zone**.

The **heat affected zone (HAZ)** is the region that experiences a peak temperature that is well below the solidus temperature while high enough that can change the microstructure of the
material. The amount of change in microstructure in **HAZ** depends on the amount of heat input, peak temp reached, time at the elevated temp, and the rate of cooling. As a result of the marked change in the microstructure, the mechanical properties also change in **HAZ** and, usually, this zone remains as the weakest section in a weldment.

The **unaffected base metal zone** surrounding the HAZ is likely to be in a state of high residual stress, due to the shrinkage in the fusion zone. However, this zone does not undergo any change in the microstructure.

The **fusion zone** and **heat affected zone** of welded joints can exhibit very different mechanical properties from that of the unaffected base metal as well as between themselves. For example, the fusion zone exhibits a typical cast structure while the **heat affected zone** will exhibit a heat-treated structure involving phase transformation, recrystallization and grain growth. The **unaffected base metal**, on the other hand, will show the original rolled structure with a slight grain growth. **Figure 4.3.2** shows how different zones of a steel weldment can be indicated on an iron-carbon equilibrium diagram.

**Figure 4.3.2**  Different zones in a steel weld vis-à-vis Iron-Carbon equilibrium diagram
The weldability of steels

The weldability of steel materials can be studied in typical Graville diagram as shown in Figure 4.3.3. The Graville diagram presents the susceptibility of hydrogen induced cracking of different class of steels based on the corresponding carbon content and carbon equivalent (C.E). Equation (1) gives the C.E. equation.

\[
\text{C.E.} = \%C + \frac{\%\text{Mn} + \%\text{Si}}{6} + \frac{\%\text{Ni} + \%\text{Cu}}{15} + \frac{\%\text{Cr} + \%\text{Mo} + \%\text{V}}{5}
\]  

(1)

In Fig. 4.3.3, the steels in Zone 1 confirm to low carbon content and low hardenability that reduce their susceptibility to hydrogen cracking during welding [1]. In contrast, the class of steels in Zone 3 (in Fig. 4.3.3) confirms to both high carbon content and high hardenability, and, is susceptible to produce crack-sensitive microstructures during fusion welding [1]. The class of steel in Zone 2 (Figure 4.3.3) has higher carbon levels with lower hardenability. The susceptibility of hydrogen induced cracking in these steels can be avoided during welding by restricting the cooling rate in HAZ through control of heat input and to a minor extent, with preheat [1].

Figure 4.3.3  Graville diagram for steels [1].
Problems Associated with Re-melting and Solidification in Welding

Formation of grains in fusion zone

In fusion welding, the existing base metal grains at the fusion line (as shown in Figure 4.3.4) serves as the substrate for nucleation of crystals during solidification of the fusion zone. Thus, new crystals or grains are formed by arranging the atoms from the base metal grains without altering their crystallographic orientations. This feature is referred to as epitaxial solidification, which is usual, in particular, in the autogeneous welding (i.e. without filler material). In Figure 4.3.4 the welding direction should be realized as perpendicular to the plane of the paper (reading screen).

Non-epitaxial solidification occurs when fusion welding is done with a filler material or with two different metals and the new grains start forming on heterogeneous sites at the fusion boundary. The boundary of the fusion zone will exhibit random misorientations between the base metal grains and the weld metal grains such that the later may not follow any special orientation relationships with the base metal grains they are in contact with.

Macro segregation

Macro segregation is a solidification related problem that occurs during solidification primarily due to lack of weld pool mixing by convection during fusion welding of dissimilar metals or alloys. Macro segregation can be avoided by (a) stirring the liquid weld pool either applying a magnetic field or in any other way to give a better mixing in the weld pool, (b) using direct current electrode negative (DCEN) mode in gas tungsten arc welding process for a deeper weld penetration and mixing, (c) using proper filler metals, (d) facilitating enough time for the weld pool to be melt, and (e) reducing weld speed.

Hot Cracking

Hot cracking occur during the terminal stage of solidification due to contraction of solidifying metal and thermal contraction. Weld joint geometry and the impurity elements in weld pool primarily contribute to solidification cracking. For example, when the penetration to width ratio is very high, hot cracking occurs due to excessive transverse contraction stress. Impurities such as sulfur and phosphorus drastically lower the solidification temperature. As a result, solidification occurs at a much lower temperature along the weld centerline, where sulfur and phosphorus tend to segregate, leading to the formation of cracks. The tendency to solidification cracking can be reduced by using filler metals or flux-wire with high
manganese content as manganese combines with sulfur to form manganese sulfide particles reducing the amount of free sulfur available to segregate to the centerline.

**Figure 4.3.4** Epitaxial solidification in fusion welding

**Cold Cracking**

*Cold cracking* occurs by the combination of the martensite that might have formed of the heat affected zone of a steel weld with entrapped hydrogen leading to the formation of cracks specially in steel welds. Hydrogen can come from moisture, or flux in the flux-cored, shielded-metal, and submerged arc welding processes, welding consumables, paint, mill oil, degreasing fluids etc. This defect can be avoided by reducing the cooling rate hence reducing the formation of martensite or by the post-weld heat treatment which convert hard martensitic structure to tempered martensitic structure.

**Lameller Tearing**

In the processing of steel, sulfur combines with manganese to form MnS inclusions in the ingot. When the ingot is rolled, these inclusions elongate into *stringers* reducing the strength of the steel in the direction transverse to these stringers. Subsequently, the transverse stress produced during solidification of welds can cause cracks if the weld is made in the rolling direction, parallel to the stringers. This is referred to as *lameller tearing*. 
Reheat Cracking
Welds in thick sections of high strength low alloy in combination with the presence of residual stress and low creep-ductility are susceptible to reheat cracking in the heat affected zone during postweld heat treatment. The cracks form along the grain boundaries in the heat affected zone, particularly in the coarse-grained region near the fusion line.

Defects in Welding
The performance of welded structure in service depends on presence or absence of defects in weld joints. Weld defects impair the strength of welded joints and may results in the failure of a complete assembly / structure in service. In a general sense, the term weld defect refers to any departure in welded structure or welded joints from the specified requirements. According to the International Institute of Welding, the weld defects are classified into six groups as follows: (a) Cracks, (b) Cavities (blowholes, porosity, shrinkage, etc.), (c) Solid Inclusion, (d) Incomplete fusion, (e) Imperfect Shape, (f) Miscellaneous defects.

Cracks
Cracks are the most dangerous amongst all types of defects as it reduce the performance of a welded joint drastically and can also cause catastrophic failure. Depending on the position, location and orientation these can be categorised as longitudinal cracks, transverse cracks, crater cracks, under-bead cracks, and toe cracks. These cracks are usually visible and hence, referred to surface defects in weld joints. In general, the cracks in weld joints occur due to high concentration stresses during solidification of weld, poor fit-up and incorrect welding procedures, and poor edge quality. Formation of cracks can be controlled by preheating the joints, reducing the cooling rate, taking proper precautions during post weld heat treatment. Figure 4.3.5 schematically shows some of the significant weld cracks.

Blowholes and porosities
These are usually subsurface defects in weld joints and are actually voids, holes or cavities formed by the entrapped gases by the solidified weld metal. The source of the trapped gas may be uncleaned rust, dirt, paint, etc. on the parent metal or electrode, damp flux (in shielded metal or submerged arc welding), impurities and moisture in the shielding gas. Normally, porosity is not considered as serious a defect as cracks since the porosity cavities usually have rounded ends which are not expected to propagate as cracks. However, porosities in weld joints are usually not permitted for pressurized containers intended for storage and transportation of liquid, gaseous or inflammable liquids. The best way to avoid
Porosity or blowhole in weld joints is to use perfectly clean base materials and baked electrodes.

![Diagram of cracks]

(a) Longitudinal Crack  (b) Under-Bead Crack

(c) Transverse Crack

**Figure 4.3.5 Different Types of Cracks**

**Shrinkage Cavity**

It is referred to the cavities which are formed due to shrinkage of weld metal during its solidification. The shrinkage cavity usually occurs during welding of thick plates in a single pass using submerged arc welding or electroslag welding processes. Proper amount of filler material has to be supplied for compensation during shrinkage to avoid this kind of defect.

**Slag Inclusion**

The slag inclusion refers to the solidified flux comprising of oxides, phosphorous compounds and nitrides, which fail to float out to the surface and get trapped in the weld. When gas tungsten arc welding is carried out with direct current electrode positive polarity and at high current, tungsten inclusion from the tungsten electrode into the weld can occur. Such inclusions can be continuous, intermittent or very randomly paced. Slag inclusions reduce the mechanical strength, in particular, the ductility, of the welds.

**Incomplete Fusion and Penetration**

Incomplete fusion can occur due to inadequate welding current, offset of electrode from the axis of the weld, too high a weld speed, improper joint preparation and fit-up. It occurs between the parent metal and the weld metal and also between intermediate layers in multi-
pass welding reducing the weld strength. Lack of penetration or inadequate penetration usually occurs at the root of the weld and also becomes a built-in crack, which can run through the base metal or weld metal or heat affected zone in actual service condition.

**Imperfect Shape**

*Dimensional deviations, undercut, under fill, overlap, excessive reinforcement, excessive penetration, bead shape are* the examples of Imperfect shape. *Underfills and Suckbacks* refer to uneven depression (such as a concave contour) respectively, on the face or on the root surface of the weld extending below the surface of the adjacent base metal. Both of these defects reduce the cross-sectional area of the weld below the designed amount and thus, a point of weakness and or stress raiser where failure may occur.

*Excessive penetration and / or reinforcement* are also undesirable in weld joints. Both are usually caused by poor fit-up, too wide a root gap or too small a root face, improper welding technique and excessive welding current. *Excessive reinforcement* tends to stiffen the weld section and make notches that would create stress concentration. Figure 4.3.6 schematically represents different types of welding defects.

![Figure 4.3.6 Schematic sketch of various fusion welding defects [4]](image)

**Postweld Heat Treatment**

Postweld heat treatment (PWHT), defined as any heat treatment after welding primarily to improve the microstructural and mechanical properties of the weldment and heat affected zone, is often used to improve the properties of a weldment. In concept, PWHT can
encompass many different potential treatments; however, in steel fabrication, the two most common procedures used are post heating and stress relieving.

Post heating is used to minimize the potential for hydrogen induced cracking. Stress relief heat treatment is used to reduce the stresses that remain locked in a structure as a consequence of manufacturing processes. Different causes and effects of residual stresses are described in the previous lecture. Some design guidelines for PWHT are given below:

1. Welding of carburized or hardened steels requires controlled conditions and proper equipment and supplies. Designers should not specify such welding unless it is unavoidable.
2. Welding removes or reduces the hardness of carburized or nitrided steels in the area of welding. So, if it is possible, hardening has to be done after the welding.
3. Carbon in welded areas will affect the physical and chemical characteristics of the weld bead, resulting in possible cracking or weld failure in or adjacent to the weld.

Postweld Inspection

From the above discussion it clear that it is very difficult to produce a perfect welded joint free from any defect. So, it is very important to detect the weld defects and to accept or reject the final component depending on its application. For example, if a weld joint is subjected to light structural load, then porosity or slag inclusion can be accepted upto a certain limit. But in case of pressure vessel application, such as boiler or pressurized chemical container, these types of defects are not at all acceptable.

To detect such defects without damaging the weld, several techniques are employed, known as non-destructive testing (NDT). Some commonly used NDT methods are outlined below.

Visual Inspection

It is the simplest and cheapest of all techniques. In this method the weld is inspected visually by an authorized personal to detect flaws, cracks appearing on the surface on the weld. Sometimes special equipment is used to guide the inspector. The disadvantages of this method are: micro sized cracks cannot be detected by humans, sub-surface defects remain undetected, and there are always chances of human error.

Liquid Penetrant based Inspection

In this process a liquid with high surface wetting characteristics is applied to the surface of the part and allowed time to seep into surface breaking defects. After removing the excess liquid, a developer (powder) is applied to pull the trapped penetrant out the defect and spread
it on the surface where it can be seen. The penetrant used contains fluorescent material and starts glowing when exposed to UV light. The principle is shown schematically in Figure 4.3.7. This procedure is sometimes called as die penetration test when the liquid penetrant used is a die. In this case upon application of developer, the die comes out from the crack and becomes visible to eye. This method can detect micro sized cracks that are not visible to naked eye but cannot detect sub surface defects.

**Figure 4.3.7** (1) Crack, (2) Penetrant applied, (3) Developer applied, (4) Crack Visible

**Magnetic Particle inspection**

This methods is based on the principle that magnetic lines change their paths whenever discontinuity is encountered in the path. The first step in a magnetic particle inspection is to magnetize the component that is to be inspected. After the component has been magnetized, iron particles, either in a dry or wet suspended form, are applied to the surface of the magnetized part. The particles will be attracted and cluster at the flux leakage fields, thus forming a visible indication that the inspector can detect. It is a very simple procedure but applicable only for Ferromagnetic materials. Often the material has to be demagnetised after performing the test.
Radiographic Testing

Radiographic Testing is a non-destructive testing method of inspecting materials for hidden flaws by using the ability of short wavelength electromagnetic radiation (high energy photons) to penetrate various materials. In this method the part is placed between the radiation source and a piece of film. A pattern will be generated on the film depending on the thickness of the inspected part. Where ever there is a defect, the amount of radiation absorbed will be different and corresponding pattern will be generated. Detection of subsurface defects is the major advantage of this test but proper safety measures have to be taken to prevent exposure to these radiations. Figure 4.3.9 schematically shows a typical radiographic testing set-up.
Ultrasonic Inspection

Ultrasonic testing uses the basic physical property that sound waves travel at known constant velocities through any medium. By measuring the time for a sound wave to travel through a material it can be determined how far that wave has travelled. In this way sound waves can be used to measure distances. So, in an ultrasonic inspection, a high frequency sound wave is passes through the material to be inspected. Presence and position of any defects can be detected by analysing the sound wave reflected by the flaw. Figure 4.3.10 schematically shows a set-up for ultrasonic testing of defects.

Various advantages of ultrasonic testing include – (a) high penetrating power leading to the detection of flaws deep in the part, (b) high sensitivity, (c) greater accuracy than other non-destructive methods in particular in determining the depth of internal flaws, (d) capability of estimating the size, orientation, shape and nature of defects, (e) non-hazardous to operations or to nearby personnel.

Besides these advantages it has few disadvantages too such as – (1) manual operation and hence, requires careful attention, (2) experienced personnel are required, (3) surface must be prepared by cleaning and removing loose scale, paint, etc.

![Principle of Ultrasonic Testing](image)

**Figure 4.3.10** Principle of Ultrasonic Testing [6]
Exercise

1. Which NDT method would you suggest to detect a surface flaw of an aluminium weld?
2. Like fusion welding, what can be the possible defects in case on non-fusion types of welding?
3. How the bead size of a weld affect the joint strength?

References

1. S. Lapman, Weld integrity and performance.
2. ASM Metals Handbook Volume 17 - Nondestructive Evaluation and Quality Control