Weldability of Steel

Weldability is the capacity of a material to be welded under a specific set of fabrication and design conditions and to perform as expected during its service life. Generally speaking, weldability is considered very good for low-carbon steel (carbon level, < 0.15% by weight), good for mild steel (carbon level, 0.15 to 0.30%), fair for medium-carbon steel (carbon level, 0.30 to 0.50%), and questionable for high-carbon steel (carbon level, 0.50 to 1.00%). Because weldability normally decreases with increasing carbon content, special precautions such as preheating, controlling heat input, and postweld heat treating are normally required for steel with a carbon content reaching 0.30%. In addition to carbon content, the presence of other alloying elements will have an effect on weldability. In lieu of more accurate data, the table below can be used as a guide to determine the weldability of steel [Blodgett, undated].

<table>
<thead>
<tr>
<th>Element</th>
<th>Range for Satisfactory Weldability (%)</th>
<th>Level Requiring Special Care (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.06–0.25</td>
<td>0.35</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.35–0.80</td>
<td>1.40</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.10 max.</td>
<td>0.30</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.035 max.</td>
<td>0.050</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.030 max.</td>
<td>0.040</td>
</tr>
</tbody>
</table>

A quantitative approach to determine the weldability of steel is to calculate its carbon equivalent value. One definition of the carbon equivalent value, $C_{eq}$ is

$$C_{eq} = \text{Carbon} + \frac{(\text{Manganese} + \text{Silicon})}{6} + \frac{(\text{Copper} + \text{Nickel})}{15} + \frac{(\text{Chromium} + \text{Molybdenum} + \text{Vanadium} + \text{Columbium})}{5}$$
A steel is considered weldable if $C_{eq} \leq 0.50\%$ for steel in which the carbon content does not exceed 0.12%, and if $C_{eq} \leq 0.45\%$ for steel in which the carbon content exceeds 0.12%.

The above equation indicates that the presence of alloying elements decreases the weldability of steel. An example of high-alloy steels is stainless steel. There are three types of stainless steel: austenitic, martensitic, and ferritic. Austenitic stainless steel is the most weldable, but care must be exercised to prevent thermal distortion, because heat dissipation is only about one third as fast as it is in plain carbon steel. Martensitic steel is also weldable, but prone to cracking because of its high ability to harden. Preheating and the maintaining of an interpass temperature are often needed, especially when the carbon content is above 0.10%. Ferritic steel is weldable, but decreased ductility and toughness in the weld area can present a problem. Preheating and postweld annealing may be required to minimize these undesirable effects.

The weldability of stainless steels

Once thought of as a major challenge the welding of stainless steels and most other corrosion resistant alloys is more often described as 'different' in stead of 'more difficult' amongst welders today. The welding of stainless steels and the properties of the welds with regard to corrosion resistance and mechanical properties do involve a mixture of metallurgical, geometrical and surface finishing aspects.

Nickel (plus carbon, manganese and nitrogen) promotes the formation of austenite and chromium (plus silicon, molybdenum and niobium) encourages the formation of ferrite, so the structure of welds in stainless steels can be largely predicted on the basis of their chemical composition. Because of their different microstructures, the alloy groups have both different welding characteristics and susceptibility to defects.

Austenitic stainless steel

Austenitic stainless steels typically have 16-26% chromium (Cr) and 8-22% nickel (Ni). Type 304, which contains approximately 18%Cr and 10%Ni, is a commonly used alloy for welded fabrications and these alloys can be readily welded using any of the arc welding processes (TIG, MIG, MMA and SA). They exhibit good toughness because they are non-hardenable on cooling, and there is no need for pre- or post-weld heat treatment.

Avoiding weld imperfections

Austenitic stainless steel is readily welded, but weld metal and HAZ cracking can occur. Weld metal solidification cracking is more likely to occur in fully austenitic structures, which are more crack sensitive than those containing a small amount of ferrite as ferrite has the capacity to dissolve harmful impurities which would otherwise form low melting point segregates and interdendritic cracks. The presence of 5-10% ferrite in the microstructure is extremely beneficical, so the choice of filler material composition is crucial in suppressing the risk of cracking. An indication of the ferrite-austenite balance for different compositions is provided by the Schaeffler diagram. For example, when welding Type 304 stainless steel, a Type 308 filler material, which has a slightly different alloy content, is used.

Ferritic stainless steel

Ferritic stainless steels have a Cr content of 11-28%. Commonly used alloys include the 430 grade, having 16-18% Cr and 407 grade having 10-12% Cr. As these alloys can be considered to be predominantly single phase and non-hardenable, they can be readily fusion welded. However, a coarse grained HAZ will have poor toughness.
Avoiding weld imperfections

The main problem when welding this ferritic stainless steel is poor HAZ toughness. Excessive grain coarsening can lead to cracking in highly restrained joints and thick section material. When welding thin section material, (less than 6mm) no special precautions are necessary. In thicker material, it is necessary to employ a low heat input to minimise the width of the grain-coarsened zone and an austenitic filler to produce a tougher weld metal. Although preheating will not reduce the grain size, it will reduce the HAZ cooling rate, maintain the weld metal above the ductile-brittle transition temperature and may reduce residual stresses. Preheat temperature should be within the range 50-250 °C depending on material composition.

Martensitic stainless steel

The most common martensitic alloys e.g. type 410, have a moderate chromium content of 12-18% with low Ni but, more importantly, have a relatively high carbon content. The principal difference compared with welding the austenitic and ferritic grades of stainless steel is the potentially hard HAZ martensitic structure and the matching composition weld metal. The material can be successfully welded providing precautions are taken to avoid cracking in the HAZ, especially in thick section components and highly restrained joints.

Avoiding weld imperfections

High hardness in the HAZ makes this type of stainless steel very prone to hydrogen cracking. The risk of cracking generally increases with the carbon content. Precautions which must be taken to minimise the risk by:
• using low hydrogen process (TIG or MIG) and ensure the flux or flux coated consumable are dried (MMA and SAW) according to the manufacturer's instructions;
• preheating to around 200 to 300°C. Actual temperature will depend on welding procedure, chemical composition (especially Cr and C content), section thickness and the amount of hydrogen entering the weld metal;
• maintaining the recommended minimum interpass temperature;
• carrying out post-weld heat treatment, e.g. at 650-750°C. The time and temperature will be determined by chemical composition.

Thin section, low carbon material, typically less than 3mm, can often be welded without preheat, providing that a low hydrogen process is used, the joints have low restraint and attention is paid to cleaning the joint area. Thicker section and higher carbon (> 0.1%) material will probably need preheat and post-weld heat treatment. The post-weld heat treatment should be carried out immediately after welding not only to temper (toughen) the structure but also to enable the hydrogen to diffuse away from the weld metal and HAZ.

Duplex stainless steels

Duplex stainless steels have a two-phase structure of almost equal proportions of austenite and ferrite. The composition of the most common duplex steels lies within the range 22-26% Cr, 4-7% Ni and 0-3% Mo normally with a small amount of nitrogen (0.1-0.3%) to stabilise the austenite. Modern duplex steels are readily weldable but the procedure, especially maintaining the heat input range, must be strictly followed to obtain the correct weld metal structure.

Avoiding weld imperfections

Although most welding processes can be used, low heat input welding procedures are usually avoided. Preheat is not normally required and the maximum interpass temperature must be controlled. Choice of filler is important as it is designed to produce a weld metal structure with a ferrite-austenite balance to match the parent metal. To compensate for nitrogen loss, the filler may be overalloyed with nitrogen or the shielding gas itself may contain a small amount of nitrogen.
Welding of Copper Alloys

Abstract:
Copper and copper alloys offer a unique combination of material properties that makes them advantageous for many manufacturing environments. They are widely used because of their excellent electrical and thermal conductivities, outstanding resistance to corrosion, ease of fabrication, and good strength and fatigue resistance. Other useful characteristics include spark resistance, metal-to-metal wear resistance, low-permeability properties, and distinctive color.

Welding Processes
In manufacturing, copper is often joined by welding. The arc welding processes are of primary concern. Arc welding can be performed using shielded metal arc welding (SMAW), gas-tungsten arc welding (GTAW), gas-metal arc welding (GMAW), plasma arc welding (PAW), and submerged arc welding (SAW).

Arc Welding Processes. Copper and most copper alloys can be joined by arc welding. Welding processes that use gas shielding are generally preferred, although SMAW can be used for many noncritical applications.

Argon, helium, or mixtures of the two are used as shielding gases for GTAW, PAW, and GMAW. Generally, argon is used when manually welding material is less than 3 mm thick, has low thermal conductivity, or both. Helium or a mixture of 75% helium and 25% argon is recommended for machine welding of thin sections and for manual welding of thicker sections of alloys that have high thermal conductivity. Small amounts of nitrogen can be added to the argon shielding gas to increase the effective heat input.

Shielded metal arc welding can be used to weld a wide range of thickness of copper alloys. Covered electrodes for SMAW of copper alloys are available in standard sizes ranging from 2.4 to 4.8 mm.

Gas-Tungsten Arc Welding. Gas-tungsten arc welding is well suited for copper and copper alloys because of its intense arc, which produces an extremely high temperature at the joint and a narrow heat-affected zone (HAZ).

In welding copper and the more thermally conductive copper alloys, the intensity of the arc is important in completing fusion with minimum heating of the surrounding, highly conductive base metal. A narrow HAZ is particularly desirable in the welding of copper alloys that have been precipitation hardened.

Many of the standard tungsten or alloyed tungsten electrodes can be used in GTAW of copper and copper alloys. The selection factors normally considered for tungsten electrodes apply in general to the copper and copper alloys. Except for the specific classes of copper alloys, thoriated tungsten (usually EWTh-2) is preferred for its better performance, longer life, and greater resistance to contamination.

Gas-Metal Arc Welding. Gas-metal arc welding is used to join of the coppers and copper alloys for thickness less than 3 mm, while GMAW is preferred for section thickness above 3 mm and for the joining of aluminum bronzes, silicon bronzes and copper-nickel alloys.

Plasma Arc Welding. The welding of coppers and copper alloys using PAW is comparable to GTAW of these alloys. Argon, helium, or mixtures of the two are used for the welding of all alloys. Hydrogen gas should never be used when welding coppers.

Plasma arc welding has two distinct advantages over GTAW: (1) the tungsten is concealed and entirely shielded, which greatly reduces contamination of the electrode, particularly for alloys with low-boiling-temperature constituents.
such as brasses, bronzes, phosphor bronzes, and aluminum bronzes, and (2) the constructed arc plume gives rise to higher arc energies while minimizing the growth of the HAZ. As with GTAW, current pulsation and current ramping may also be used. Plasma arc welding equipment has been miniaturized for intricate work, known as microplasma welding.

Plasma arc welding of coppers and copper alloys may be performed either autogenously or with filler metal. Filler metal selection is identical to that outlined for GTAW. Automation and mechanization of this process is readily performed and is preferable to GTAW where contamination can restrict production efficiencies. Welding positions for PAW are identical to those for GTAW. However, the plasma keyhole mode has been evaluated for thicker sections in a vertical-up position. Generally, all information presented for GTAW is applicable to PAW.

**Submerged Arc Welding.** The welding of thick gage material, such as pipe formed from heavy plate, can be achieved by continuous metal-arc operation under a granular flux. Effective deoxidation and slag-metal reactions to form the required weld-metal composition are critical and the SAW process is still under development for copper-base materials. A variation on this, process can be used for weld cladding or hardfacing. Commercially available fluxes should be used for the copper-nickel alloys.

**Alloy Metallurgy and Weldability**

Many common metals are alloyed with copper to produce the various copper alloys. The most common alloying elements are aluminum, nickel, silicon, tin, and zinc. Other elements and metals are alloyed in small quantities to improve certain material characteristics, such as corrosion resistance or machinability.

Copper and its alloys are divided into nine major groups. These major groups are:

- **Coppers**, which contain a minimum of 99.3% Cu
- **High-copper alloys**, which contain up to 5% alloying elements
- **Copper-zinc alloys** (brasses), which contain up to 40% Zn
- **Copper-tin alloys** (phosphor bronzes), which contain up to 10% Sn and 0.2% P
- **Copper-aluminum alloys** (aluminum bronzes), which contain up to 10% Al
- **Copper-silicon alloys** (silicon bronzes), which contain up to 3% Si
- **Copper-nickel alloys**, which contain up to 30% Ni
- **Copper-zinc-nickel alloys** (nickel silvers), which contain up to 7% Zn and 18% Ni
- **Special alloys**, which contain alloying elements to enhance a specific property or characteristic, for example machinability

Many copper alloys have common names, such as oxygen-free copper (99.95% Cu min), beryllium copper (0.02 to 0.2% Be), Muntz metal (Cu40Zn), Naval brass (Cu-39.5Zn-0.75Sn), and commercial bronze (Cu-10Zn).

Many of the physical properties of copper alloys are important to the welding processes, including melting temperature, coefficient of thermal expansion, and electrical and thermal conductivity. Certain alloying elements greatly decrease the electrical and thermal conductivities of copper and copper alloys.

Several alloying elements have pronounced effects on the weldability of copper and copper alloys. Small amounts of volatile, toxic alloying elements are often present in copper and its alloys. As a result, the requirement of an effective ventilation system to protect the welder and/or the welding machine operator is more critical than when welding ferrous metals.

**Zinc** reduces the weldability of all brasses in relative proportion to the percent of zinc in the alloy. Zinc has a low boiling temperature, which results in the production of toxic vapors when welding copper-zinc alloys.

**Tin** increases the hot-crack susceptibility during welding when present in amounts from 1 to 10%. Tin, when compared with zinc, is far less volatile and toxic. During the welding tin may preferentially oxidize relative to copper. The results will be an oxide entrapment, which may reduce the strength of the weldment.

**Beryllium, aluminum, and nickel** form tenacious oxides that must be removed prior to welding. The formation of these oxides during the welding process must be prevented by shielding gas or by fluxing, in conjunction with the use of the appropriate welding current. The oxides of nickel interfere with arc welding less than those beryllium or aluminum. Consequently, the nickel silvers and copper-nickel alloys are less sensitive to the type of welding current used during the process. Beryllium containing alloys also produce toxic fumes during the welding.
Silicon has a beneficial effect on the weldability of copper-silicon alloys because of its deoxidizing and fluxing actions.

Oxygen can cause porosity and reduce the strength of welds made in certain copper alloys that do not contain sufficient quantities of phosphorus or other deoxidizers. Oxygen may be found as a free gas or as cuprous oxide. Most commonly welded copper alloys contain deoxidizing element, usually phosphorus, silicon, aluminum, iron, or manganese.

Iron and manganese do not significantly affect the weldability of the alloys that contain them. Iron is typically present in some special brasses, aluminum bronzes, and copper-nickel alloys in amounts of 1.4 to 3.5%. Manganese is commonly used in these same alloys, but at lower concentrations than iron.

Free-Machining Additives. Lead, selenium, tellurium and sulfur are added to copper alloys to improve machinability. Bismuth is beginning to be used for this purpose as well when lead-free alloys are desired. These minor alloying agents, while improving machinability, significantly affect the weldability of copper alloys by rendering the alloys hot-crack susceptible. The adverse effect on weldability begins to be evident at about 0.05% of the additive and is more severe with larger concentrations. Lead is the most harmful of the alloying agents with respect to hot-crack susceptibility.

Factors Affecting Weldability

Besides the alloying elements that comprise a specific copper alloy, several other factors affect weldability. These factors are the thermal conductivity of the alloy being welded, the shielding gas, the type of current used during welding, the joint design, the welding position, and the surface condition and cleanliness.

Effect of Thermal Conductivity. The behavior of copper and copper alloys during welding is strongly influenced by the thermal conductivity of the alloy. When welding commercial copperers and lightly alloyed copper materials with high thermal conductivities, the type of current and shielding gas must be selected to provide maximum heat input to the joint. This high heat input counteracts the rapid head dissipation away from the localized weld zone. Depending on section thickness, preheating may be required for copper alloys with lower thermal conductivities. The interpass temperature should be the same as for preheating. Copper alloys are not post-weld head treated as frequently as steels, but some alloys may require controlled cooling rates to minimize residual stresses and hot shortness.

Welding Position. Due to the highly fluid nature of copper and its alloys, the flat position is used whenever possible for welding. The horizontal position is used in some fillet welding of comer joints and T-joints.

Precipitation-Hardenable Alloys. The most important precipitation-hardening reactions are obtained with beryllium, chromium, boron, nickel, silicon, and zirconium. Care must be taken when welding precipitation-hardenable copper alloys to avoid oxidation and incomplete fusion. Whenever possible, the components should be welded in the annealed condition, and then the weldment should be given a precipitation-hardening heat treatment.

Hot Cracking. Copper alloys, such as copper-tin and copper-nickel, are susceptible to hot cracking at solidification temperatures. This characteristic is exhibited in all copper alloys with a wide liquidus-to-solidus temperature range. Severe shrinkage stresses produce interdendritic separation during metal solidification. Hot cracking can be minimized by reducing restraint during welding, preheating to slow the cooling rate and reduce the magnitude of welding stresses, and reducing the size of the root opening and increasing the size of the root pass.

Porosity. Certain elements (for example, zinc, cadmium, and phosphorus) have low boiling points. Vaporization of these elements during welding may result in porosity. When welding copper alloys containing these elements, porosity can be minimized by higher weld speeds and a filler metal low in these elements.

Surface Condition. Grease and oxide on work surfaces should be removed before welding. Wire brushing or bright dipping can be used. Miliscale on the surfaces of aluminum bronzes and silicon bronzes is removed for a distance from the weld region of at least 13 mm, usually by mechanical means. Grease, paint, crayon marks, shop dirt, and similar contaminants on copper-nickel alloys may cause embrittlement and should be removed before welding. Miliscale on copper-nickel alloys must be removed by grinding or pickling; wire brushing is not effective.
WELDING OF CAST IRON Cast iron is an extremely versatile material, used in thousands of industrial products. It is hard, wear-resistant, and relatively inexpensive. Like steel, it is available in many different grades and compositions. While we usually think of cast iron as being brittle (having low ductility), this is not true of all cast irons, as we shall see shortly. Cast iron, like steel, is an iron-carbon alloy. In composition and structure, and in some of its properties, it is quite different from steel. While many grades of cast iron can be welded successfully, not all cast iron is weldable, and welding of any cast iron presents problems not usually encountered in the welding of steel.

Composition and Grades of Cast Iron Cast iron is by no means pure iron. In fact, there is less iron in any grade of cast iron than there is in a low-carbon steel, which may be 98% iron. Almost every cast iron contains well over 2.0% carbon; some contain as much as 4.0%. In addition, cast iron usually contains 1.2 to 2.5% silicon, 0.5 to 0.8% manganese, and (as in steel) small percentages of sulphur and phosphorous. It is the high percentage of carbon that make cast iron different from steel in many of its properties. In a finished steel, all the carbon is combined with iron in the form of iron carbides, whereas those carbides are in grains of pearlite, in grains of cementite, or in scattered small particles of carbide. In cast iron, most of the carbon is usually present in uncombined form, as graphite. Graphite is one of the two crystalline forms of carbon; diamond is the other. The differences between the general types of cast iron most widely used arise chiefly from the form which the graphite assumes in the finished iron. Gray Iron. Of the general types of cast iron, gray iron is by far the most widely used. The term "gray iron" was adopted originally to distinguish it, by color of the fractured metal, from white iron, a form of cast iron in which all the carbon is combined. We'll have more to say about white iron later. At this point, we wish to stress the point that gray iron is a very broad term. All gray irons contain graphite in the form of flakes. This makes the gray irons readily machinable. All gray irons have almost no ductility, again because of the flake form of the graphite, which causes the metal to break before any appreciable amount of permanent elongation has occurred. However, not all Gray cast iron can usually be welded without loss of essential properties. For fusion welding, preheating of the casting is absolutely essential. Since a higher level of preheat is required for oxy-acetylene welding then for arc welding, arc welding is likely to be chosen where fusion welding is essential (as it is whenever good color match is desired). For many repair jobs, however, oxy-acetylene braze welding is the ideal method. Much less preheating is required; in many cases, preheating can be done with the torch. If the work is properly done, the braze-welded joint will have a strength equal to that of the base metal, and excellent machinability. Welding of gray iron castings which have chilled white iron surfaces is seldom attempted, since the desirable properties of white iron will always be affected by welding temperatures. Welding of white iron generally is limited to malleable iron foundries, where castings may be reclaimed by welding before conversion to malleable iron takes place. Malleable Iron. The chemical composition of malleable cast iron is much the same as that of a typical gray iron, but its properties are much different. It is tough; it can resist shock; it has ductility approaching that of mild steel. How is such a remarkable change achieved? By cooling the original casting so rapidly that white cast iron, with no free carbon, is formed; then heating the casting to about 800°C and holding it at that temperature for several days. Under those conditions, virtually all the carbon is released from the iron carbide to form fine rounded particles of graphite (sometimes called temper carbon) scattered among grains of ferrite. Malleable iron has good wear resistance, and is widely used for parts where the toughness of steel is required, and the economy of casting (instead of forming or machining) will result in lower cost. However, malleable iron is substantially more expensive to make than gray iron, and is usually selected only where its toughness and ductility are essential. Malleable iron cannot be successfully fusion welded and retain its unique properties; to put it another way, you can weld malleable iron as easily as you can weld gray iron, but in the act of welding you will convert some of the malleable iron casting into a gray iron casting. Seldom will that yield a satisfactory result. However, malleable iron castings can usually be braze welded successfully. You may wonder how to tell a malleable iron casting from a gray iron casting. There's one almost infallible method: use a high-speed grinder to make a spark test. The difference between the spark streams produced by gray iron and malleable iron is quite pronounced. Spark testing is covered in the Appendix.

Gray irons are equally strong, or equally hard. As in steel, tensile strength and hardness are closely related. In gray irons, tensile strength ranges from about 14 MPa (20,000 psi) to more than 35 MPa (50,000 psi). The hardness of the strongest grades is double that of the weakest grades. All gray irons have high compressive strength – three to four times their tensile strength. While all gray cast irons contain free carbon (graphite) in flake form, they also contain combined carbon (iron carbide) in almost every case. This combined carbon is often present in pearlite grains, such as found in most carbon steels. It may also be found as cementite or martensite. The composition of the cast iron, the rate at which it cooled after casting, and heat treatment after casting all have a bearing on the structure. Small amounts of alloying elements are used in the strongest gray irons; they tend to prevent the formation of pearlite. While the hardness and strength of steel almost always increase as carbon content rises, in the case of gray cast iron the strongest, hardest grades have less carbon than some of the lower-strength, less expensive grades. Gray iron is usually cast in sand molds, and allowed to cool normally in the mold. Heat treatment after casting is not always necessary, but is frequently employed, either to increase or to decrease hardness. Almost all gasoline and diesel engine blocks are gray iron castings. Whenever industry desires an intricate form which can be machined to close tolerances, and must withstand abrasive wear, gray iron gets consideration. Only when it is essential that the finished item have some ductility and good shock resistance is some other material – such as nodular cast iron or cast steel,
both more expensive – likely to be substituted. White iron, mentioned above, is about the same as gray iron in composition, but has been cooled rapidly so that graphite does not have time to form, and all the carbon winds up in the combined form, as pearlite, cementite, or martensite. Many white iron castings are subsequently converted to malleable iron, which we shall take up next. However, some gray iron castings are made with white iron wearing surfaces, since white iron is much harder than gray iron, although extremely brittle. This is accomplished by inserting metal or graphite chill blocks at appropriate places in the mold. The molten metal that solidifies against those chill blocks cools so rapidly that white iron surfaces are created. Plowshares, railroad car wheels, and various types of dies are often made with such chilled white iron surfaces.

**Heat-affected zone**

The cross-section of a welded butt joint, with the darkest gray representing the weld or fusion zone, the medium gray the heat affected zone, and the lightest gray the base material.

Heat affected zone around a weld

The **heat-affected zone** (HAZ) is the area of base material, either a metal or a thermoplastic, which has had its microstructure and properties altered by welding or heat intensive cutting operations. The heat from the welding process and subsequent re-cooling causes this change
from the weld interface to the termination of the sensitizing temperature in the base metal. The extent and magnitude of property change depends primarily on the base material, the weld filler metal, and the amount and concentration of heat input by the welding process.

The thermal diffusivity of the base material plays a large role—if the diffusivity is high, the material cooling rate is high and the HAZ is relatively small. Alternatively, a low diffusivity leads to slower cooling and a larger HAZ. The amount of heat inputted by the welding process plays an important role as well, as processes like oxyfuel welding use high heat input and increase the size of the HAZ. Processes like laser beam welding and electron beam welding give a highly concentrated, limited amount of heat, resulting in a small HAZ. Arc welding falls between these two extremes, with the individual processes varying somewhat in heat input. To calculate the heat input for arc welding procedures, the following formula is used:

\[ Q = \left( \frac{V \times I \times 60}{S \times 1000} \right) \times \text{Efficiency} \]

where \( Q \) = heat input (kJ/mm), \( V \) = voltage (V), \( I \) = current (A), and \( S \) = welding speed (mm/min). The efficiency is dependent on the welding process used, with shielded metal arc welding having a value of 0.75, gas metal arc welding and submerged arc welding, 0.9, and gas tungsten arc welding, 0.8.

**Welding defect**

A welding defect is any flaw that compromises the usefulness of a weldment.

According to the American Society of Mechanical Engineers (ASME), welding defect causes are broken down as follows: 45 percent poor process conditions, 32 percent operator error, 12 percent wrong technique, 10 percent incorrect consumables, and 5 percent bad weld grooves.\(^1\)

**Major causes**

Hydrogen embrittlement

Residual stresses

The magnitude of stress that can be formed from welding can be roughly calculated using:\(^2\)

\[ E\alpha\Delta T \]

Where \( E \) is Young’s modulus, \( \alpha \) is the coefficient of thermal expansion, and \( \Delta T \) is the temperature change. For steel this calculates out to be approximately 3.5 GPa (510,000 psi).

**Types**

Cracks
Defects related to fracture.

Arc strike cracking

Arc strike cracking occurs when the arc is struck but the spot is not welded. This occurs because the spot is heated above the material's upper critical temperature and then essentially quenched. This forms martensite, which is brittle and micro-cracks. Usually the arc is struck in the weld groove so this type of crack does not occur, but if the arc is struck outside of the weld groove then it must be welded over to prevent the cracking. If this is not an option then the arc spot can be postheated, that is, the area is heated with an oxy-acetylene torch, and then allowed to cool slowly.[3]

Cold cracking

Residual stresses can reduce the strength of the base material, and can lead to catastrophic failure through cold cracking, as was the case with several of the World War II Liberty ships' hulls. Cold cracking is limited to steels and is associated with the formation of martensite as the weld cools. The cracking occurs in the heat-affected zone of the base material. To reduce the amount of distortion and residual stresses, the amount of heat input should be limited, and the welding sequence used should not be from one end directly to the other, but rather in segments.[4]

Cold cracking only occurs when all the following preconditions are met.[citation needed]
• susceptible microstructure (e.g. martensite)
• hydrogen present in the microstructure (hydrogen embrittlement)
• service temperature environment (normal atmospheric pressure): -100 to +100 °F
• high restraint

Eliminating any one of these will eliminate this condition.

Crater crack

Crater cracks occur when a crater is not filled before the arc is broken. This causes the outer edges of the crater to cool more quickly than the crater, which creates sufficient stresses to form a crack. Longitudinal, transverse and/or multiple radial cracks may form.\(^5\)

Fusion-line crack

Creep crack growth and fracture toughness tests were performed using test material machined from a seam welded ASTM A-155-66 class 1 (2.25Cr-1Mo) steel steam pipe that had been in service for 15 years. The fracture morphology was examined using scanning electron microscope fractography. Dimpled fracture was found to be characteristic of fracture toughness specimens. Creep crack growth generally followed the fusion line region and was characterized as dimpled fracture mixed with cavities. These fracture morphologies were similar to those of an actual steam pipe. It was concluded that creep crack growth behavior was the prime failure mechanism of seam-welded steam pipes.

Hat crack

Hat cracks get their name from the shape of the cross-section of the weld, because the weld flares out at the face of the weld. The crack starts at the fusion line and extends up through the weld. They are usually caused by too much voltage or not enough speed.\(^5\)

Hot cracking

Hot cracking, also known as solidification cracking, can occur with all metals, and happens in the fusion zone of a weld. To diminish the probability of this type of cracking, excess material restraint should be avoided, and a proper filler material should be utilized.\(^4\) Other causes include
too high welding current, poor joint design that does not diffuse heat, impurities (such as sulfur and phosphorus), preheating, speed is too fast, and long arcs.\[6\]

**Underbead crack**

An underbead crack, also known as a heat-affected zone (HAZ) crack,\[7\] is a crack that forms a short distance away from the fusion line; it occurs in low alloy and high alloy steel. The exact causes of this type of crack are not completely understood, but it is known that dissolved hydrogen must be present. The other factor that affects this type of crack is internal stresses resulting from: unequal contraction between the base metal and the weld metal, restraint of the base metal, stresses from the formation of martensite, and stresses from the precipitation of hydrogen out of the metal.\[8\]

**Longitudinal crack**

Longitudinal cracks run along the length of a weld bead. There are three types: check cracks, root cracks, and full centerline cracks. Check cracks are visible from the surface and extend partially into weld. They are usually caused by high shrinkage stresses, especially on final passes, or by a hot cracking mechanism. Root cracks start at the root and extent part way into the weld. They are the most common type of longitudinal crack because of the small size of the first weld bead. If this type of crack is not addressed then it will usually propagate into subsequent weld passes, which is how full centerline cracks (a crack from the root to the surface) usually form.\[5\]

**Reheat cracking**

Reheat cracking is a type of cracking that occurs in HSLA steels, particularly chromium, molybdenum and vanadium steels, during postheating. It is caused by the poor creep ductility of the heat affected zone. Any existing defects or notches aggravate crack formation. Things that help prevent reheat cracking include heat treating first with a low temperature soak and then with a rapid heating to high temperatures, grinding or peening the weld toes, and using a two layer welding technique to refine the HAZ grain structure.\[9][10\]

**Root and toe cracks**

A root crack is the crack formed by the short bead at the root(of edge preparation) beginning of the welding, low current at the beginning and due to improper filler material used for welding.Major reason for happening of these types of cracks is hydrogen embrittlement. These types of defects can be eliminated using high current at the starting and proper filler material. Toe crack occurs due to moisture content present in the welded area,it as a part of the surface crack so can be easily detected. Preheating and proper joint formation is must for eliminating these types of defects.
Transverse crack

A gap or break in the surface of a weld perpendicular to the weld axis that may be completely within the weld metal or may extend from the weld metal into the base metal. Excess hydrogen, an excessively strong weld metal, and high levels of residual stress result in transverse cracks.

Distortion

Welding methods that involve the melting of metal at the site of the joint necessarily are prone to shrinkage as the heated metal cools. Shrinkage then introduces residual stresses and distortion. Distortion can pose a major problem, since the final product is not the desired shape. To alleviate certain types of distortion the workpieces can be offset so that after welding the product is the correct shape.\textsuperscript{[11]} The following pictures describe various types of welding distortion:\textsuperscript{[12]}

- Transverse shrinkage
- Angular distortion
- Longitudinal shrinkage
- Fillet distortion
Neutral axis distortion

Gas inclusion

Gas inclusions is a wide variety of defects that includes porosity, blow holes, and pipes (or wormholes). The underlying cause for gas inclusions is the entrapment of gas within the solidified weld. Gas formation can be from any of the following causes: high sulphur content in the workpiece or electrode, excessive moisture from the electrode or workpiece, too short of an arc, or wrong welding current or polarity.[7]

Inclusions

There are two types of inclusions: linear inclusions and rounded inclusions. Inclusions can be either isolated or cumulative. Linear inclusions occur when there is slag or flux in the weld. Slag forms from the use of a flux, which is why this type of defect usually occurs in welding processes that use flux, such as shielded metal arc welding, flux-cored arc welding, and submerged arc welding, but it can also occur in gas metal arc welding. This defect usually occurs in welds that require multiple passes and there is poor overlap between the welds. The poor overlap does not allow the slag from the previous weld to melt out and rise to the top of the new weld bead. It can also occur if the previous weld left an undercut or an uneven surface profile. To prevent slag inclusions the slag should be cleaned from the weld bead between passes via grinding, wire brushing, or chipping.[13]

Isolated inclusions occur when rust or mill scale is present on the base metal.[14]

Lack of fusion and incomplete penetration

Lack of fusion is the poor adhesion of the weld bead to the base metal; incomplete penetration is a weld bead that does not start at the root of the weld groove. Incomplete penetration forms channels and crevices in the root of the weld which can cause serious issues in pipes because corrosive substances can settle in these areas. These types of defects occur when the welding procedures are not adhered to; possible causes include the current setting, arc length, electrode angle, and electrode manipulation.[15]

Lamellar tearing

Lamellar tearing is a type of welding defect that occurs in rolled steel plates.[16] It has rarely been an issue since the 1970s because steel produced since then has less sulfur.[17]
There is a combination of causes: non-metallic inclusions, too much hydrogen in the material, and shrinkage forces perpendicular to the face of the plates. The main factor among these reasons is the non-metal inclusions, of which the sulfur is the main problem. Lamellar tearing is no longer a problem anymore because sulfur levels are typically kept below 0.005%.\[17\]

Some things that are done to overcome lamellar tearing are: reducing amount of sulfur in the material or adding alloying elements that control the shape of sulfide inclusions, such as rare earth elements, zirconium, or calcium.\[18\] A more drastic option is change the workpieces to castings or forgings because this type of defect does not occur in those workpieces.\[16\]

**Undercut**

Undercutting is when the weld reduces the cross-sectional thickness of the base metal, which reduces the strength of the weld and workpieces. One reason for this type of defect is excessive current, causing the edges of the joint to melt and drain into the weld; this leaves a drain-like impression along the length of the weld. Another reason is if a poor technique is used that does not deposit enough filler metal along the edges of the weld. A third reason is using an incorrect filler metal, because it will create greater temperature gradients between the center of the weld and the edges. Other causes include too small of an electrode angle, a dampened electrode, excessive arc length, and slow speed.\[19\]

**Hydrogen embrittlement**

Hydrogen embrittlement is the process by which various metals, most importantly high-strength steel, become brittle and fracture following exposure to hydrogen. Hydrogen embrittlement is often the result of unintentional introduction of hydrogen into susceptible metals during forming or finishing operations and increases cracking in the material. This phenomenon was first described in 1875.\[1\]
Hydrogen embrittlement is also used to describe the formation of zircaloy hydride. Use of the term in this context is common in the nuclear industry.

**Process**

The mechanism starts with lone hydrogen atoms diffusing through the metal. At high temperatures, the elevated solubility of hydrogen allows hydrogen to diffuse into the metal (or the hydrogen can diffuse in at a low temperature, assisted by a concentration gradient). When these hydrogen atoms re-combine in minuscule voids of the metal matrix to form hydrogen molecules, they create pressure from inside the cavity they are in. This pressure can increase to levels where the metal has reduced ductility and tensile strength up to the point where it cracks open (hydrogen induced cracking, or HIC). High-strength and low-alloy steels, nickel and titanium alloys are most susceptible. Austempered iron is also susceptible. Steel with an ultimate tensile strength of less than 1000 MPa or hardness of less than 30 HRC are not generally considered susceptible to hydrogen embrittlement. Jewett *et al.* reports the results of tensile tests carried out on several structural metals under high-pressure molecular hydrogen environment. These tests have shown that austenitic stainless steels, aluminum (including alloys), copper (including alloys, e.g. beryllium copper) are not susceptible to hydrogen embrittlement along with few other metals. For example of a severe embrittlement measured by Jewett, the elongation at failure of 17-4PH precipitation hardened stainless steel was measured to drop from 17% to only 1.7% when smooth specimens were exposed to high-pressure hydrogen.

Hydrogen embrittlement can occur during various manufacturing operations or operational use - anywhere that the metal comes into contact with atomic or molecular hydrogen. Processes that can lead to this include cathodic protection, phosphating, pickling, and electroplating. A special case is arc welding, in which the hydrogen is released from moisture (for example in the coating of the welding electrodes; to minimize this, special low-hydrogen electrodes are used for welding high-strength steels). Other mechanisms of introduction of hydrogen into metal are galvanic corrosion, chemical reactions of metal with acids, or with other chemicals (notably hydrogen sulfide in sulfide stress cracking, or SSC, a process of importance for the oil and gas industries).

**Counteractions**

If the metal has not yet started to crack, the condition can be reversed by removing the hydrogen source and causing the hydrogen within the metal to diffuse out, possibly at elevated temperatures. Susceptible alloys, after chemical or electrochemical treatments where hydrogen is produced, are often subjected to heat treatment to remove absorbed hydrogen. There is a 4-hour time limit for baking out entrapped hydrogen after acid treating the parts. This is the time between the end of acid exposure and the beginning of the heating cycle in the baking furnace. This per SAE AMS 2759/9 Section 3.3.3.1 which calls out the correct procedure for eliminating entrapped hydrogen.
In the case of welding, often pre- and post-heating the metal is applied to allow the hydrogen to diffuse out before it can cause any damage. This is specifically done with high-strength steels and low alloy steel such as the chrome/molybdenum/vanadium alloys. Due to the time needed to re-combine hydrogen atoms into the harmful hydrogen molecules, hydrogen cracking due to welding can occur over 24 hours after the welding operation is completed.

Products such as ferrosilicates can be used to treat surfaces normally subject to hydrogen embrittlement in order to prevent it from taking place.