# Welding and Joining Guidelines

The HASTELLOY® and HAYNES® alloys are known for their good weldability, which is defined as the ability of a material to be welded and to perform satisfactorily in the imposed service environment. The service performance of the welded component should be given the utmost importance when determining a suitable weld process or procedure. If proper welding techniques and procedures are followed, high-quality welds can be produced with conventional arc welding processes. However, please be aware of the proper techniques for welding these types of alloys and the differences compared to the more common carbon and stainless steels. The following information should provide a basis for properly welding the HASTELLOY® and HAYNES® alloys. For further information, please consult the references listed throughout each section. It is also important to review any alloy-specific welding considerations prior to determining a suitable welding procedure.

The most common welding processes used to weld the HASTELLOY® and HAYNES® alloys are the gas tungsten arc welding (GTAW / “TIG”), gas metal arc welding (GMAW / “MIG”), and shielded metal arc welding (SMAW / “Stick”) processes. In addition to these common arc welding processes, other welding processes such plasma arc welding (PAW), resistance spot welding (RSW), laser beam welding (LBW), and electron beam welding (EBW) are used. Submerged arc welding (SAW) is generally discouraged as this process is characterized by high heat input to the base metal, which promotes distortion, hot cracking, and precipitation of secondary phases that can be detrimental to material properties and performance. The introduction of flux elements to the weld also makes it difficult to achieve a proper chemical composition in the weld deposit.

While the welding characteristics of Ni-/Co-base alloys are similar in many ways to those of carbon and stainless steel, there are some important differences that necessitate the use of different welding techniques. Ni-/Co-base molten weld metal is comparatively “sluggish”, meaning it is not as fluid compared to carbon or stainless steel. In addition to the sluggish nature of the weld pool, Ni- and Co-base alloys exhibit shallow weld penetration characteristics. Therefore, weld joint design must be carefully considered, and proper welding techniques are needed to ensure that there is adequate fusion. Since the oxides that form on the surface of the metal typically melt at much higher temperatures than the Ni-/Co-base alloys being welded, it is especially important that they be removed prior to welding and between passes in multi-pass welds. These important considerations will be discussed in more detail in later sections.

Generally, it is suggested that welding heat input be controlled in the low-to-moderate range. In arc welding, heat input is directly correlated with welding current and arc voltage, and is inversely correlated to travel speed. To achieve successful welding results, it is suggested that relatively low welding currents and slow travel speeds be employed. Stringer bead welding techniques, with some electrode/torch manipulation, are preferred; wide weave beads are not recommended. Preferably, weld beads should be slightly convex, and flat or concave beads that may be acceptable with carbon and stainless steel should be avoided. Both Ni- and Co-base alloys have a tendency to crater crack, so grinding of starts and stops is recommended.

# Welding and Joining Guidelines Continued

It is suggested that welding be performed on base materials that are in the annealed condition.  Materials with greater than 7% cold work should be solution annealed before welding.  The welding of materials with large amounts of residual cold work can lead to cracking in the weld metal and/or the weld heat-affected zone.

Chemical treatments, such as passivation, are normally not required to achieve corrosion resistance in Ni-/Co-base weldments.  The solid-solution strengthened alloys can typically be put into service in the as-welded condition.  In certain instances, a postweld stress relief may be desirable prior to exposure to certain service environments.  Precipitation-strengthened alloys must be heat treated after welding to achieve their full properties.

As a way of achieving quality production welds, development and qualification of welding procedure specifications is suggested.  Such welding procedures are usually required for code fabrication, and should take into account parameters such as base and filler metals, weld joint design/geometry, preheat/interpass temperature control, and postweld heat treatment (PWHT) requirements.  Haynes International does not develop or provide specific welding procedures.  The general welding guidelines and any alloy-specific welding considerations should be used to develop a specific welding procedure.

# Weld Joint Design

Selection of a correct weld joint design is critical to the successful fabrication of HASTELLOY® and HAYNES® alloys. Poor joint design can negate even the most optimum welding conditions. The main consideration in weld joint design of Ni-/Co-base alloys is to provide sufficient accessibility and space for movement of the welding electrode or filler metal.  Slightly different weld joint geometries are required compared to those for carbon or stainless steel; in particular, a larger included weld angle, wider root opening (gap), and reduced land (root face) thickness are typically required.

The most important characteristic that must be understood when considering weld joint design is that Ni- and Co-base molten weld metal is relatively “sluggish”, meaning that it does not flow or spread out as readily to "wet" the sidewalls of the weld joint.  Therefore, care must be taken to ensure that the joint opening is wide enough to allow proper electrode manipulation and placement of the weld bead to achieve proper weld bead tie-in and fusion.  The welding arc and filler metal must be manipulated in order to place the molten metal where it is needed.  The joint design should allow for the first weld bead to be deposited with a convex surface.  An included weld angle or root opening that is too narrow promotes the formation of a concave weld bead that places the weld surface in tension and promotes solidification cracking in the weld metal.

Additionally, weld penetration is significantly less than that of a typical carbon or stainless steel.  This characteristic requires the use of reduced land thickness at the root of the joint compared to carbon and stainless steel.  Since this is an inherent property of Ni-/Co-base alloys, increasing weld current will not significantly improve their shallow weld penetration characteristics.

# Weld Joint Design Continued

Typical butt joint designs that are used with the gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), and shielded metal arc welding (SMAW) processes are: (i) Square-Groove, (ii) Single-V-Groove, and (iii) Double-V-Groove, as shown in Figure 1. Gas tungsten arc welding is often the preferred method for depositing the root pass for square-groove or single-V-groove joints, where there is access to only one side of the joint. The remainder of the joint can then be filled using other welding processes as appropriate. For groove welds on heavy section plates greater than 3/4 inch (19 mm) thick, a J-groove is permissible. Such a joint reduces the amount of filler metal and time required to complete the weld. Other weld joint designs for specific situations are shown in Figure 2.

Various welding documents are available to assist in the design of welded joints. Two documents that provide detailed guidance are:

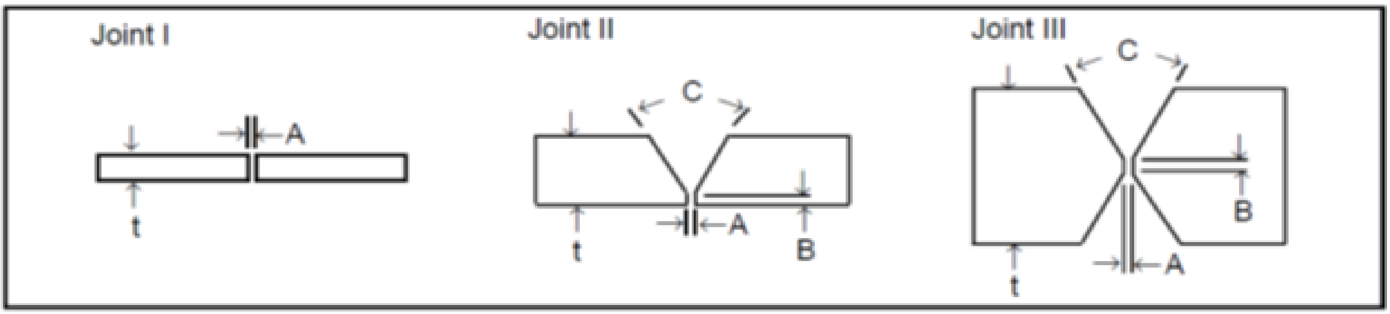
*Welding Handbook, Ninth Edition, Volume 1, Welding Science and Technology, Chapter 5, Design for Welding, pg. 157-238, American Welding Society, 2001.*

*ASM Handbook, Volume 6, Welding, Brazing and Soldering, Welding of Nickel Alloys, pg. 740-751, ASM International, 1993.*

In addition, fabrication codes such as the ASME Pressure Vessel and Piping Code may impose design requirements.

The actual number of passes required to fill the weld joint depends upon a number of factors that include the filler metal size (electrode or wire diameter), the amperage, and the travel speed. The estimated weight of weld metal required per unit length of welding is provided in Figure 1.

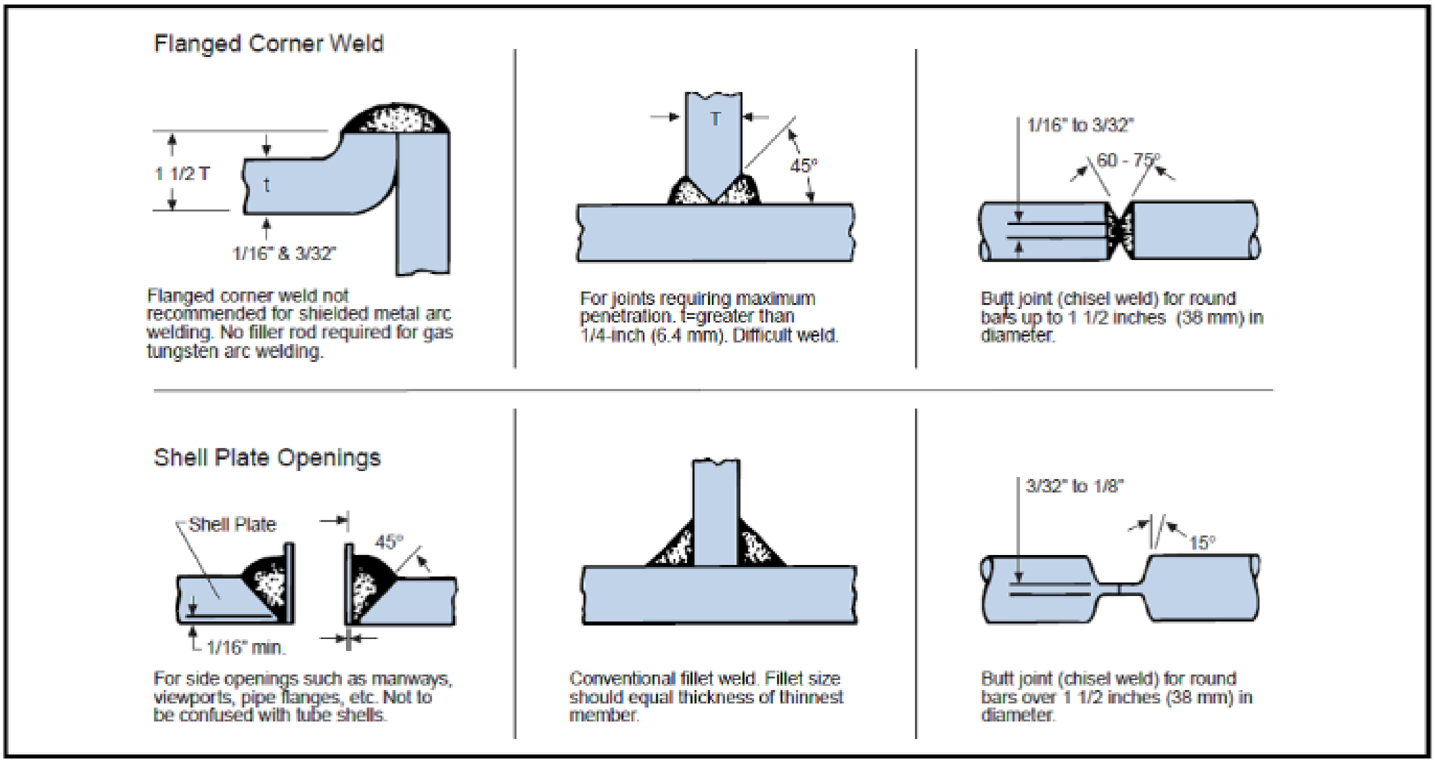
**Figure 1: Typical Butt Joints for Manual Welding**



# Weld Joint Design Continued

| Material Thickness (t) | | Preferred Joint Design | Root Opening (A) | | Land Thickness (B) | | Included Weld Angle (C) | Approx. Weight of Weld Metal Required | |
|---|---|---|---|---|---|---|---|---|---|
| in | mm | - | in | mm | in | mm | degrees | lbs/ft | kg/m |
| 1/16 | 1.6 | I | 0-1/16 | 0-1.6 | N/A | | None | 0.02 | 0.03 |
| 3/32 | 2.4 | I | 0-3/32 | 0-2.4 | N/A | | None | 0.04 | 0.06 |
| 1/8 | 3.2 | I | 0-1/8 | 0-3.2 | N/A | | None | 0.06 | 0.09 |
| 1/4 | 6.3 | II | 1/16-1/8 | 1.6-3.2 | 1/32-3/32 | (0.8-2.4) | 60-75 | 0.3 | 0.45 |
| 3/8 | 9.5 | II | 1/32-5/32 | (0.8-4.0) | | | 60-75 | 0.6 | 0.89 |
| 1/2 | 12.7 | II | | | | | 60-75 | 0.95 | 1.41 |
| 1/2 | 12.7 | III | | | | | 60-75 | 0.6 | 0.89 |
| 5/8 | 15.9 | II | | | | | 60-75 | 1.4 | 2.08 |
| 5/8 | 15.9 | III | | | | | 60-75 | 0.82 | 1.22 |
| 3/4 | 19.1 | II | | | | | 60-75 | 1.9 | 2.83 |
| 3/4 | 19.1 | III | | | | | 60-75 | 1.2 | 1.79 |

**Figure 2: Other Weld Joint Designs for Specific Situations**



Flanged Corner Weld

Flanged corner weld not recommended for shielded metal arc welding. No filler rod required for gas tungsten arc welding.

For joints requiring maximum penetration. t=greater than 1/4-inch (6.4 mm). Difficult weld.

Butt joint (chisel weld) for round bars up to 1 1/2 inches (38 mm) in diameter.

Shell Plate Openings

For side openings such as manways, viewports, pipe flanges, etc. Not to be confused with tube shells.

Conventional fillet weld. Fillet size should equal thickness of thinnest member.

Butt joint (chisel weld) for round bars over 1 1/2 inches (38 mm) in diameter.

# Weld Joint Preparation

Proper preparation of the weld joint is considered a very important part of welding HASTELLOY® and HAYNES® alloys. A variety of mechanical and thermal cutting methods are available for initial weld joint preparation. The plasma arc cutting process is commonly used to cut alloy plate into desired shapes and prepare weld angles. Waterjet cutting and laser beam cutting are also permissible. Edge preparation can be performed using machining and grinding techniques applicable to Ni- and Co-base alloys. Air carbon-arc cutting and gouging are permissible, but generally not suggested due to the very likely possibility of carbon pick-up from the carbon electrode. Not completely removing carbon contamination from the surface could lead to metallurgical issues during subsequent welding or processing. Additionally, high heat input during arc gouging could promote excessive grain growth and reduce material ductility. Thus, plasma arc cutting is generally a better alternative to air carbon-arc cutting and gouging because it does not introduce carbon contamination in the re-solidified layer and requires minimal post-cutting conditioning. The use of oxyacetylene welding and cutting is not recommended because of carbon pick-up from the flame.

It is necessary to condition all cut edges to bright and shiny metal prior to welding. In addition to the weld angle, generally a 1 inch (25 mm) wide band on the top and bottom (face and root) surface of the weld zone should be conditioned to bright metal with an 80 or 120 grit flapper wheel or disk. The purpose is to have a weld joint surface that is free of oxides, scale, and foreign contaminates. Using a lower grit size abrasive may be desirable, although it should be understood that coarse abrasive scratches could make it difficult to identify fine surface cracks during inspection of the weld joint. The use of progressively higher grit sizes provides a finer surface finish. Liquid/dye penetrant inspection could be more difficult or invalid with a lower grit size surface finish since coarser scratches are more likely to trap penetrant.

Cleanliness is considered an extremely important aspect of Ni-/Co-base weld joint preparation. Prior to any welding operation, the welding surface and adjacent regions should be thoroughly cleaned with an appropriate solvent, such as acetone, or an appropriate alkaline cleaner. All greases, cutting oils, crayon marks, machining solutions, corrosion products, paints, scale, dye penetrant solutions, and other foreign matter should be completely removed. Any cleaning residue should also be removed prior to welding. Contamination of the weld region by lead, sulfur, phosphorus, and other low-melting point elements can lead to severe embrittlement or cracking. For Co- and Fe-base alloys, surface contact with copper or copper-bearing materials in the weld region should be avoided. Even trace amounts of copper on the surface can result in copper contamination cracking, a form of liquid metal embrittlement, in the heat-affected zone of the weld.

Surface iron contamination resulting from contact with carbon steel can result in rust staining, but it is not considered a serious problem and, therefore, it is generally not necessary to remove such rust stains prior to service. In addition, melting of small amounts of such surface iron contamination into the weld pool is not expected to significantly affect weld-metal corrosion-resistance. While such contamination is not considered a serious problem, if reasonable care is exercised to avoid the problem, no particular corrective measures should be necessary prior to service.

It is especially important that surface oxides be removed between weld passes or layers in multi-pass welds. Since the melting temperatures of the surface oxides are much higher than the base metals being welded, they are more likely to stay solid during welding and become trapped in the weld pool to form inclusions and incomplete fusion defects. Stainless steel wire brushing is often sufficient for interpass surface cleaning, although light grinding may be necessary to remove thick oxide layers. The wire brushes that are used during welding should be reserved for use on Ni- and Co-base alloys only, and should not have been used for carbon or stainless steel. There will be a stronger tendency to form surface oxides with certain alloys and welding processes, and thicker oxide layers can form during successive passes of multi-pass welds. The grinding of starts and stops is recommended for all arc welding processes. Slag removal during SMAW will require chipping and grinding followed by wire brushing.

# Temperature Control and Heat-treatment of Weldments

Preheating of HASTELLOY® and HAYNES® alloys is generally not required. Ambient or room temperature is generally considered a sufficient preheat temperature. However, the alloy base material may require warming to raise the temperature above freezing or to prevent condensation of moisture. For example, condensation may occur if the alloy is brought into a warm shop from cold outdoor storage. In this case, any metal near the weld should be warmed slightly above room temperature to prevent the formation of condensate, which could cause weld metal porosity. Warming should be accomplished by indirect heating if possible, e.g. infrared heaters or natural warming to room temperature. If oxyacetylene warming is used, the heat should be applied evenly over the base metal rather than in the weld zone. The torch should be adjusted so that the flame is not carburizing. A "rosebud" tip, which distributes the flame evenly, is suggested. Care should be taken to avoid local or incipient melting as a result of the warming process.

Interpass temperature refers to the temperature of the weldment just prior to the deposition of an additional weld pass. It is suggested that the maximum interpass temperature be 200°F (93°C). Auxiliary cooling methods may be used to control the interpass temperature; water quenching and rapid air cooling are acceptable. Care must be taken to ensure that the weld zone is not contaminated with traces of oil from air lines, grease/dirt, or mineral deposits from hard water used to cool the weld joint. When attaching hardware to the outside of a thin-walled vessel, it is good practice to provide auxiliary cooling to the inside (process side) of the vessel to minimize the extent of the heat-affected zone.

Under the vast majority of service environments, corrosion-resistant alloys and solid-solution-strengthened high-temperature alloys are used in the as-welded condition, and post-weld heat-treatment (PWHT) of these alloys is generally not required to assure good weldability. Post-weld heat-treatment may be required, or advantageous in certain situations, such as to relieve weld residual stresses. However, stress relief heat-treatments at temperatures commonly used for carbon steels are normally ineffective for these alloys. If PWHT is conducted at these intermediate temperatures, it may result in the precipitation of secondary phases in the microstructure which can have a detrimental effect on material properties, such as corrosion resistance. For most alloys, PWHT in the 1000 to 1500ºF (538 to 816ºC) temperature range should be avoided. If stress relief heat treatment of attendant carbon steel components is required, contact Haynes International for guidance. In general, the only acceptable PWHT for solid-solution strengthened alloys is a full solution-anneal. The heat-treatment guidelines should be consulted to determine the appropriate solution-annealing temperature for an alloy. Annealing time is normally commensurate with weld joint thickness.

For precipitation-strengthened alloys, PWHT is normally required in order to develop appropriate material/weldment properties. In almost all cases, this involves a full solution-anneal followed by an age hardening heat treatment. Consult the heat-treatment guidelines to determine the appropriate annealing and age-hardening heat-treatment schedule for an alloy.

# Welding Defects

A weld discontinuity is defined by the American Welding Society as “an interruption of the typical structure of a material, such as a lack of homogeneity in its mechanical, metallurgical, or physical characteristics.” Welding defects are a type of discontinuity that compromises the usefulness of a weldment, which could render it unable meet minimum applicable acceptance standards/specifications. Welding defects can be welding process-/procedure-related, or related to the chemical composition or metallurgy of the alloy(s) being welded.

Weld metal porosity is a cavity-type of welding defect formed by gas entrapment during solidification as a result of contamination by certain gases, such as hydrogen, oxygen, or nitrogen. Porosity caused by hydrogen pickup can be minimized by keeping the weld joint area and filler metal free of hydrocarbon contaminants and moisture. To avoid porosity caused by oxygen and nitrogen, it is important that the weld pool is properly shielded through the use of high purity shielding gases, and sufficient shielding gas flow rates are being utilized. Although porosity can occur in HASTELLOY® and HAYNES® weldments, they are not particularly susceptible to porosity since most alloys contain a significant amount of Cr, which has a natural affinity for the gases that are formed during welding.

Weld metal inclusions can form as a result of oxides that become trapped in the weld pool. This can occur from the tenacious oxide film that forms on the surface of most alloys. Since the melting temperatures of surface oxides are usually much higher than the base metal, they are more likely to stay solid during welding and become trapped in the weld pool. Thus, it is especially important that surface oxides be removed prior to welding and between passes in multi-pass welds. During GTAW, if the tungsten electrode accidentally contacts the molten weld pool or if there is excessive weld current, tungsten inclusions can be produced in the weld metal. Elements with a strong affinity for oxygen, such as aluminum or magnesium, can combine with oxygen to form oxide inclusions in the weld metal. Slag inclusions are associated with flux-based processes such as SMAW, SAW, and FCAW. These inclusions form in the weld metal when residual slag becomes entrapped in cavities or pockets that form due to inadequate weld bead overlap, excessive undercut at the weld toe, or an uneven surface profile of the preceding weld bead. Thus, an important consideration in flux-based processes is the ease with which the slag can be removed between weld passes. Inclusions must be ground out from the weld or they will act to initiate fracture prematurely, which can have a detrimental effect on mechanical properties and service performance.

Other common process-related defects that are encountered are undercut, incomplete fusion/penetration, and distortion. These defects are generally attributed to improper welding technique and/or welding parameters. Undercut is a groove that is melted into the base metal, usually at the root or toes of the weld, and can occur due to excessive welding current. This discontinuity creates a notch at the periphery of the weld and can significantly weaken the strength of the weldment. Incomplete fusion defects are promoted by the “sluggish” nature of Ni-/Co-base molten weld metal and their poor weld penetration characteristics.

# Welding Defects Continued

Distortion characteristics of the HASTELLOY® and HAYNES® alloys are similar to those of carbon steel, with less tendency to distort than austenitic stainless steel weldments due to their lower coefficient of thermal expansion. Jigs, fixturing, cross supports, bracing, and weld bead placement and sequence will help to hold distortion to a minimum. Where possible, balanced welding about the neutral axis will assist in keeping distortion to a minimum. Proper fixturing and clamping of the assembly makes the welding operation easier and minimizes buckling and warping of thin sections. It is suggested that, where possible, extra stock be allowed to the overall width and length. Excess material can then be removed in order to achieve final dimensions. Weld distortion for different joint designs are shown in Figure 3.

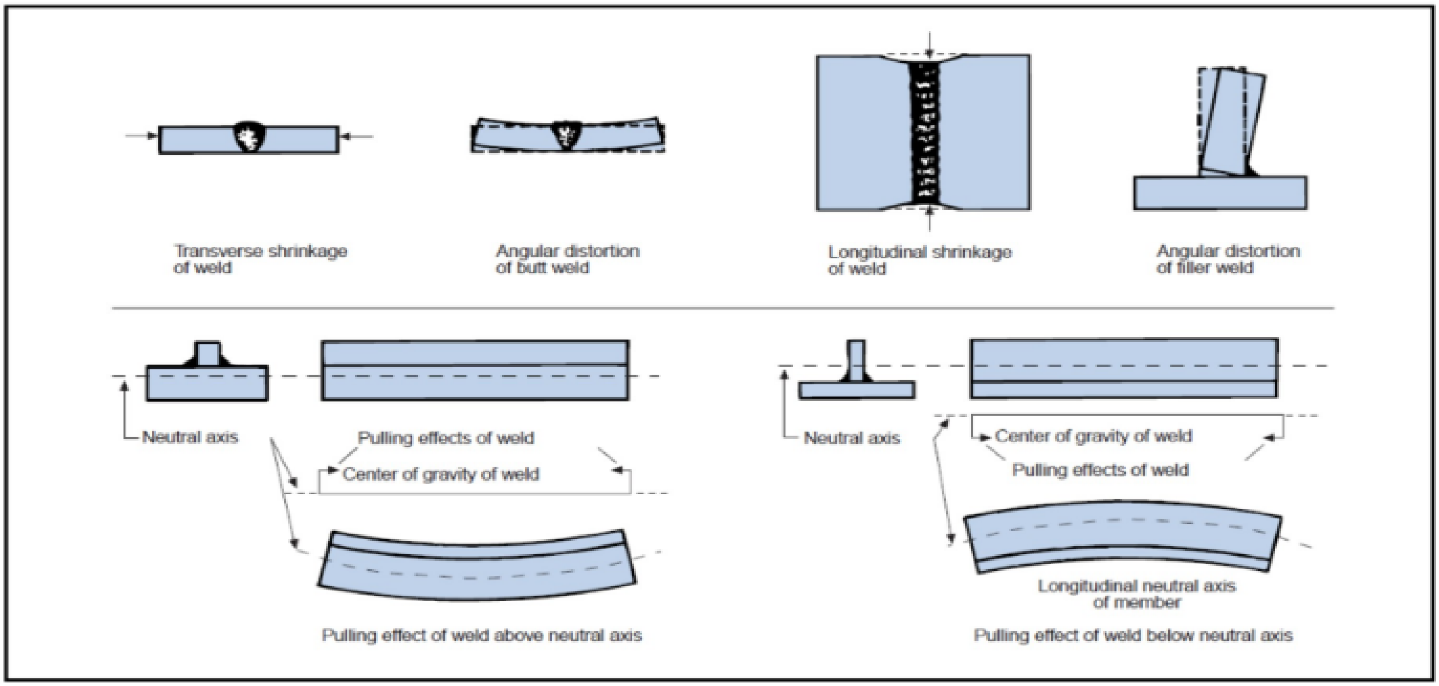
During normal fabrication of HASTELLOY® and HAYNES® alloys, weld-cracking is rare and one should expect to fabricate large, complex components with few instances of cracking. The most common type of weld-cracking encountered is hot-cracking, which is associated with the presence of liquid in the microstructure. Hot-cracking can occur in the weld metal and heat-affected zone of a weld, and usually results from liquid films along grain boundaries. These strain-intolerant microstructures temporarily occur at elevated temperatures within the melting and solidification range of all alloys. Due to their nominal chemical composition, certain alloys are more susceptible to hot-cracking than other alloys. In general, hot-cracking is a more common occurrence with high-temperature alloys due to their higher alloy content. Impurity elements, such as sulfur and phosphorus, and minor alloying additions, such as boron and zirconium, can have a strong influence on cracking susceptibility even though they are present in very low concentrations.

In addition to a susceptible microstructure, the level of tensile stress on the weld is a critical factor for hot-cracking. The development of stress is inevitable during welding because of the complex thermal stresses that are created when metal solidifies and cools. This is in part related to the inherent restraint placed on the weldment due to weld-joint geometry and thickness. In general, weldments with increased joint thickness are more susceptible to hot-cracking. Additionally, a “teardrop-shaped” weld pool created due to fast travel speed tends to increase cracking susceptibility since it produces a distinct weld centerline where elemental segregation is enhanced and transverse stresses can be high. Large concave weld beads that place the weld surface in tension tend to promote solidification cracking and should be avoided. Further information about weld-cracking mechanisms and welding metallurgy of Ni-base alloys can be found in the following textbook:

*J.N. DuPont, J.C. Lippold, and S.D. Kiser, Welding Metallurgy and Weldability of Nickel-Base Alloys, John Wiley & Sons, Inc., 2009.*

# Welding Defects Continued

**Figure 3: Weld Distortion for Different Joint Designs**



# Post-weld Inspection and Repair

In order to determine the suitability of the weldment for its intended purpose, some degree of nondestructive examination/testing (NDE/NDT) should be conducted as part of sound fabrication practice and quality assurance. For non-code fabrication, NDE may be as simple as visual or liquid/dye penetrant inspection. For code fabrication, certain mandatory inspections may be required. These NDE methods should be considered for both intermediate inspections during multi-pass welding, as well as for final acceptance of the weldment.

NDE methods are similar to those used for carbon and stainless steels. Liquid/dye penetrant inspection is commonly used to reveal surface defects, such as hot-cracking. Radiographic and ultrasonic testing can be used to detect for subsurface defects and thoroughly check the soundness of the weldment; however, the results can be difficult to interpret and these methods are generally not well suited for inspection of fillet welds. Magnetic particle inspection is not an effective NDE method for Ni-/Co-base alloys since they are non-magnetic. If further information is required, it is suggested that the fabricator consult with an outside laboratory that is experienced with NDE of Ni-/Co-base alloy welds.

Welding defects that are believed to affect quality or mechanical integrity should be removed and repaired. Removal techniques include grinding, plasma arc gouging, and air carbon-arc gouging. As explained previously in the weld joint preparation section, extreme care must be exercised during air carbon-arc gouging to insure that carbon contamination of the weld joint area does not occur. It is suggested that the prepared cavity is liquid/dye penetrant inspected to insure that all objectionable defects have been removed. The repair cavity should then be thoroughly cleaned prior to any welding repair. Since Ni-/Co-base alloys have low weld penetration characteristics, the ground cavity must be broad enough and have sufficient sidewall clearance in the weld groove to allow for weld electrode/bead manipulation. The technique of "healing” or "washing out" cracks and defects by autogenously re-melting weld beads, or by depositing additional filler metal over the defect, is not recommended.

# Gas Tungsten Arc Welding (GTAW / “TIG”)

The gas tungsten arc welding (GTAW) process is a very versatile, all-position welding process that is widely used to join Ni-/Co-base alloys. In GTAW, the heat for welding is generated from an electric arc established between a non-consumable tungsten electrode and the workpiece. GTAW can be performed manually or adapted to automatic equipment, and can be used in production as well as repair welding situations. It is a process that offers precise control of welding heat, and is therefore routinely used for welding thin base metal and depositing root passes of thicker section welds. The major drawback of the GTAW process is productivity, as weld metal deposition rates during manual welding are low.

Two percent thoriated tungsten electrodes (AWS A5.12 EWTh-2) have been traditionally used for GTAW of Ni-/Co-base alloys, but now other compositions are becoming more common due to possible health concerns associated with EWTh-2 and other thoriated tungsten electrodes. The thorium oxide contained in the EWTh-2 electrode is a low-level radioactive material that presents a small external radiation hazard and an internal hazard from ingestion or inhalation. The greatest risk for a welder is associated with the inhalation of radioactive dust while grinding the tungsten electrode tip to maintain the desired conical shape. Consequently, it is necessary to use local exhaust ventilation to control the dust at the source, complemented if necessary by respiratory protective equipment, and precautions must be taken in order to control any risks of exposure during the disposal of dust from grinding devices. As a result of these health concerns, thoriated tungsten electrodes are being phased out by certain governing bodies and organizations. Fortunately, there are alternatives that provide comparable performance to EWTh-2, including two percent ceriated (AWS A5.12 EWCe-2) and lanthanated (AWS A5.12 EWLa-2) electrodes. For further information on the different types of tungsten electrodes, the reader is referred to: AWS A5.12/A5.12M, Specification for Tungsten and Oxide Dispersed Tungsten Electrodes for Arc Welding and Cutting, American Welding Society.

The diameter of the tungsten electrode should be selected according to weld joint thickness and filler wire diameter. It is suggested that the electrode be ground to a cone shape (included angle of 30 to 60 degrees) with a small flat of 0.040 to 0.060 in (1.0 to 1.5 mm) ground at the point. See Figure 4 for the suggested tungsten electrode geometry.

Welding-grade argon shielding gas with a 99.996% minimum purity is suggested for most welding situations. Helium, or mixtures of argon/helium or argon/hydrogen may be advantageous in certain situations, such as high travel speed, highly mechanized welding operations, in order to increase weld penetration. Shielding gas flow rates are critical; too low of a rate will not provide adequate protection of the weld pool, while too high of a rate can increase turbulence and aspirate air. Typically, flow rates for 100%Ar shielding gas are in the 20 to 30 cubic feet per hour (CFH) (9 to 14 L/min) range. Generally, the shielding gas cup should be as large as practical so that the shielding gas can be delivered at lower velocity. It is also recommended that the welding torch be equipped with a gas lens in order to stabilize the gas flow and provide optimum shielding gas coverage. While welding-grade shielding gases are of a very high purity, even a small amount of air can compromise the protective shielding and cause weld metal oxidation/discoloration and porosity. This can be caused by air movement from fans, cooling systems, drafts, etc., or from leakage of air into the shielding due to a loose gas cup or other welding torch components. When proper shielding is achieved, the as-deposited weld metal should typically have a bright-shiny appearance and require only minor wire brushing between passes.

# Gas Tungsten Arc Welding (GTAW / “TIG”) Continued

In addition to welding torch shielding gas, a back-purge at the root side of the weld joint with welding-grade argon is suggested. The flow rates are normally in the range of 5 to 10 CFH (2 to 5 L/min). Copper backing bars are often used to assist in weld bead shape on the root side of the weld. Backing gas is often introduced though small holes along the length of the backing bar. There are situations where backing bars cannot be used. Under these conditions, open-butt welding is often performed. Such welding conditions are often encountered during pipe or tube circumferential butt welding. Under these conditions where access to the root side of the joint is not possible, special gas flow conditions have been established. Under these open-butt welding conditions, the torch flow rates are reduced to approximately 10 CFH (5 L/min) and the back purge flow rates are increased to about 40 CFH (19 L/min). Detailed information concerning back-purging during pipe welding is available from Haynes International upon request.

It is recommended that the welding torch be held essentially perpendicular to the work-piece, with the work angle at 90° from the horizontal and only a slight travel angle of 0° to 5°. If a large drag angle is utilized, air may be drawn into the shielding gas and contaminate the weld. The arc length should be maintained as short as possible, especially during autogenous welding. Stringer bead techniques, or narrow weave techniques, using only enough current to melt the base material and allow proper fusion of the filler, are recommended. Filler metal should be added carefully at the leading edge of the weld pool to avoid contact with the tungsten electrode. During welding, the tip of the welding filler metal should always be held under the shielding gas to prevent oxidation. Pausing or “puddling” the weld pool adds to the weld heat input and is not recommended.

Electrical polarity for the GTAW process should be direct current electrode negative (DCEN / “straight polarity”). Typical manual GTAW parameters for welding HASTELLOY® and HAYNES® alloys are provided in Table 1. The parameters should be viewed as approximate values that are ultimately dependent on many other factors, including the particular welding power source, weld joint geometry, and welder skill level. Thus, it is suggested that the parameters be used as a guideline for developing a specific welding procedure. Smaller diameter filler wire is suggested for depositing root passes. A power source equipped with high-frequency start, pre-purge/post-purge and up-slope/down-slope (or foot peddle) controls is highly recommended. Weld travel speed has a significant influence on the quality of Ni-/Co-base welds, and is typically lower than for carbon and stainless steel. The suggested travel speed for manual GTAW is 4 to 6 inches per minute (ipm) / 100 to 150 mm/min.

# Gas Tungsten Arc Welding (GTAW / "TIG") Continued

**Figure 4: Tungsten Electrode Geometry**

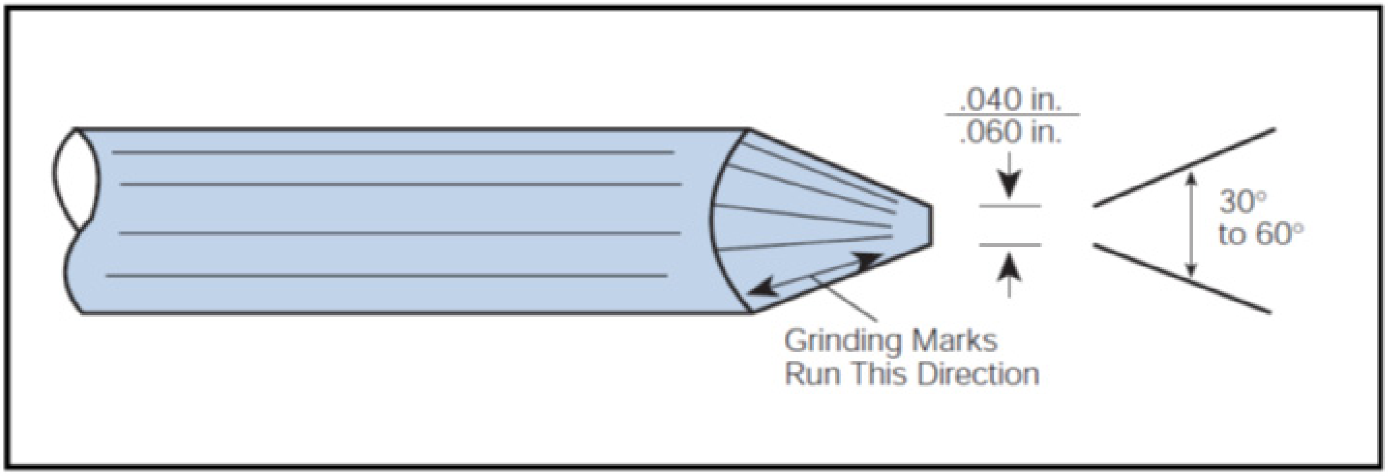


**Table 1: Typical Manual Gas Tungsten Arc Welding Parameters (Flat Position)**

| Joint Thickness | | Tungsten Electrode Diameter | | Filler Wire Diameter | | Welding Current | Arc Voltage |
|---|---|---|---|---|---|---|---|
| in | mm | in | mm | in | mm | Amps | Volts |
| 0.030-0.062 | 0.8-1.6 | 0.062 | 1.6 | 0.062 | 1.6 | 15-75 | 9-15 |
| 0.062-0.125 | 1.6-3.2 | 0.062/0.093 | 1.6/2.4 | 0.062/0.093 | 1.6/2.4 | 50-125 | 9-15 |
| 0.125-0.250 | 3.2-6.4 | 0.093/0.125 | 2.4/3.2 | 0.093/0.125 | 2.4/3.2 | 100-175 | 12-18 |
| > 0.250 | >6.4 | 0.093/0.125 | 2.4/3.2 | 0.093/0.125 | 2.4/3.2 | 125-200 | 12-18 |

# Gas Metal Arc Welding (GMAW / "MIG")

The gas metal arc welding (GMAW / "MIG") process utilizes an electric arc established between a consumable wire electrode and the workpiece. GMAW can be implemented as a manual, semi-automatic, or automatic process, and the flexibility offered by the various process variations is advantageous in many applications. GMAW provides a considerable increase in weld metal deposition rates compared to GTAW or SMAW, and when implemented as a semi-automatic process, less welder skill is typically required. However, GMAW equipment is more complex, less portable, and generally requires more routine maintenance than for the GTAW and SMAW processes. GMAW is the most common process for welding corrosion-resistant alloys and for performing thick-section welds.

In GMAW, the mechanism by which the molten metal at the end of the wire electrode is transferred to the workpiece has a significant effect on the weld characteristics. Three modes of metal transfer are possible with GMAW: short-circuiting transfer, globular transfer, and spray transfer. In addition, there is a variation of the spray transfer mode called pulsed spray.

Electrical polarity for GMAW of HASTELLOY® and HAYNES® alloys should be direct current electrode positive (DCEP / "reverse polarity"). Typical parameters for different GMAW transfer modes are provided in Table 2 for flat position welding. Since different GMAW power sources vary greatly in design, operation, and control systems, the parameters should be viewed as an estimated range for achieving proper welding characteristics with specific welding equipment. GMAW travel speeds are typically 6 to 10 inches per minute (ipm) / 150 to 250 mm/min.

# Gas Metal Arc Welding (GMAW / “MIG”) Continued

Short-circuiting transfer occurs at the lowest current and voltage ranges, which results in low weld heat input.  It is typically used with smaller diameter filler wire, and produces a relatively small and easily controlled weld pool that is well-suited for out-of-position welding and joining thin sections.  However, the low heat input makes short-circuiting transfer susceptible to incomplete fusion (cold lap) defects, especially when welding thick sections or during multipass welds.

Globular transfer occurs at higher current and voltage levels than short-circuiting, and is characterized by large, irregular drops of molten metal.  The globular transfer mode can theoretically be used to weld Ni-/Co-base alloys, but is seldom used because it creates inconsistent penetration and uneven weld bead contour that promotes the formation of defects.  Since the force of gravity is critical for drop detachment and transfer, globular transfer is generally limited to flat position welding.

Spray transfer occurs at the highest current and voltage levels, and is characterized by a highly directed stream of small metal droplets.  It is a high heat input process with relatively high deposition rates that is most effective for welding thick sections of material.  However, it is mainly useful only in the flat position, and its high heat input promotes weld hot-cracking and the formation of secondary phases in the microstructure that can compromise service performance.

Pulsed spray transfer is a highly controlled variant of spray transfer, in which the welding current alternates between a high peak current, where spray transfer occurs, and a lower background current.  This results in a stable, low-spatter process at an average welding current significantly below that for spray transfer.  Pulsed spray offers lower heat input compared to spray transfer, but is less susceptible to the incomplete fusion defects that are common to short-circuiting transfer.  It is useful in all welding positions and for a wide range of material thickness.  In most situations, Haynes International highly encourages the use of pulsed spray transfer for GMAW of HASTELLOY® and HAYNES® alloys.  The use of a modern power source with synergic control and the provision for waveform adjustment (“adaptive pulse”) is highly beneficial for pulsed spray transfer. These advanced technologies have facilitated the use of pulsed spray transfer, in which pulse parameters such as pulse current, pulse duration, background current, and pulse frequency are included in the control system and linked to the wire feed speed.

# Gas Metal Arc Welding (GMAW / “MIG”) Continued

Shielding gas selection is critical to GMAW procedure development. For Ni-/Co-base alloys, the protective shielding gas atmosphere is usually provided by argon or argon mixed with helium. The relatively low ionization energy of argon facilitates better arc starting/stability and its low thermal conductivity provides a deeper finger-like penetration profile. If used alone, helium creates an unsteady arc, excessive spatter, and a weld pool that can become excessively fluid, but when added to argon, it provides a more fluid weld pool that enhances wetting and produces a flatter weld bead. Additions of oxygen or carbon dioxide, while commonly used with other metals, is to be avoided when welding Ni-/Co-base alloys. These additions produce a highly oxidized surface and promote weld metal porosity, irregular bead surfaces, and incomplete fusion defects. The optimum shielding gas mixture is dependent on many factors, including weld joint design/geometry, welding position, and desired penetration profile. In most instances, a mixture of 75% Ar and 25% He is suggested; good results have been obtained with helium contents of 15 to 30%. During short-circuiting transfer, the addition of helium to argon helps to avoid overly convex weld beads that can lead to incomplete fusion defects. For spray transfer, good results can be obtained with pure argon or argon-helium mixtures. The addition of helium is generally required for pulsed spray transfer as it greatly enhances wetting.

Since argon and helium are inert gases, the as-deposited weld surface is expected to be bright and shiny with minimal oxidation. In this case, it is not mandatory to grind between passes during multipass welding. However, some oxidation or "soot" may be noted on the weld surface. If so, heavy wire brushing and/or light grinding/conditioning (80 grit) between weld passes is suggested in order to remove the oxidized surface and ensure the sound deposit of subsequent weld beads. Shielding gas flow rates should generally be in the 25 to 45 CFH (12 to 21 L/min) range. A flow rate that is too low does not provide adequate shielding of the weld, while excessively high flow rates can interfere with the stability of the arc. As with GTAW, back-purge shielding is recommended to ensure the root side of the weld joint does not become heavily oxidized. If back-purge shielding is not possible, the root side of the weld joint should be ground after welding to remove all oxidized weld metal and any welding defects. The weld joint can then be filled from both sides as needed.

During GMAW, the welding gun should be held perpendicular to the work-piece at both a work angle and travel angle of approximately 0°. A very slight deviation from perpendicular may be necessary for visibility. If the gun is positioned too far from perpendicular, oxygen from the atmosphere may be drawn into the weld zone and contaminate the molten weld pool. A water-cooled welding gun is always recommended for spray transfer welding and anytime higher welding currents are being utilized.

It should be recognized that some parts of the GMAW equipment, such as the contact tip and filler wire conduit/liner, experience high wear and should be replaced periodically. A worn or dirty liner can cause erratic wire feed that will result in arc instability, or cause the filler wire to become jammed, a situation known as a “bird nest”. It is recommended that sharp bends in the gun cable be minimized. If possible, the wire feeder should be positioned so that the gun cable is nearly straight during welding.

# Gas Metal Arc Welding (GMAW / “MIG”) Continued

**Table 2: Typical Gas Metal Arc Welding Parameters (Flat Position)**

| Wire Diameter | | Wire Feed Speed | | Welding Current | Average Arc Voltage | Shielding Gas |
|---|---|---|---|---|---|---|
| in | mm | ipm | mm/s | Amps | Volts | - |
| **Short-Circuiting Transfer Mode** | | | | | | |
| 0.035 | 0.9 | 150-200 | 63-85 | 70-90 | 18-20 | 75Ar-25He |
| 0.045 | 1.1 | 175-225 | 74-95 | 100-160 | 19-22 | 75Ar-25He |
| **Spray Transfer Mode** | | | | | | |
| 0.045 | 1.1 | 250-350 | 106-148 | 190-250 | 28-32 | 100Ar |
| 0.062 | 1.6 | 150-250 | 63-106 | 250-350 | 29-33 | 100Ar |
| **Pulsed Spray Transfer Mode*** | | | | | | |
| 0.035 | 0.9 | 300-450 | 127-190 | 75-150 Avg. | 30-34 | 75Ar-25He |
| 0.045 | 1.1 | 200-350 | 85-148 | 100-175 Avg. | 32-36 | 75Ar-25He |

*Detailed pulsed spray parameters are available upon request

# Shielded Metal Arc Welding (SMAW / “Stick”)

The shielded metal arc welding (SMAW / “Stick”) process generates an arc between a flux-coated consumable electrode and the work-piece. SMAW is well known for its versatility because it can be used in all welding positions, and in both production and repair welding situations. It is one of the simplest welding processes in terms of equipment requirements and can be easily operated in remote locations. However, it is strictly a manual welding process that generally requires a high welder skill level. In addition, it is typically restricted to material thickness greater than approximately 0.062 in (1.6 mm).

HASTELLOY® and HAYNES® coated electrodes for SMAW undergo a number of qualification tests to determine the usability of the electrode, the chemical composition of the weld deposit, and the soundness and mechanical properties of the weld metal. Coated electrodes are generally formulated to produce a weld deposit with a chemical composition that corresponds to that of the matching base metal. The coating formulations are generally classified as slightly basic to slightly acidic depending on the particular alloy. For further information on the requirements for the classification of Ni-base coated electrodes, the reader is referred to: AWS A5.11/A5.11M, Specification for Nickel and Nickel-Alloy Welding Electrodes for Shielded Metal Arc Welding, American Welding Society.

Prior to their use, coated electrodes should remain sealed in a moisture-proof canister. After the canister has been opened, all coated electrodes should be stored in an electrode storage oven. It is recommended that the electrode storage oven be maintained at 250 to 400ºF (121 to 204ºC). If coated electrodes are exposed to an uncontrolled atmosphere, they can be reconditioned by heating in a furnace at 600 to 700ºF (316 to 371ºC) for 2 to 3 hours.

# Shielded Metal Arc Welding (SMAW / “Stick”) Continued

Typical SMAW parameters are presented in Table 3 for flat position welding. While the coated electrodes are classified as AC/DC, in almost all situations electrical polarity should be direct current electrode positive (DCEP / “reverse polarity”). For maximum arc stability and control of the molten pool, it is important to maintain a short arc length. The electrode is generally directed back toward the molten pool (backhand welding) with about a 20° to 40° drag angle. Even though stringer bead welding techniques are generally preferred, some electrode manipulation and weaving may be required to place the molten weld metal where it is needed. The amount of weave is dependent on weld joint geometry, welding position, and type of coated electrode. A rule of thumb is that the maximum weave width should be about three times the electrode core wire diameter. Once deposited, weld beads should preferably exhibit a slightly convex surface contour. Appropriate welding current is based on the diameter of the coated electrode. When operated within the suggested current ranges, the electrodes should exhibit good arcing characteristics with minimum spatter. The use of excessive current can lead to overheating of the electrode, reduced arc stability, spalling of the electrode coating, and weld metal porosity. Excessive spatter is an indication that arc length is too long, welding current is too high, polarity is not reversed, or there has been absorption of moisture by the electrode coating. The suggested travel speed for SMAW is 3 to 6 inches per minute (ipm) / 75 to 150 mm/min.

Out-of-position welding is recommended only with 0.093 in (2.4 mm) and 0.125 in (3.2 mm) diameter electrodes. During out-of-position welding, the amperage should be reduced to the low end of the suggested range in Table 3. In order to keep the bead profile relatively flat during vertical welding, a weave bead technique is necessary. Using 0.093 in (2.4 mm) electrodes will reduce the weave width that is required and produce flatter beads. In vertical welding, a range of electrode positions is possible from forehand (up to 20° push angle) to backhand welding (up to 20° drag angle). In overhead welding, backhand welding (drag angle of 0°to 20°) is required.

Starting porosity may occur because the electrode requires a short time to begin generating a protective atmosphere. This is a particular problem with certain alloys, such as HASTELLOY® B-3® alloy. The problem can be minimized by using a starting tab of the same alloy as the work-piece or by grinding each start to sound weld metal. Small crater cracks may also occur at the weld stops. These can be minimized by using a slight back-stepping motion to fill the crater just prior to breaking the arc. It is recommended that all weld starts and stops be ground to sound weld metal.

The slag formed on the weld surface should be completely removed. This can be accomplished by first chipping with a welding/chipping hammer, then brushing the surface with a stainless steel wire brush. In multi-pass welds, it is essential that all slag is removed from the last deposited weld bead before the subsequent bead is deposited. Any remaining weld slag can compromise the corrosion resistance of the weldment.

# Shielded Metal Arc Welding (SMAW / “Stick”) Continued

**Table 3: Typical Shielded Metal Arc Welding Parameters (Flat Position)**

| Electrode Diameter | | Arc Voltage | Welding Current |
|---|---|---|---|
| **in** | **mm** | **Volts** | **Amps** |
| 0.093 | 2.4 | 22-25 | 45-75 |
| 0.125 | 3.2 | 22-25 | 75-110 |
| 0.156 | 4 | 23-26 | 110-150 |
| 0.187 | 4.7 | 24-27 | 150-180 |

# Plasma Arc Welding (PAW)

The plasma arc welding (PAW) process is a gas-shielded process that utilizes a constricted arc between a non-consumable tungsten electrode and the workpiece. The transferred arc possesses high energy density and plasma jet velocity. Two distinct operating modes are possible, referred to as melt-in-mode and keyhole mode. The melt-in-mode utilizes lower welding current and generates a weld pool similar to that formed in GTAW, whereby a portion of the workpiece material under the arc is melted. In the keyhole mode, higher welding current is utilized so that the arc fully penetrates the workpiece material to form a concentric hole through the joint thickness. The molten weld metal solidifies behind the keyhole as the torch traverses the workpiece. Shielding of the weld pool is provided by the ionized plasma gas that is issued from the torch orifice, which is supplemented by an auxiliary source of shielding gas. The PAW process can be utilized with or without a filler metal addition.

Since the constricted arc of PAW allows for greater depth of fusion compared to GTAW, PAW is potentially advantageous for autogenous welding (i.e. without the use of filler metal) of Ni-/Co-base material in the thickness range of approximately 0.125 to 0.3 in (3.2 to 7.6 mm). In comparison, filler metal is typically required for GTAW of material greater than about 0.125 in (3.2 mm) thickness. Square-groove weld joints can be utilized up to about 0.3 in (7.6 mm) thickness. While it is possible to weld a wide range of thicknesses with PAW, better results can usually be achieved with other welding processes for thicknesses outside of the 0.125 to 0.3 in (3.2 to 7.6 mm) range. For joint thicknesses greater than 0.3 in (7.6 mm), autogenous keyhole welding can be utilized for the first pass, followed by non-keyhole (melt-in) PAW with filler metal. Another welding process, such as GTAW, could also be utilized for the second and succeeding passes.

# Plasma Arc Welding (PAW) Continued

Electrical polarity for the PAW process should be direct current electrode negative (DCEN / “straight polarity”). A proper balance must be achieved between welding current, gas flow, and travel speed to provide consistent keyhole welding. An unstable keyhole can result in turbulence in the weld pool. Argon or argon-hydrogen mixtures are normally utilized for the orifice gas and shielding gas. The orifice gas has a strong effect on the penetration depth and profile. Small amounts of hydrogen (~5%) are typically sufficient to increase the arc energy for autogenous keyhole welding, and higher amounts can lead to porosity in the weld metal. For greater joint thicknesses, increased orifice gas flow and upslope of the welding current may be required to initiate the keyhole. To fill the keyhole cavity at the end of the weld, decreased orifice gas flow and downslope of the welding current may be required. Higher travel speeds require higher welding currents to obtain keyhole welding. Excessive travel speeds can produce undercut, which is a groove melted into the base metal adjacent to the weld toe or weld root and left unfilled by weld metal. The welding torch should be held essentially perpendicular to the work piece in both the longitudinal and transverse directions, and maintained on the centerline of the weld joint. Even a slight deviation from this condition can cause incomplete fusion defects in the weld metal.

# Electron Beam Welding (EBW) and Laser Beam Welding (LBW)

The electron beam welding (EBW) and laser beam welding (LBW) processes are high-energy density welding processes that offer several possible advantages, including low welding heat input, high weld depth-to-width ratio, narrow heat-affected zone (HAZ), and reduced distortion. To impinge on the weld joint and produce coalescence, EBW utilizes a moving concentrated beam of high-velocity electrons, while LBW utilizes the heat from a high-density coherent laser beam.

Most Ni-/Co-base alloys that can be joined with conventional arc welding processes can also be successfully joined via EBW and LBW. These beam welding processes are even considered more suitable for alloys that are difficult to arc weld and can provide better overall weld properties compared to arc welding. The low welding heat input results in a shorter time spent in the solidification temperature range and relatively fast cooling rates, which suppresses precipitation of secondary phases during weld solidification.

# Electron Beam Welding (EBW) and Laser Beam Welding (LBW) Continued

Weld joint preparation and fit-up are especially important for the EBW and LBW processes. In most cases, a square butt joint design is utilized. Although filler metal is not normally added to the weld pool, it can be added via bare wire. EBW generally needs to be performed in a vacuum environment without the use of shielding gas, which provides excellent protection against atmospheric contamination. LBW is normally performed with argon or helium shielding gases to prevent oxidation of the molten weld pool. Porosity can be a weldability issue due to the rapid solidification rates and deep weld pools that do not readily allow for dissolved gases to escape; this effect is exacerbated by high weld travel speeds. Oscillation or agitation of the weld pool by weaving the beam may provide the time necessary to help gases escape the weld pool and reduce porosity. Susceptibility to liquation cracking in the 'nail-head' region of the HAZ is promoted by the stress/strain state in this region. Slower weld travel speeds produce a shallower temperature gradient in the HAZ and are beneficial towards reducing liquation cracking susceptibility.

*For detailed information on EBW, please refer to: AWS C7.1M/C7.1, Recommended Practices for Electron Beam Welding and Allied Processes.*

*For detailed information on LBW, please refer to: AWS C7.2M, Recommended Practices for Laser Beam Welding, Cutting, and Allied Processes.*

# Brazing and Soldering

### Brazing

Brazing refers to a group of joining processes that produces the coalescence of materials by heating them to the brazing temperature in the presence of a brazing filler metal having a liquidus above 840°F (450°C) and below the solidus of the base metal, i.e. without melting of the base metal. The liquidus, or melting point, is the lowest temperature at which a metal or an alloy is completely liquid, and the solidus is the highest temperature at which a metal or an alloy is completely solid. Brazing is characterized by the distribution of a brazing filler metal between the closely fitted faying surfaces of the joint. With the application of heat, the brazing filler metal flows by capillary action, and is melted and re-solidified to form a metallurgical bond between the surfaces at the joint. Furnace brazing is the usual method of brazing Ni-/Co-base alloys, especially when high-temperature brazing filler metals are employed, and the information that follows will focus on furnace brazing. The keys to successful brazing of Ni-/Co-base alloys are:

- Thorough cleaning and preparation of base metal surfaces
- Proper filler metal selection for the intended application
- Proper fit-up and freedom from restraint during brazing
- Proper atmospheric protection during brazing
- Minimal thermal exposure to avoid secondary precipitation in the base metal

# Brazing and Soldering Continued

**Base Metal Surface Preparation**

All forms of contamination such as dust, paint, ink, chemical residues, oxides, and scale must be removed from part surfaces prior to brazing. Otherwise, the molten brazing material will have difficulty "wetting" and flowing along the surface of the base metal. Surfaces must be cleaned by solvent scrubbing or degreasing and then by mechanical cleaning or pickling. Tenacious surface oxides and scales may require grinding. Once cleaned, the parts should be assembled as soon as possible using clean gloves to prevent subsequent contamination. It is important to note that proper cleaning techniques should be used on the entire component assembly prior to brazing, not just the surfaces being brazed.

Some high-temperature alloys may benefit from the application of a thin nickel flashing layer before brazing, particularly those alloys containing higher aluminum and titanium contents. This layer is normally applied by electroplating; electroless nickel deposits using nickel-phosphorus alloys are not recommended. Flashing layer thicknesses of up to about 0.001 in (0.025 mm) maximum are normally employed, depending upon the specific base metal alloy and the specific joint geometry.

**Brazing Filler Metal Selection**

Proper selection of a brazing filler metal for the intended application depends upon a number of factors, including component design, base metal alloy(s), and service environment. Brazing filler metals are typically classified according to chemical composition. HASTELLOY® and HAYNES® alloys may be successfully brazed using a variety of nickel-, cobalt-, silver-, copper-, and gold-based filler metals; some of the possible brazing filler metals are listed in Table 4. The exact alloying content of the brazing filler metal determines the temperature range between the liquidus and solidus, i.e. the melting temperature range. The magnitude of the melting temperature range indicates the potential filling capability, and a brazing filler metal with a larger melting range is generally more capable of filling a larger joint clearance. If the brazing filler metal melts at a specific temperature, it is referred to as a eutectic filler metal. As a result, eutectic filler metals have less filling capability and require tight joint clearances. Examples of eutectic filler metals are the AWS A5.8 BAg-8, BAu-4, and BCu-1 classifications.

Filler metals are commonly applied as a powder mixed with a liquid binder. The brazing filler metal powder can also be mixed with a water-based gel suspension agent to produce a paste. Filler metals are also available as foil and tape. Every effort should be made to confine the brazing filler metal to the joint area as any spatter upon non-joint surfaces could severely degrade the environmental resistance at that location, particularly if it is exposed to service temperatures above the melting point of the brazing filler metal. Since most brazing filler metals do not possess the same level of corrosion resistance as Ni-base corrosion-resistant alloys, it is preferable that brazing is used for joining only when the brazed joint will be isolated from the corrosive environment.

# Brazing and Soldering Continued

**Brazing Filler Metal Selection Continued**

Nickel-based brazing filler metals can be utilized for high-temperature service applications up to 2000°F (1093°C). They generally have additions of boron, silicon, and manganese to depress the melting range and accommodate brazing at various temperatures. The boron-containing brazing filler metals are used for aerospace and other applications subject to high temperature and stress conditions. However, they are susceptible to the formation of brittle borides. These brazing filler metals may also contain chromium to provide for more oxidation-resistant joints.

Cobalt-based brazing filler metals are typically useful for achieving compatibility with Co-base alloys, and obtaining good high-temperature strength and oxidation resistance. Silver-based brazing filler metals have been successfully used for brazing Ni-base corrosion-resistant alloys intended for service applications below approximately 400ºF (204ºC). They are known for excellent flow characteristics and ease of usage. Filler metals containing low-temperature constituents, such as zinc and tin, are difficult for furnace brazing since they will evaporate prior to reaching the brazing temperature. Most furnace brazing with silver-based filler metals should be conducted in an argon atmosphere. It should be cautioned that most Ni-base alloys are subject to stress-corrosion cracking when exposed to molten silver-rich compositions, so it is imperative that the base metal be stress-free during brazing when utilizing silver-based filler metals. This liquid metal embrittlement form of cracking occurs catastrophically at the brazing temperature.

Copper-based brazing filler metals tend to alloy rapidly with Ni-base alloys, raising the liquidus and reducing fluidity. Therefore, they should be placed as close to the joint as possible, and the assembly should be heated rapidly to the brazing temperature. Copper-based brazing filler metals are only suggested for joining components to be used at service temperatures below 950°F (510°C). Copper-based brazing filler metals that contain significant amounts of phosphorus should be used with caution since they tend to form nickel phosphides at the bond line that promote brittle fracture. Copper-based filler metals should not be used for brazing Co-base alloys.

Gold-based brazing filler metals are mostly used when joining thin base metals due to their low interaction with the base metal. They are also useful when good joint ductility and/or resistance to oxidation and corrosion are primary concerns.

For more detailed information on different brazing filler metal classifications, please refer to: *AWS A5.8M/A5.8, Specification for Filler Metals for Brazing and Braze Welding, American Welding Society*. There are also numerous proprietary brazing filler metals and alloy compositions that are commercially available. It is suggested that brazing filler metal manufacturers be consulted when selecting a filler metal for a specific base metal alloy or application.

# Brazing and Soldering Continued

**Fit-Up and Fixturing**

Since most brazing alloys flow under the force of capillary action, proper fit-up of the parts being brazed is crucially important. To facilitate uniform flow of the molten brazing filler metal through the joint area, joint gap clearances on the order of 0.001 to 0.005 in (0.025 to 0.125 mm) must be maintained at the brazing temperature. Excessive external stresses or strains imposed on the brazed joint during brazing may cause cracking, especially when brazing fluxes are involved. If possible, components should be brazed in the annealed condition (i.e., not cold worked).

Making use of appropriate joint fixturing is also helpful. Fixtures used in furnace brazing must have good dimensional stability and generally low thermal mass to facilitate rapid cooling. Metallic fixtures are limited in their ability to maintain close tolerances through repeated thermal cycles, and are relatively high in thermal mass. Accordingly, graphite and ceramic fixtures are normally better suited for use in high-temperature furnace brazing applications. Graphite has been widely used in vacuum and inert gas furnace brazing, and provides excellent results. However, graphite should not be used for fixturing in hydrogen furnace brazing without a suitable protective coating, as it will react with the hydrogen and possibly produce carburization of the parts being brazed. Ceramics are also used, but typically for smaller fixtures.

# Brazing and Soldering Continued

## Protective Atmospheres and Fluxes

In addition to proper cleaning procedures prior to brazing, control of furnace environment and purity of the brazing atmosphere is vitally important to ensure proper flow characteristics of the brazing filler metal. Since most Ni-/Co-base alloys are designed to form tenacious oxide films, these same oxide films will cause problems during brazing if atmospheres are not rigorously controlled. Exclusion of oxygen, oxidizing gas species, and reducible oxide compounds from the furnace environment is required as oxygen derived from any source within the furnace can produce surface contamination in the joint area. Ni-based brazing filler metals, for instance, are commonly used in conjunction with vacuum, high purity argon, or hydrogen (reducing) furnace atmospheres. The interior of the furnace and fixtures should be kept clean and free of any type of reducible oxide deposits, and outside atmospheric leak rates should be kept as low as possible. A high atmospheric leak rate through a vacuum furnace could easily cause a thin oxide film to form on the base metal surfaces being brazed. The presence of a surface oxide film impedes the flow of the brazing filler metal, and often results in a poor brazed joint. Flux-based brazing operations can be carried out by using an induction coil heating source, or in a furnace with a reducing atmosphere.

Brazing fluxes are utilized to protect and assist in wetting of base metal surfaces. Fluxes are usually mixtures of fluorides and borates that melt below the melting temperature of the brazing filler metal. Standard brazing fluxes can be used with most Ni-/Co-base alloys. Specialized formulations may be necessary for use with certain brazing filler metals or for base metal alloys containing aluminum and titanium. There are many variables that influence the choice of the most appropriate flux, including base metal, filler metal, brazing time, and joint design. To be effective, a brazing flux must remain active throughout the brazing temperature range. Recommendations from a brazing flux supplier should be sought when considering the use of a specific flux for the first time. Flux removal after brazing is necessary, and particularly important on brazed components that will experience corrosive or high-temperature environments. Grinding or abrasive blasting may be required to remove any tenacious flux residue.

# Brazing and Soldering Continued

## Effect of Brazing Thermal Cycles

The thermal cycles associated with brazing can have deleterious effects upon the microstructure and properties of HAYNES® and HASTELLOY® alloys. Thermal cycle exposure during brazing includes both the time at the selected brazing temperature, and the time taken to heat and cool from elevated temperature. Care should be taken to ensure that the respective brazing thermal cycle does not produce deleterious precipitation of secondary phases in the component. Thus, thermal cycles associated with the brazing operation should be controlled to minimize exposure to temperatures in the approximate range of 1000 to 1800ºF (538 to 982ºC) where most Ni-/Co-base alloys tend to precipitate secondary phases. For corrosion-resistant alloys, such secondary precipitation could strongly influence their corrosion resistance in service. Normal cooling rates from the brazing temperature, particularly in vacuum furnace brazing, are usually too slow to prevent carbide precipitation in most Ni-/Co-base alloys. Cooling rates in a vacuum environment can be increased by backfilling the furnace with argon or helium. Where brazing is performed in the solution annealing temperature range of the base metal alloy, there is the possibility for both normal and abnormal grain growth, which could be deleterious to service performance.

Table 4: Some Possible Brazing Filler Metals for HASTELLOY® and HAYNES® Alloys

| Designation/Specification | | | Nominal Composition (wt.%) | Liquidus - Solidus | Brazing Temperature Range |
|---|---|---|---|---|---|
| **AWS A5.8** | **ISO 17672** | **AMS** | | | |
| BAg-1 | Ag 345 | 4769 | 45Ag-15Cu-16Zn-24Cd | 1125-1145°F (607-618°C) | 1145-1400°F (620-760°C) |
| BAg-2 | Ag 335 | 4768 | 35Ag-26Cu-21Zn-18Cd | 1125-1295°F (607-702°C) | 1295-1550°F (700-840°C) |
| BAg-3 | Ag 351 | 4771 | 50Ag-15.5Cu-15.5Zn-16Cd-3Ni | 1170-1270°F (632-688°C) | 1270-1500°F (690-815°C) |
| BAg-4 | Ag 440 | ---- | 40Ag-30Cu-28Zn-2Ni | 1240-1435°F (671-779°C) | 1435-1650°F (780-900°C) |
| BAg-8 | Ag 272 | ---- | 72Ag-28Cu | 1435°F (779°C) | 1435-1650°F (780-900°C) |
| | | | | | |
| BAu-4 | Au 827 | 4787 | Au-18Ni | 1740°F (949°C) | 1740-1840°F (950-1005°C) |
| BAu-5 | Au 300 | 4785 | Au-36Ni-34Pd | 2075-2130°F (1135-1166°C) | 2130-2250°F (1165-1230°C) |
| BAu-6 | Au 700 | 4786 | Au-22Ni-8Pd | 1845-1915°F (1007-1046°C) | 1915-2050°F (1045-1120°C) |
| | | | | | |
| BCu-1 | Cu 141 | ---- | Cu-0.075P-0.02Pb | 1981°F (1083°C) | 2000-2100°F (1095-1150°C) |
| | | | | | |
| BNi-1 | Ni 600 | 4775 | Ni-14Cr-3.1B-4.5Si-4.5Fe-0.75C | 1790-1900°F (977-1038°C) | 1950-2200°F (1065-1205°C) |
| BNi-1a | Ni 610 | 4776 | Ni-14Cr-3.1B-4.5Si-4.5Fe-0.06C | 1790-1970°F (977-1077°C) | 1970-2200°F (1080-1205°C) |
| BNi-2 | Ni 620 | 4777 | Ni-7Cr-3.1B-4.5Si-3Fe-0.06C | 1780-1830°F (971-999°C) | 1850-2150°F (1010-1180°C) |
| BNi-3 | Ni 630 | 4778 | Ni-3.1B-4.5Si-0.5Fe-0.06C | 1800-1900°F (982-1038°C) | 1850-2150°F (1010-1180°C) |
| BNi-4 | Ni 631 | 4779 | Ni-1.9B-3.5Si-1.5Fe-0.06C | 1800-1950°F (982-1066°C) | 1850-2150°F (1010-1180°C) |
| BNi-5 | Ni 650 | 4782 | Ni-19Cr-0.03B-10.1Si-0.06C | 1975-2075°F (1079-1135°C) | 2100-2200°F (1150-1205°C) |
| BNi-6 | Ni 700 | ---- | Ni-11P-0.06C | 1610°F (877°C) | 1700-2000°F (930-1095°C) |
| BNi-7 | Ni 710 | ---- | Ni-14Cr-0.02B-0.1Si-0.2Fe-0.06C-10P | 1630°F (888°C) | 1700-2000°F (930-1095°C) |
| | | | | | |
| BCo-1 | Co 1 | 4783 | Co-19Cr-17Ni-0.8B-8Si-1Fe-4W-0.4C | 2050-2100°F (1120-1149°C) | 2100-2250°F (1150-1230°C) |

# Brazing and Soldering Continued

## Soldering

Soldering refers to a group of joining processes that produces the coalescence of materials by heating them to the soldering temperature in the presence of a soldering filler metal having a liquidus below 840°F (450°C) and below the solidus of the base metal, i.e. without melting of the base metal. Ni/Co-base alloys can be successfully soldered, although alloys containing higher levels of chromium, aluminum, and titanium can be more difficult to solder. Many of the considerations for soldering are similar to those previously outlined for brazing of HASTELLOY® and HAYNES® alloys.

Common soldering filler metals are composed of mixtures of lead and tin. Most of the common types of filler metals can be used to solder Ni-/Co-base alloys. Soldering filler metals with a relatively high tin content provide the best wettability, such as the 60 wt. % tin-40% wt. % lead or 50 wt. % tin-50 wt. % lead compositions. If color matching is a priority, certain filler metals, such as the 95 wt. % tin-5 wt. % antimony composition, may be best. However, the soldered joint may eventually oxidize and become noticeable if there is exposure to elevated temperatures.

The soldering filler metal can be used to seal the joint, but should not be expected to provide a mechanically strong joint or carry the structural load. Mechanical strength needs to be provided for by another means of reinforcement, such as lock seaming, riveting, spot welding, or bolting. For precipitation-strengthened alloys, soldering should be performed after the alloy has gone through its age hardening heat treatment. The relatively low temperatures involved in soldering should not soften or weaken the precipitation-strengthened alloy. Any welding, brazing, or other heating treating operations should also take place before soldering. Ni-/Co-base alloys are susceptible to liquid metal embrittlement when in contact with lead and other metals with low melting points. While this will not occur at normal soldering temperatures, overheating of the soldered joint should be avoided.

Fluxes containing hydrochloric acid are typically required for soldering most Ni/Co-base alloys that contain chromium. Rosin-base fluxes are generally ineffective. Since most flux residues absorb moisture and can become highly corrosive, they should be thoroughly removed from the workpiece after soldering. Rinsing in water or aqueous alkaline solutions should be effective for removing most residues; however, in the presence of oil or grease, the material must be degreased before rinsing.

Joint designs that will be inaccessible for cleaning after soldering, such as long lap joints, should be coated with soldering filler metal prior to assembly. This is generally performed with the same filler metal alloy to be used for soldering. The workpieces may be immersed in a molten bath of the soldering filler metal or the surfaces may be coated with flux and heated to allow the soldering filler metal to coat the joint. Pre-coating may also be accomplished by tin plating.

Visual inspection is usually sufficient for evaluating the quality of a soldered joint. The soldered metal should be smooth and continuous; lumps or other visual discontinuities are indicative of insufficient heat. Holes are most likely caused by contamination or overheating, and can result in leaks. Soldered joints with leak-tight requirements should be pressure tested.