SPECIAL METALS

Joining

Table of Contents

Joining

Introduction

High-quality joints are readily produced in nickel alloys by conventional welding processes. However, some of the characteristics of nickel alloys necessitate the use of somewhat different techniques than those used for commonly encountered materials such as carbon and stainless steels. This bulletin endeavors to educate the reader in the processes and products used for joining the various high-performance alloy products manufactured by Special Metals and the basic information required to develop joining procedures.

Special Metals Corporation (SMC) manufactures companion welding products for the full range of its wrought alloys and for many other materials. The flux-covered electrodes, bare filler and flux-cored wires, weldstrip and fluxes are designed to provide strong, corrosion-resistant weld joints with the properties required to meet the rigors of the service for which the fabricated component is designed. When used with SMC alloys, they ensure single-source reliability in welded fabrications. The SMC line of welding products also includes high-quality consumables for welding iron castings and for joining dissimilar metals. Descriptions and properties of all the welding products manufactured by Special Metals Corporation and guidelines for welding product selection are found in the brochure, “Special Metals Welding Products Company: Welding Products Summary” and on the websites, **www.special metals.com** and **www.specialmetalswelding.com.**

The scope of “Special Metals: Joining” is generally limited to the joining of nickel alloys to themselves, other nickel alloys, or steels. While the NI-ROD® line of welding products are used for joining iron castings, specific information on their use and the development of procedures for joining cast iron are not specifically addressed here. For detailed information on welding iron castings with the nickel-base NI-ROD welding products, the reader is directed to “Special Metals Welding Products Company: NI-ROD Welding Products”.

The choice of welding process is dependent upon many factors. Base metal thickness, component design, joint design, position in which the joint is to be made, and the need for jigs or fixtures all must be considered for a fabrication project. Service conditions and corrosive environments to which the joint will be exposed and any special shop or field-construction conditions and capabilities which might be required are also important. Also, a welding procedure must specify appropriate welding products. The information contained in “Special Metals: Joining” should assist those tasked to develop procedures for joining materials with SMC welding products with identifying significant variables and determining optimum joining processes, products, process variables, and procedure details. To discuss specific applications and needs, the reader is encouraged to contact sales, marketing, or technical service representatives at any of the Special Metals Corporation offices listed on the back cover.

Unless specifically noted otherwise, all procedures described in this publication are intended for joining alloy products that are in the annealed condition.

Values reported in the publication were derived from extensive testing and experience and are typical of the subject discussed, but they are not suitable for specifications. Additional product information and publications are available on the Special Metals websites, **www.specialmetals.com** and **www.special-metalswelding.com.**

General Considerations

Most persons experienced in welding operations and design have had experience with joining carbon, alloy, and/or stainless steels. Thus, much of the information in "Special Metals: Joining" is presented as a comparison of the characteristics of nickel alloys and steels and the processes and procedures used to join them.

Welding procedures for nickel alloys are similar to those used for stainless steel. The thermal expansion characteristics of the alloys approximate those of carbon steel so essentially the same tendency for distortion can be expected during welding.

All weld beads should have slightly convex contours. Flat or concave beads such as those commonly encountered when joining stainless and carbon steels should be avoided.

Preheating nickel alloys prior to welding is not normally required. However, if the base metal is cold (35°F (2°C) or less), metal within about 12 in. (300 mm) of the weld location should be warmed to at least 10° above the ambient temperature to prevent the formation of condensate as moisture can cause weld porosity. Preheat of the steel component may be required when joining a nickel alloy to alloy or carbon steel. Preheat is often beneficial when joining iron castings.

The properties of similar composition weldments in nickel alloys are usually comparable to those of the base metal in the annealed condition. Chemical treatment (e.g., passivation) is not normally required to maintain or restore corrosion resistance of a welded nickel alloy component. Most solid solution nickel alloys are serviceable as welded. Precipitation-hardenable alloys welded with hardenable welding products must be heat treated to develop full strength. It may also be desirable to stress relieve or anneal heavily stressed welded structures to be exposed to environments which can induce stress corrosion cracking.

In most corrosive media, the resistance of the weld metal is similar to that of the base metal. Overmatching or non-matching weld metals may be required for some aggressive environments.

Safety

Like many industrial processes, there are potential dangers associated with welding. Exposure of skin to the high temperatures to which metals are heated and molten weld metal can cause very serious burns. Ultraviolet radiation generated by the welding arc, spatter from the transfer of molten weld metal, and chipped slag from SMA weldments cause serious eye damage. Welding fumes can be harmful especially if the welder is working in a confined area with limited circulation. Thus, welders must be cognizant of the dangers associated with their craft and exercise nec-

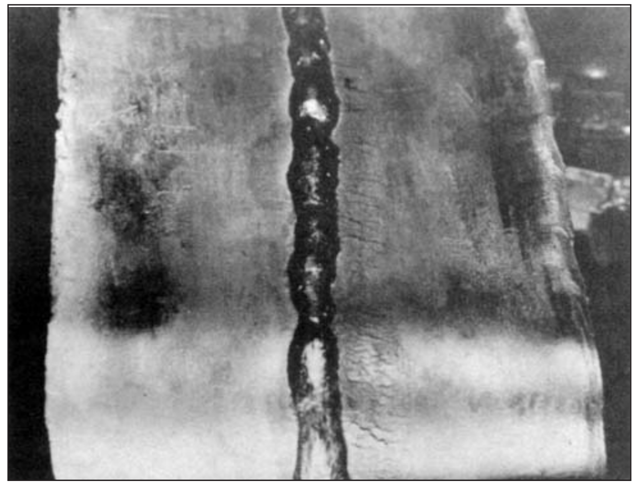


Figure 1. Sulfur embrittlement of root bend in Nickel 200 sheet. Left side of joint cleaned with solvent and clean cloth before welding; right side cleaned with solvent and dirty cloth exhibits cracking.

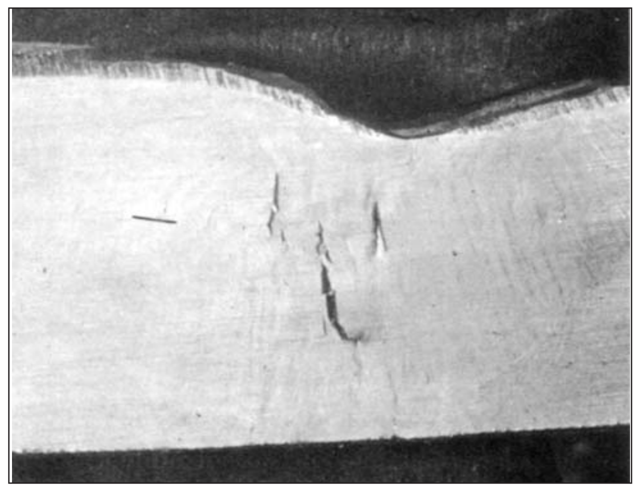


Figure 2. Typical effect of lead in MONEL alloy 400 welds.

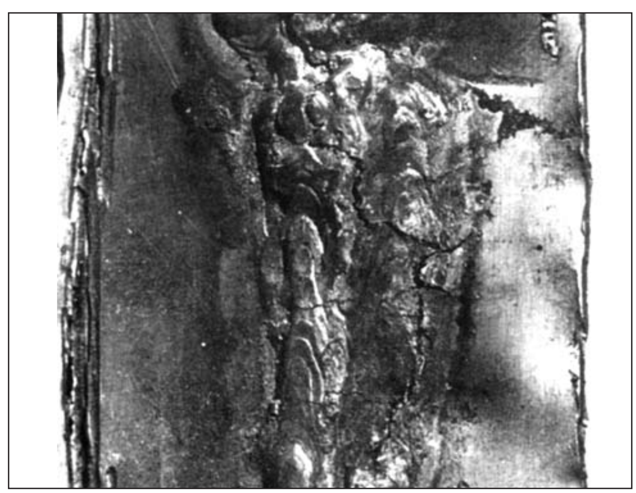


Figure 3. Combined effects of sulfur and lead contamination. Specimen removed from fatty-acid tank previously lined with lead and not properly cleaned before installation of MONEL alloy 400 lining.

essary precautions. Care must be taken and personal protection equipment must always be used.

The American Welding Society (AWS) has established guidelines and standards for welding safety and is an excellent source of information on the subject. AWS headquarters is at 550 LeJeune Road, Miami, FL 33126-5671. Their telephone number is (305) 443-9353. Those involved in welding operations are encouraged to visit their website, **www.aws.org.**

Surface Preparation

Cleanliness is the single most important requirement for successfully welding nickel and nickel-based alloys. At high temperatures, nickel and its alloys are susceptible to embrittlement by sulfur, phosphorus, lead, and some other low-melting point substances. Such substances are often present in materials used in normal manufacturing processes. Examples are grease, oil, paint, cutting fluids, marking crayons and inks, processing chemicals, machine lubricants, and temperature-indicating sticks, pellets, or lacquers. Since it is frequently impractical to avoid the use of these materials during processing and fabrication of the alloys, it is mandatory that the metal be thoroughly cleaned prior to any welding operation or other high-temperature exposure.

The depth of attack will vary with the embrittling element and its concentration, the alloy system involved, and the heating time and temperature. Damage under reducing conditions generally occurs more quickly and is more severe than that taking place in oxidizing environments. Figures 1, 2 and 3 show typical damage to welded joints that can result from inadequate cleaning.

For a welded joint in material that will not be subsequently reheated, a cleaned area extending 2 in. (50 mm) from the joint on each side will normally be sufficient. The cleaned area should include the edges of the work piece and the interiors of hollow or tubular shapes.

The cleaning method depends on the composition of the substance to be removed. Shop dirt, marking crayons and ink, and materials having an oil or grease base can be removed by vapor degreasing or swabbing with suitable solvents. Paint and other materials require the use of alkaline cleaners or special proprietary compounds. If alkaline cleaners that contain sodium sesquisilicate or sodium carbonate are used, they must be removed prior to welding. Wire brushing will not completely remove the residue; spraying or scrubbing with hot water is the best method. The manufacturer's safety precautions must be followed during the use of solvents and cleaners.

A process chemical such as a caustic that has been in contact with the material for an extended time may be embedded and require grinding, abrasive blasting, or swabbing with 10% (by volume) hydrochloric acid solution followed by a thorough water wash.

Defective welds can also be caused by the presence of surface oxide on the material to be joined. This is usually important in repair welding since new material is normally supplied annealed and pickled clean. The light oxide that results when clean material is exposed to normal atmospheric temperatures will not cause difficulty during welding unless the material is very thin, below about 0.010 in. (0.254 mm). However, the heavy oxide scale that forms during exposure to high temperatures (hot-working, heat-treating, or high-temperature service) must be removed.

Oxides must be removed because they normally melt at higher temperatures than the base metal. For example, Nickel 200 melts at 2615 – 2635°F (1435 – 1446°C), whereas nickel oxide melts at 3794°F (2090°C). During welding, the base metal may melt and the oxide remain solid, causing lack-of-fusion defects. The oxide should be removed from the joint area before welding by grinding, abrasive blasting, machining, or pickling.

Joint Design

Many different joint designs may be used when joining nickel alloy products. Examples of some of the joints commonly used are shown in Figure 4 (page 5). Approximate amounts of weld metal needed with these designs are given in Table 1 (page 4). The same basic designs are used for all welding processes. However, modification of the designs may be required for submerged arc and gas metal arc welding to allow adequate access to the joint. This is normally accomplished by either increasing the root gap or increasing the included angle.

The most economical joint is usually that which requires the minimum of preparation, requires the least amount of welding consumables and welding time while still resulting in the deposition of a satisfactory weldment.

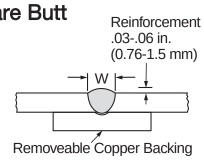
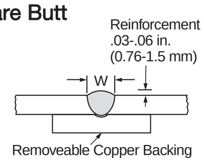
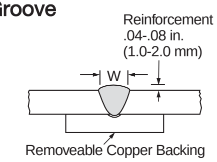
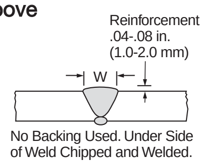
JOINT DESIGN CONSIDERATIONS

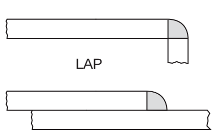
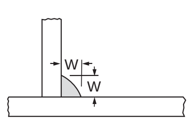
The first consideration in designing joints for nickel alloys is to provide proper accessibility. The joint opening must be sufficient to permit the torch, electrode, or filler metal to extend to the bottom of the joint.

In addition to the basic requirement of accessibility, the characteristics of nickel-alloy weld metal necessitate the use of joint designs that are different than those commonly used for ferrous materials. The most significant characteristic is the sluggish nature of the molten weld metal. Nickel alloy weld metal does not flow or spread as readily as steel weld metal. The operator must manipulate the weld puddle so as to direct the weld metal to the proper location in the joint. The joint must, therefore, be sufficiently open to provide space for movement of the torch or filler metal. The importance of producing slightly convex beads has been stated previously and cannot be overemphasized. The joint design chosen must allow for the first weld bead to be deposited with a convex surface. Small included angles and narrow roots induce concave beads and often lead to centerline cracking.

Another different characteristic is the lower weld penetration encountered when welding nickel alloys. This is caused by the physical properties of nickel alloys and must be considered in the weld design. The lower penetration makes necessary the use of smaller lands in the root of the joint. Increases in weld current will not significantly

Table 1 - Weld Metal Required for Various Joint Designs

Joint Type	Base Material Thickness		Width of Bead or Groove		Maximum Root Spacing		Approximate Amount of Metal Deposited				Approx. Weight of Electrode Required[a]	
	in	mm	in	mm	in	mm	in^3/ft	cm^3/m	lb/ft	kg/m	lb/ft	kg/m
Square Butt 	0.037	0.94	1/8	3.18	0	0	0.07	3.7	0.02	0.029	0.025	0.037
	0.050	1.27	5/32	3.97	0	0	0.13	7.0	0.04	0.060	0.05	0.079
	0.062	1.57	3/16	4.76	0	0	0.13	7.0	0.04	0.060	0.06	0.089
	0.093	2.36	3/16-1/4	4.76-6.35	1/32	0.792	0.18	9.7	0.06	0.089	0.08	0.119
	0.125	3.18	1/4	6.35	1/16	1.59	0.22	12	0.07	0.104	0.09	0.134
Square Butt 	1/8	3.18	1/4	6.35	1/32	0.792	0.35	19	0.11	0.164	0.15	0.223
	3/16	4.76	3/8	9.53	1/16	1.59	0.74	40	0.24	0.357	0.32	0.476
	1/4	6.35	7/16	11.1	3.32	2.38	0.97	52	0.31	0.461	0.42	0.625
V Groove 	3/16	4.76	0.35	8.9	1/8	3.18	0.72	39	0.227	0.338	0.31	0.461
	1/4	6.35	0.51	13.0	3/16	4.76	1.39	75	0.443	0.659	0.61	0.908
	5/16	7.94	0.61	15.0	3/16	4.76	1.84	99	0.582	0.866	0.80	1.19
	3/8	9.53	0.71	18.0	3/16	4.76	2.36	127	0.745	1.11	1.02	1.52
	1/2	12.7	0.91	23.0	3/16	4.76	3.68	198	1.16	1.73	1.59	2.37
	5/8	15.9	1.16	29.5	3/16	4.76	5.10	274	1.61	2.40	2.21	3.29
V Groove 	1/4	6.35	0.41	10.4	3/32	2.38	1.33	72	0.42	0.625	0.58	0.863
	5/16	7.94	0.51	13.0	3/32	2.38	1.71	92	0.54	0.803	0.74	1.10
	3/8	9.53	0.65	16.5	1/8	3.18	2.30	124	0.73	1.09	1.00	1.49
	1/2	12.7	0.85	21.6	1/8	3.18	3.85	207	1.21	1.80	1.67	2.49
	5/8	15.9	1.06	26.9	1/8	3.18	4.63	249	1.46	2.17	2.00	2.98

Joint Type	Base Material Thickness		Width of Groove (W)		Approximate Amount of Metal Deposited				Approx. Weight of Electrode Required[a]	
	in	mm	in	mm	in^3/ft	cm^3/m	lb/ft	kg/m	lb/ft	kg/m
Corner 	1/16	1.59	–	–	0.05	2.69	0.02	0.029	0.04	0.060
	3/32	2.38	–	–	0.09	4.84	0.03	0.045	0.05	0.074
	1/8	3.18	–	–	0.15	8.06	0.05	0.074	0.07	0.104
	3/16	4.76	–	–	0.33	17.7	0.10	0.149	0.14	0.208
	1/4	6.35	–	–	0.59	31.7	0.19	0.283	0.26	0.387
	5/16	7.94	–	–	0.92	49.5	0.29	0.432	0.40	0.595
	3/8	9.53	–	–	1.32	71.0	0.42	0.625	0.57	0.848
	1/2	12.7	–	–	2.35	126	0.74	1.10	1.02	1.52
Fillet 	–	–	1/8	3.18	0.09	4.84	0.03	0.045	0.04	0.060
	–	–	3/16	4.76	0.22	11.8	0.07	0.104	0.10	0.149
	–	–	1/4	6.35	0.38	20.4	0.12	0.179	0.16	0.238
	–	–	5/16	7.94	0.59	31.7	0.19	0.283	0.26	0.387
	–	–	3/8	9.53	0.84	45.2	0.27	0.402	0.37	0.551
	–	–	1/2	12.7	1.50	80.6	0.47	0.699	0.64	0.952
	–	–	5/8	15.9	2.34	126	0.74	1.10	1.01	1.50
	–	–	3/4	19.1	3.38	182	1.07	1.59	1.46	2.17
	–	–	1	25.4	6.00	323	1.90	2.83	2.60	3.87

(a) To find linear feet of weld per pound of electrode, take reciprocal of pounds per linear foot. If underside of first bead is chipped out, and welded, add 0.21 lb of metal deposited (equivalent to 0.29 lb of electrode).

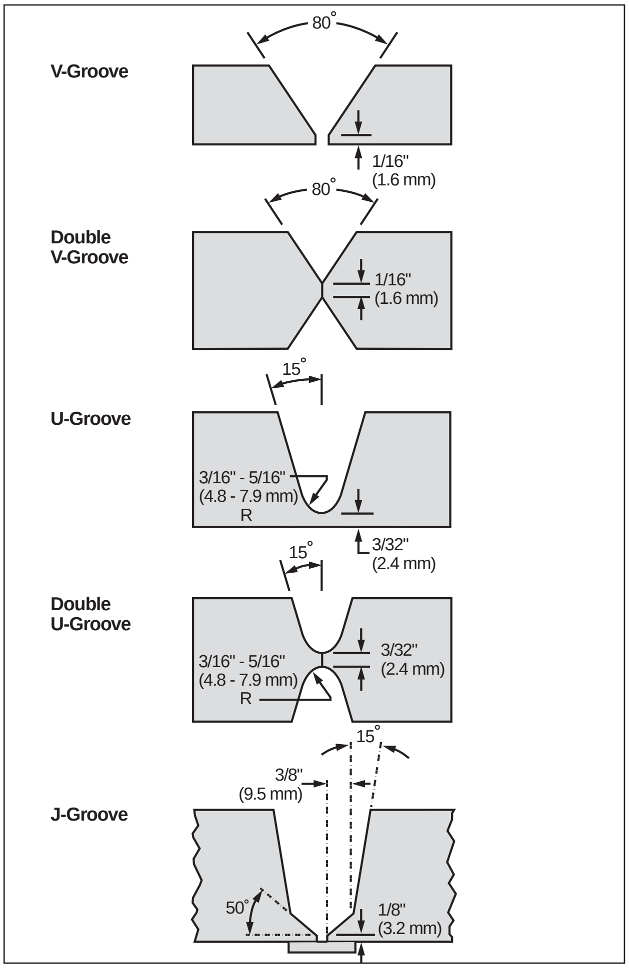


Figure 4. Typical joint designs.

increase the penetration of the arc. Excessive weld current when shielded metal arc welding can cause overheating of covered electrodes such that the flux spalls off and the deoxidizers in the flux are destroyed. The use of excessive heat with gas shielded processes results in weld spatter and overheating of the welding equipment. With proper joint selection and design, the welding product can be effectively used within the recommended current ranges and a sound, full penetration weld deposited.

GROOVE JOINTS

Beveling is not normally required for material 3/32 in. (2.36 mm) or less in thickness.

Material thicker than 3/32 in. (2.4 mm) should be beveled to form a V-. U-, or J- groove, or it should be welded from both sides. Otherwise, erratic penetration will result, leading to crevices and voids that will be potential areas of accelerated corrosion in the underside of the joint. It is generally that surface which must withstand corrosion. Notches resulting from erratic penetration can also act as mechanical stress risers and propagate to form cracks.

Deposition of the root pass by gas tungsten-arc welding results in the best underbead contour on joints that cannot be welded from both sides. A common example is the root pass of butt welds in pipes and tubes.

For material over 3/8 in. (9.5 mm) thick, a double U-or double V-joint design is preferred. The increased cost of joint preparation is usually offset by savings in welding products and welding time. The double joint design also results in less residual stress than will be developed with a single-groove design.

As shown in Figure 4, V-groove joints are normally beveled to an 80-degree included angle, and U-groove joints to a 15-degree side angle and a 3/16 in. to 5/16 in. (4.8-7.9 mm) bottom radius. Single beveled for T-joints between dissimilar thicknesses of material should have an angle of 45 degrees. The bottom radius of a J-groove in a T-joint should be 3/8 in. (9.5 mm) minimum.

CORNER AND LAP JOINTS

Corner and lap joints may be used where high service stresses will not be developed. It is especially important to avoid their use at high temperatures or under thermal or mechanical cycling conditions. Butt joints (in which stresses act axially) are preferred to corner and lap joints (in which stresses tend to be eccentric). When corner joints are used, a full-thickness weld must be made. In most cases, a fillet weld on the root side will be required.

JIGS AND FIXTURES

When fabricating thin sections (e.g., sheet and strip), jigs, clamps, and fixtures can reduce the cost of welding and promote consistent, high-quality welds. Proper jigging and clamping will facilitate welding by holding the material firmly in place, minimizing buckling, maintaining alignment, and when needed, providing compressive stress in the weld.

Steel and cast iron may be used for all parts of gas-welding fixtures. For arc welding processes, any portion of the fixture which might potentially come in direct contact with the arc should be made of copper.

Backup or chill bars should be provided with a groove of the proper contour to permit penetration of weld metal and to avoid the possibility of gas or flux being trapped at the bottom of the weld. The width of

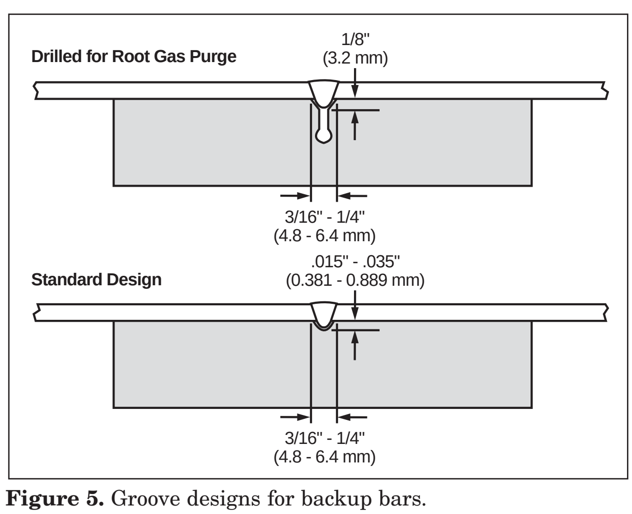


Figure 5. Groove designs for backup bars.

the groove and the spacing of hold-down bars should be adjusted to obtain a proper balance of restraint, heat transfer, and heat input.

Grooves in backup bars for arc welding should be shallow. They are usually 0.015 to 0.035 in. (0.381-0.889 mm) deep and 3/16 to 1/4 in. (4.8 to 6.4 mm) wide. The grooves are normally rounded; drilled grooves are generally used in conjunction with backup gas. Both types are shown in Figure 5.

Nickel alloy parts require about the same amount of clamping or restraint as mild steel. The hold-down bars should be located sufficiently close to the weld to maintain alignment and the proper degree of heat transfer. Except as described below, the hold-down pressure should be sufficient to maintain alignment of the parts.

The restraint provided by a properly constructed fixture can be utilized to particular advantage when the gas tungsten-arc process is used to weld thin material. If the groove is appropriately contoured and if a high level of hold-down force is used with the hold-down bars placed near the line of welding, the expansive force created in the exposed welding area will result in compressive force in the weld. The compression will have an upsetting effect on the hot weld metal, and welds having a slight top and bottom reinforcement can be produced without filler metal.

Shielded Metal-Arc Welding

In general, shielded metal-arc welding is used for material about 1/16 in. (1.6 mm) and over in thickness. Thinner material, however, can be welded by the process if appropriate jigs and fixtures are used.

ELECTRODES

For most welding applications, the composition of the deposit of the welding electrode resembles that of the base metal with which it is used. The weld metal composition is sometimes adjusted by the manufacturer to better satisfy weld requirements.

Prior to their use, flux covered electrodes should remain sealed in their moisture-proof containers in a dry storage area. All opened containers of electrodes should be stored in a cabinet equipped with a desiccant or heated to 10-15°F (6-8°C) above the highest expected ambient temperature. The flux coating is hygroscopic and will absorb excessive moisture if exposed to normal humidity.

Electrodes that have absorbed excessive moisture can be reclaimed by heating to drive off the absorbed moisture. They may be baked at 600°F (316°C) for 1 hr or 500° (260°C) for 2 hrs. Heating should be in a vented oven. The electrodes must be removed from the containers during baking.

CURRENT

Each electrode diameter has an optimum range of operating current. When operated within the prescribed current range, the electrodes have good arcing characteristics and burn with a minimum of spatter. When used outside that range, however, the arc becomes unstable and the products tend to overheat before the entire electrode is consumed. Excessive current can also lead to porosity, compromised properties and bend test failures because alloying elements and deoxidizers are destroyed (oxidized) before they can be melted into the weld puddle.

The current density required for a given joint is influenced by such variables as material thickness, welding position, type of backing, tightness of clamping, and joint design. Slight reductions in current (5 to 15A) are necessary for overhead welding. Vertical welding requires 10 to 20% less current than welding in the flat position. Actual operating current levels should be developed by trial welding on scrap material of the same thickness having the specified joint design. Recommended operating ranges for current are printed on the product label affixed to each electrode container.

WELDING PROCEDURE

Nickel and nickel-alloy weld metals do not flow and spread like steel weld metal. The operator must direct the flow of the puddle so the weld metal wets the joint sidewalls and the joint is filled appropriately. This is sometimes accomplished by weaving the electrode slightly. The amount of weave will depend on such factors as joint design, welding position, and type of electrodes. A straight drag (stringer) bead deposited without weaving may be used for single-bead work, or in close quarters on thick sections such as in the bottom of a deep groove. However, a weave bead is generally desirable. When the weave progression is used, it should not be wider than three times the electrode core diameter. Regardless of whether the welder uses weaving or the straight stringer technique, all weld beads should be deposited such that they exhibit the recommended slightly convex surface contour.

When used properly, SMC flux covered welding electrodes should exhibit a smooth arc and no pronounced spatter. When excessive spatter occurs, it is generally an indication that the arc is too long, amperage is too high, polarity is not reversed, or that the electrode has absorbed moisture. Excessive spatter can also be caused by magnetic arc below.

When the welder is ready to break the arc, it should first be shortened slightly and the travel speed increased to reduce the puddle size. This practice reduces the possibility of crater cracking and oxidation, eliminates the rolled leading edge of the crater, and prepares the way for the restrike.

The manner in which the restrike is made will significantly influence the soundness of the weld. A reverse or “T” restrike is recommended. The arc should be struck at the leading edge of the crater and carried back to the extreme rear of the crater at a normal drag-bead speed. The direction is then reversed, weaving started, and the weld continued. This restrike method has several advantages. It establishes the correct arc length away from the unwelded joint so any porosity resulting from the strike will not be introduced into the weld. The first drops of quenched or rapidly cooled weld metal are deposited where they will be remelted, thus, minimizing porosity.

Another commonly used restrike technique is to strike the arc on the existing bead In this manner, the weld metal likely to be porous can be readily removed by grinding. The restrike is made 1/2 to 1 in. (13 to 25 mm) behind the crater on top of the previous pass, and the restrike area is later ground level with the rest of the bead. This technique is often used for applications requiring that welds meet stringent radiographic inspection standards. It is also noteworthy that it is much easier for welders with lesser levels of skill to produce high quality welds than they can using the "T" restrike technique.

CLEANING

The slag on shielded metal-arc welds is quite brittle. It is best removed by first chipping with a hammer and chisel or a welder's chipping hammer. It should then be brushed clean with a stainless steel wire brush that has not been contaminated with other metals or deleterious compounds. Brushing may be manual or by using powered brushes.

Complete slag removal from all welds is recommended. When depositing a multiple pass weldment, it is essential that all slag be removed from a bead before the subsequent one is deposited. Removal is mandatory for applications requiring resistance to aqueous corrosion. Weld slag can act as a crevice and induce localized corrosion in aqueous environments. Also, the slag contains halides which can greatly increase the corrosivity of aqueous media. At high temperatures the slag can become molten and reduce the protective oxide layer on the surface of nickel-base alloys, thus accelerating corrosion (oxidation, sulfidation, carburization, etc.).

Gas Tungsten-Arc Welding

Gas tungsten-arc welding is widely used for nickel alloys. It is especially useful for joining thin sections and when flux residues are undesirable. The GTAW process is also the primary joining method for precipitation-hardenable alloys. GTAW is performed with direct current and straight polarity (DCEN).

GASES

Recommended shielding gases are helium, argon, or a mixture of the two. Additions of oxygen, carbon dioxide or nitrogen can cause porosity in the weld or erosion of the electrode and should be avoided. Small quantities (up to 5%) of hydrogen can be added to argon for single-pass welding. The hydrogen addition produces a hotter arc and more uniform bead surfaces. The use of hydrogen is normally limited to automatic welding such as the production of tubing from strip.

For welding thin material without the addition of filler metal, helium has shown the advantages over argon of reduced porosity and increased welding speed. Welding travel speeds can be increased as much as 40% over those achieved with argon. The arc voltage for a given arc length is about 40% greater with helium. Consequently, the heat input is greater. Since welding speed is a function of heat input, the hotter arc permits higher speeds.

The arc is more difficult to start and maintain in helium when the welding current is below about 60 amps. When low currents are required for joining small parts or thin material, either argon shielding gas should be used or a high-frequency current arc-starting system should be added.

Shielding gas flow rate is critical. Low rates will not protect the weld while high rates can cause turbulence and aspirate air, thus, destroying the gas shield. For argon, 10 to 20 cu.ft./hr (0.28 to 0.57 cu.m./hr) is typical for manual welding. Machine welding may require considerably higher rates. Helium should flow at 1-1/2 to 3 times the rates for argon to compensate for helium's greater buoyancy. The largest gas cup practical for the job should be used. The cup should be maintained at the minimum practical distance from the work.

Welding grades of argon and helium are produced to a very high degree of purity of the gases. Even a small amount of air will contaminate the protective gas shield and cause porosity in the weld. Shielding gas flow can be disrupted by drafts, wind, fans, and the cooling systems of electric equipment. Air movement from such sources should be avoided. A gas lens should be used on the torch to stabilize the gas column and provide more efficient shielding. Contamination can also result from air picked up in the gas stream as it leaves the torch or from inefficient distribution of the gas shield around the electrode and joint. The gas protection afforded an edge weld is not as good as that for a flat butt joint.

Proper maintenance of equipment is essential. If the electrode extension cap or the gas cup is loose, a Venturi effect can be created that will draw air into the gas stream. The O-rings in water-cooled equipment should be checked periodically. Even a small leakage of air or water into the shielding can provide sufficient contamination to cause porosity and weld oxidation and discoloration.

ELECTRODES

Tungsten electrodes or those alloyed with thorium may be used. A 2% thoria electrode will give good results for most welding applications. Although the initial cost of the alloyed electrodes is greater, their longer life, resulting from lower vaporization and cooler operation in conjunction with greater current-carrying capacity make them more economical in the long term. Regardless of the electrode used, it is important to avoid overheating them at excessive current levels.

The shape of the electrode tip can have a significant effect on the depth of penetration and the width of the bead, especially with welding current over 100 amps. The best arc stability and penetration control are achieved with a tapered tip. For most work, the vertex angle should be between 30 and 120 degrees with a flat land of about 0.015 in (0.38 mm) diameter on the tip end. Larger angles (blunter tips) can be used to produce narrower beads and deeper penetration.

The tungsten electrode will become contaminated if it contacts the weld metal or the base metal surface during the welding operation. If this occurs, the electrode should be cleaned and reshaped by grinding. Chemical compounds that chemically react with the electrode to point it are also available.

CURRENT

Direct current, straight polarity (electrode negative) is recommended for both manual and automated welding. A high-frequency circuit for assistance in starting the arc and a current-decay unit for slowly stopping the arc should also be used when GTA welding nickel base alloys. Contact starts and "pull away" arc stops are unacceptable techniques.

A high-frequency circuit eliminates the need to contact the work with the electrode to start the arc. Contact starting can damage the electrode tip and also result in tungsten inclusions in the weld metal. Another advantage of a high-frequency circuit is that the starting point can be chosen before the welding current starts, eliminating the possibility of arc marks on the base material.

Rough, porous, or fissured craters can result from an abrupt arc break. A current-decay unit gradually lowers the current before the arc is broken to reduce the puddle size and end the bead smoothly. Units with stepless control are preferred over those using step reduction.

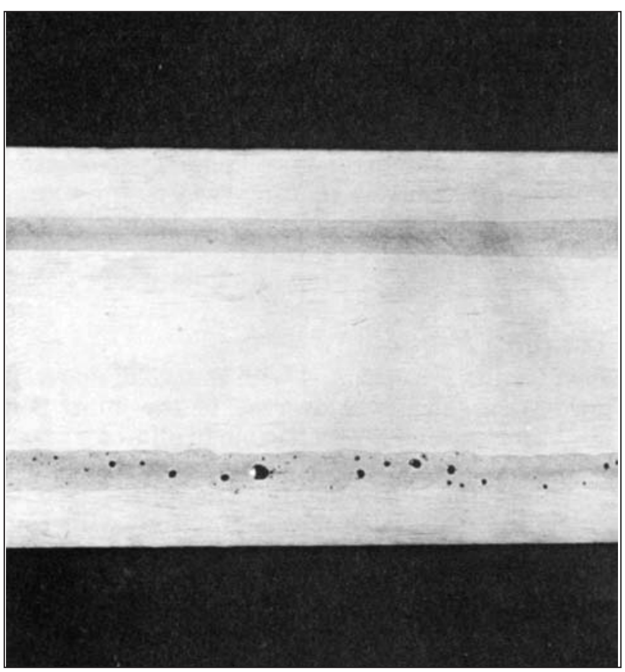


Figure 6. Effect of arc length on soundness of welds in MONEL alloy 400. Top weld made with correct 0.050 in. (1.27 mm), arc length. Bottom weld made excessive, 0.150 in. (3.81 mm), arc length.

FILLER METALS

Welding products for the gas-tungsten arc process are normally similar in chemical composition to the base metals with which they are used. Because of high arc currents and high puddle temperatures, the filler metals often contain small additions of alloying elements to deoxidize the weldment to prevent solidification and hot cracking.

WELDING PROCEDURE

The torch should be held at nearly 90 degrees to the work. A slight inclination in the forehand position is necessary for good visibility during manual welding. However, too acute an angle can cause aspiration of air into the shielding gas.

The electrode extension beyond the gas cup should be as short as possible. However, it must be appropriate for the particular joint design. For example, an extension of 3/16 in. (4.8 mm) maximum is used for butt joints in thin material, whereas 3/8 to to 1/2 in. (9.5 to 13 mm) may be required for some fillet welds.

To ensure a sound weld, the arc length must be maintained as short as possible. When no filler metal is added, the arc length should be 0.05 in. (1.27 mm) maximum and preferably 0.02 to 0.03 in (0.51 to 0.76 mm). Excessive arc length during autogenous GTAW can cause porosity as shown in Figure 6.

The arc length may be longer if filler metal is to be added but it should be the minimum length practical for the diameter of filler metal to be used.

The size of filler metal used must be appropriate for the thickness of the material being welded. The filler metal should be added carefully at the leading edge of the puddle to avoid contact with the electrode. The hot end of the filler metal should always be kept in the protective atmosphere. Agitation of the puddle should be avoided. The molten pool must be kept as quiet as possible to prevent burning out of the deoxidizing elements.

Filler metals contain elements which impart resistance to cracking and porosity to the weld metal. For optimum benefit from these elements, the completed weld should consist of at least 50% and preferably 75% filler metal.

Welding speed has a significant effect on the soundness of the weld, especially when no filler metal is added. For a given thickness of material, there is an optimum speed range for minimum porosity. Travel speeds outside that range can result in porosity.

Shielding of the weld root is usually required with gas-tungsten-arc welding. If a full penetration weld is made without root protection, the underside of the weld bead will likely be discolored (oxidized) and porous. Shielding can be provided by grooved backup bars or inert-gas backing.

Gas Metal-Arc Welding

Gas metal-arc welding is a popular process because of its high deposition rate and welder appeal. Most nickel alloys may be GMA welded using the spray,

Table 2 - Guideline Settings for Spray-Arc-Transfer Gas-Metal-Arc Welding[a]					
Filler Metal	Diameter (in)	Wire Feed (in/min)	Voltage (volts)	Current (amps)	Shielding Gas
MONEL Filler Metal 60	.035	475-520	26-32	175-260	Argon
	.045	250-300	26-32	225-300	
	.062	150-200	27-33	250-330	
MONEL Filler Metal 67	.035	475-575	26-32	200-300	Argon
	.045	250-320	26-32	225-325	
	.062	175-220	27-33	275-350	
Nickel Filler Metal 61	.035	425-520	26-32	200-300	Argon
	.045	275-320	26-32	250-325	
	.062	175-220	27-33	275-350	
INCONEL Filler Metal 62	.035	425-520	26-32	175-240	Argon or A/25-He
	.045	250-310	26-32	225-300	
	.062	175-220	27-33	250-330	
INCOLOY Filler Metal 65 INCONEL Filler Metal 82	.030	550-700	26-32	175-240	Argon or Ar/25-He
	.035	450-520	26-32	175-240	
	.045	250-310	26-32	225-300	
	.062	125-200	27-33	250-330	
INCONEL Filler Metal 52 INCONEL Filler Metal 92	.035	425-520	26-32	175-240	Argon or Ar/25-He
	.045	250-320	26-32	225-300	
	.062	125-200	27-33	250-330	
NILO Filler Metal CF36 NILO Filler Metal CF42	.045	300-400	29-33	200-270	Argon
	.062	175-250	29-33	250-330	
INCONEL Filler Metal C-276 INCONEL Filler Metal 617 INCONEL Filler Metal 622 INCONEL Filler Metal 625 INCONEL Filler Metal 686CPT	.030	550-700	26-32	175-240	Argon or Ar/25-He
	.035	450-600	26-32	180-245	
	.045	250-350	26-32	225-300	
	.062	125-225	27-33	250-345	

(a) Gas flow of 35 - 60 ft^3/h (CFH), Polarity Direct Current Electrode Positive (DCEP).

short-circuiting, and pulsing modes of transfer with excellent results. Welding in the globular transfer mode is not recommended as the erratic arc often results in inconsistent penetration and uneven bead contour.

Guidelines for selection of mode of transfer are much the same for nickel alloys as those for ferrous materials. Some power sources are capable of multiple mode use while others may only be used in a single mode. Power sources for welding nickel alloys in the short-circuiting mode of transfer must have good slope control. The current generation of power sources for GMAW in the pulsing transfer offer excellent solid state controls and very pleasing welding characteristics. Their arc wave control makes them particularly useful for out-of-position welding.

Short-circuiting transfer is normally used for joining thin sections of material (up to about 1/8-in (3.2-mm) thick). Short-circuiting transfer takes place at low heat input and gives good results in joining material such as thin sections that could be distorted by excessive heat. Short-circuiting transfer is normally limited to single pass welding. When used for multiple pass welds, it often results in lack of fusion and penetration defects.

GMAW in the spray transfer mode is a very effective means of welding heavy sections of material. Spray transfer takes place at high heat input which results in a stable arc and high deposition rates.

Table 3 - Guidelines for Pulsed-Arc-Transfer Gas-Metal-Arc Welding of Nickel Base Filler Metals										
Wire Diameter in (mm)	Wire Feed (in/min)	Gas (%)	Flow Rate (cFH)	Voltage (volts)	Average Current (amps)	Frequency (pps)	Peak Current (amps)	Start Current (amps)	Time @ Peak (ms)	Background Current (amps)
.035 (0.9)	300-500	75Ar/25 He or 65Ar/35 He	35-50	22-29	90-140	50-110	250-400	300	1.5-3.5	40-80
.045 (1.2)	250-450	75Ar/25 He or 65Ar/35 He	35-50	24-30	120-170	60-120	300-450	300	1.8-4.0	40-120

Spray transfer is generally limited to flat-position welding. GMAW in the spray transfer mode is a very severe process with respect to its effect on the metals being welded. Some alloys are not capable of being welded by this process due to problems with solidification and hot cracking. Settings for spray transfer are found in Table 2.

When GMA welding in the pulsing mode of transfer, the current actually pulses generally along a square wave pattern. At the peak current transfer is in the spray mode. The background current is much lower so transfer is in the globular range. The current normally pulses 60 or 120 cycles per second. However, some machines allow the operator to adjust the pulse frequency. The result of the high pulse rates is that the arc action resembles spray transfer but the puddle is cold enough so the process can be used out-of-position. The high peak current eliminates the erratic arc and limited penetration problems associated with conventional globular transfer. Settings for pulsing transfer are found in Table 3.

SHIELDING GASES

The protective atmosphere for gas metal-arc welding is dependent upon the metals being joined and the welding procedure. The optimum shielding gas will vary with the type of metal transfer used. Argon or argon mixed with helium are used for most nickel alloy GMA welding applications. Carbon dioxide (CO_2) or a mixture of argon and CO_2 are often used when welding iron castings with NI-ROD filler metals.

Welding torches that are rated for use with inert gases (argon and helium) should be selected for use with nickel alloy filler metals. They are shielded with inert gas with an air-cooled torch. Occasionally wire feed problems are reported. These problems are usually traced to torch overheating. This is because air-cooled torches are normally rated for use with CO_2 shielding gas. CO_2 provides significantly more cooling than inert gases. When inert gas shielding is used, the torch rating is reduced by approximately half of the standard duty cycle rating with CO_2.

GASES FOR SHORT-CIRCUITING TRANSFER

Argon with an addition of helium usually gives the best results with short-circuiting transfer. Argon alone provides a pronounced pinch effect, but it may also produce excessively convex beads which leads to cold lapping (lack of fusion). The wetting action provided by helium results in flatter beads, and the tendency for cold lapping is reduced.

Gas flow rates for short-circuiting transfer range from 25 to 45 ft^3/h (0.71 to 1.3 m^3/h). As the percentage of helium is increased, the flow rate must be increased to maintain adequate protection.

The size of the gas cup can have important effects on welding conditions. For example, with 50:50 argon-helium at a flow rate of 40 ft^3/h (1.1 m^3/h), a 3/8-in (9.5-mm) diameter cup limits wire feed to 250 in/min (6.4 m/min) and current to about 120 A. With a 5/8-in (16-mm) diameter cup, however, wire feed can be increased to over 400 in/min (10.2 m/min) and current 160-180 A without oxidation of the weld bead.

GASES FOR PULSING TRANSFER

Argon with an addition of helium is recommended as the atmosphere for pulsing-arc transfer. Good results have been obtained with helium contents of 15-20%. The flow rate should be at least 25 ft^3/min (0.7 m^3/h) and 45 ft^3/min (1.3 m^3/h) maximum. Excessive rates can interfere with the arc. For some specialized applications, pure helium and higher helium mixes have been used with the pulsed-GMAW process. As the percentage of helium increases, there is greater tendency for arc instability. However, for this low heat input process, helium greatly enhances wetting.

GASES FOR SPRAY AND GLOBULAR TRANSFER

With spray and globular transfer, good results have been obtained with pure argon. The addition of oxygen or carbon dioxide to argon will result in heavily oxidized and irregular bead surfaces. Oxygen and carbon dioxide additions can cause severe porosity in pure nickel and MONEL alloy welds. Pure helium has also been used. However, its use results in an unsteady arc and excessive spatter.

Gas flow rates range from 25 to 100 ft^3/h (0.71 to 2.83 m^3/h), depending on joint design, welding position, gas-cup size, and whether a trailing shield is used.

FILLER METALS

The proper wire diameter depends on the type of metal transfer and the thickness of the base material. In general, 0.062 in (1.1 mm) diameter wire is used with spray transfer, 0.035 in (0.9 mm) and 0.045 in (1.1 mm) with pulsing-arc transfer, and 0.035 in. (0.9 mm) with short-circuiting transfer.

CURRENT

Reverse-polarity direct current (DCEP) should be used for gas metal-arc welding with all methods of metal transfer.

Spray transfer requires current in excess of the transition point, the value at which transfer changes from the globular to the spray mode. The transition point is affected by variables such as wire diameter, wire composition, and power source characteristics.

Constant-voltage power sources are recommended for all gas metal-arc welding. For short-circuiting transfer, the equipment must have separate slope and secondary inductance controls. Power sources for welding in the pulsing transfer vary greatly in design, operation, and control systems. It is suggested that the user contact the manufacturer for specific operating instructions.

WELDING PROCEDURE

Best results are obtained with the welding gun positioned at about 90 degrees to the joint. Some slight inclination is permissible to allow for visibility for manual welding. However, excessive displacement can result in aspiration of the surrounding atmosphere into the shielding gas. Such contamination will cause porous or heavily oxidized welds.

Optimum welding conditions vary with method of metal transfer. The arc should be maintained at a length that will not cause spatter. Too short an arc will cause spatter, but an excessively long arc is difficult to control. The wire feed should be adjusted in combination with the current to give the proper arc length.

Lack of fusion can occur with the short-circuiting method if proper manipulation is not used. The gun should be advanced at a rate that will keep the arc in contact with the base metal and not the puddle. In multiple pass welding, highly convex beads can increase the tendency toward cold lapping. With pulsing transfer, manipulation is similar to that used for shielded metal-arc welding. A slight pause at the limit of the weaves is required to avoid undercut.

The filler wire and guide tube must be kept clean. Dust or dirt carried into the guide tube can cause erratic feed and wire jams ("bird nests"). The tube must be blown out periodically, and the spool of wire must be covered when not in use to avoid dirt buildup.

Flux-Cored Arc Welding (FCAW)

The flux-cored arc welding (FCAW) process is becoming more widely accepted for nickel alloys. The feature that best distinguishes this process from other semi-automatic arc welding processes is the flux in the core of the filler metal. The process can be either self-shielded or gas-shielded depending on the composition of the flux. The type of flux also determines whether or not the process can be used in the down-hand position or out of position. The flux also provides for better protection of the weld surface against oxidation, and provides uniform and superior wetting characteristics which may, at times, be marginal for a bare wire that is shielded only by inert gases. This assists in producing a slightly convex bead shape or profile.

WELDING EQUIPMENT

The equipment for welding with flux-cored wire is usually the same as that used for GMAW or SAW. Direct-current power sources with constant potential and reverse polarity generally give the best results. Wire feed rolls should be knurled and have grooves of either "U" or "V" shape. Smooth rolls can slip or flatten the wire. The wire must feed evenly through the gun. Four-roll feeders generally feed wire more reliably than those with two rolls. Contact tips should be the same diameter as the wire used.

GAS

Most FCAW wires are used with additional gas coverage. A wide range of gases are used, including argon, carbon dioxide, or a combination of the two. The shielding gas protects the arc and molten metal from the oxygen and nitrogen in air. The slag ingredients shape the weld bead, stabilize the arc, deoxidize the molten weld puddle, and form the protective slag covering. When additional shielding gas is used, a gas flow rate of 25 to 50 ft^3/h (.7 to 1.4 m^3/h) is recommended. Like other welding processes, the FCAW process generates fumes. Smoke extracting equipment or ventilation systems improve operator comfort and are essential for operator safety.

Self-shielding FCAW electrodes contain flux ingredients which vaporize and displace the air protecting the weld from gas contaminants. The self-shielding process lends itself to use in field welding applications. Generally, longer electrode extensions are used with self-shielding electrodes, while shorter electrode extensions are used with additional shielding gases.

FLUX

The flux ingredients have a dramatic effect on the welding operability of the product. Fluxes can be designed for down-hand or out of position welding. For down-hand or flat welding, the nature of the molten flux allows for ease of arc control, superior flow of weld metal, and penetration.

All position FCAW products utilize flux systems from which the molten slag freezes more quickly, thus, holding the weld metal in place. They generally form a smaller puddle. Even though, in most cases, the product will perform satisfactory in the down-hand position, the operability characteristics are optimum when used out-of-position. FCAW products specifically designed for flat position welding will give better results.

The fused flux should be removed from the deposited weld bead before proceeding with the next bead. Welds should be completely free of all slag

Table 4 -Recommended Welding Parameters for Flux-Cored Wire

Wire diameter in (mm)	Wire feed speed in/min (m/min)	Welding current (DCRP) amps	Welding voltage volts	Electrode extension (stick out) in (mm)
0.093 (2.4)	100-200 (2.5-5)	250-350	28-33	0.75-1 (19-25)
0.078 (2.0)	150-250 (3.75-6.3)	225-325	28-32	5/8-7/8(16-22)
0.062 (1.6)	200-300 (5-7.5)	200-300	27-32	1/2-3/4 (12.5-19)
0.045 (1.1)	250-350 (6.3-9)	130-180	26-30	3/8-5/8 (9.5-16)
0.045 (1.1)*	275-350 (7-9)	150-210	26-31	0.5-1 (12.5-25)

Note: Above referenced parameters are for INCO-CORED 82 DH & 82 AP, NI-ROD FC55, INCO-CORED 625 DH & 625 AP, FCAW consumables where "DH" denotes (1G) or Down Hand Position and "AP" denotes (1G through 6G) or all positions.

*INCO-CORED 82 AP and 625 AP only.

before entering service for the same reasons discussed under SMAW. Prior to use, the wire should be stored so it does not absorb moisture. Wire which is not being used should be stored in a cabinet equipped with a desiccant or heated to 10°-15°F (6°-8°C) above the highest expected ambient temperature. Flux-cored wires which have absorbed moisture may be re-baked at 400°F (204°C) for 6 hours.

WELDING PARAMETERS

The current setting can significantly affect the welding deposition rate and finished weld characteristics. The average welding current (direct current, reverse polarity) for 0.045 in. (1.1 mm) diameter wire is approximately 170 amps. An increase in welding current will increase penetration and dilution, and a decrease in welding current may improve out-of-position welding operability and lower dilution. Excessive current can cause a lack of slag coverage and excessive spatter, and increase cracking susceptibility.

Arc length increases with increasing voltage. High voltage levels increase the possibility of contamination from the atmosphere and, thus, the likelihood of porosity. Bead width and weld spatter also will increase with higher voltage levels. Since a short arc length should be maintained with all nickel alloys, the average welding voltage should be approximately 28 volts.

The amount of electrode extension ("stickout") also affects spatter and penetration. With longer extension, more of the available power is used to heat the wire, leaving less power to penetrate the workpiece. In addition, the overheating of the wire could cause excessive spatter. Shorter extensions may be necessary for better penetration and reducing spatter, but should generally be 3/8 - 5/8 in. (9.5 - 16.0 mm). After electrode extension is established for a particular application, it should be closely maintained for consistent results.

Welding travel speed has a major effect on heat input, penetration and dilution. At a given current level, faster travel speeds reduce heat input but increase penetration and dilution. Slower travel speeds increase the amount of weld metal deposited in a given length of bead, providing a molten metal "cushion" which decreases penetration, dilution and undercutting tendencies. Flux-cored wires may be deposited with a slight "drag" or a "push", but generally perform better with the torch angle perpendicular to the work. Stringer or weave techniques can be employed depending upon the application and joint design.

WELDING PROCEDURE

High quality, crack-resistant welds are readily attainable with proper welding procedure. In general, even though the nature of the flux allows for some cleaning of surface impurities and oxides, joint preparation and base metal cleanliness are just as important as when welding with solid nickel alloy wires. The condition of the base metal greatly affects the quality of the welded joints. As with all nickel alloys, all surfaces to be welded should be relatively free from oxides (especially scale from base metal heat treatments) and impurities. A light sanding or grinding is recommended, followed by a solvent wipe.

Best results are obtained with the welding gun positioned at about 90 degrees to the joint. Excessive inclination can result in aspiration of air into the shielding gas and cause porous or oxidized welds. Slag entrapment is always a possibility with any welding process involving a flux. Proper joint design and bead placement is essential to ensure good results. For multiple pass welds, beads should be deposited so as to provide reasonable access to the next bead to be deposited.

Submerged-Arc Welding

The submerged-arc process can be used to advantage in many applications, especially for welds in thick sections. For example, compared with automatic gas metal-arc welding, submerged-arc welding provides 35-50% higher deposition rates, thicker beads, a more stable arc, and smoother as-welded surfaces. The process is also readily applicable to overlay applications. Submerged-arc welding is usually done with automated equipment. Because the low penetration and viscous molten puddle of nickel alloys require precise electrode positioning, manual (hand held) submerged-arc welding is not recommended.

FLUX

Use of the proper flux is essential to successful submerged-arc welding. In addition to protecting the molten weld metal from atmosphere contamination, the fluxes provide arc stability and contribute important metallic additions to the weld deposit.

The flux burden should be only sufficient to prevent arc breakthrough. Excessive amounts of flux can cause defects, such as "pock" marks, craters, and embedded flux. Conventional submerged-arc welding equipment may require modification to be usable with SMC's submerged-arc welding fluxes. The flux delivery nozzle should be removed or adjusted such that the flux is delivered in front of the torch about 1-2 in. to a depth of about 3/4-7/8 in. deep. Feeding the flux directly onto the arc can result in excessive flux burden and the problems previously described.

Fused flux ("slag") is readily removed from most joints and is self-lifting on exposed weld beads. The slag is inert and should be discarded. Unfused flux can be recovered by clean vacuum systems and reused. To maintain optimum particle size, reclaimed flux should be mixed with an equal amount of new (unused) flux.

Submerged-arc fluxes are somewhat hygroscopic and must be protected from moisture. The fluxes should be stored in a dry area, and open containers of flux should be resealed immediately after use. Flux that has absorbed moisture can be reclaimed by baking at 600°F (315° to 480°C) for 2 hrs. Fused fluxes

Table 5 - Typical Submerged Arc Welding Parameters							
Flux Type	Filler Metal	Wire Diameter in (mm)	Polarity	Current (Amps)	Voltage (V)	Travel Speed in/min (mm/min)	Electrode Extension in (mm)
4	INCONEL 82	0.062 (1.6)	DCEP	250	30-33	8-11 (200-280)	7/8-1 (22-25)
		0.093 (2.4)	DCEP	250-300	30-33	8-11 (200-280)	7/8-1 (22-25)
5	MONEL 60	0.062 (1.6)	DCEP	260-280	30-33	8-11 (200-280)	7/8-1 (22-25)
	NI-ROD FC 55	0.093 (2.4)	DCEP	300-350	28-30	8-12 (200-300)	3/4 (20)
6	Nickel 61	0.062 (1.6)	DCEP	250	28-30	10-12 (250-300)	7/8-1 (22-25)
	NI-ROD 44	0.062 (1.6)	DCEP	250	32	10 (254)	1 (25)
	NI-ROD 99	0.062 (1.6)	DCEP	250	28-30	8-12 (200-300)	3/4 (20)
	CF 36	0.045 (1.1)	DCEP	230-260	31-34	8-12 (203-300)	1/2-3/4 (13-19)
	CF 42	0.045 (1.1)	DCEP	230-260	31-34	8-12 (203-300)	1/2-3/4 (13-19)
7	INCONEL 625	0.062 (1.6)	DCEP	250-260	32-33	8-9 (200-230)	1.0 (25)
		0.093 (2.4)	DCEP	300-320	32-33	8-9 (200-230)	1.0 (25)
8	MONEL 67	0.062 (1.6)	DCEP	280-300	31-33	7-9 (178-230)	7/8-1 (22-25)
		0.093 (2.4)	DCEP	300-400	34-37	8-10 (200-250)	7/8-1 (22-25)
NT 100	Nickel 61	0.062 (1.6)	DCEP	250	28-30	10-12 (250-300)	7/8-1 (22-25)
	NI-ROD 44	0.062 (1.6)	DCEP	250	32	10 (254)	1 (25)
	NI-ROD 99	0.062 (1.6)	DCEP	250	28-30	10 (254)	1 (25)
	CF 36	0.045 (1.1)	DCEP	230-260	31-34	8-12 (203-300)	1/2-3/4 (13-19)
	CF 42	0.045 (1.1)	DCEP	230-260	31-34	8-12 (203-300)	1/2-3/4 (13-19)
NT 120	INCONEL C-276	0.062 (1.6)	DCEP	260	31-32	8-10 (200-254)	7/8 (22)
	INCO-WELD 686CPT	0.062 (1.6)	DCEP	260	31-32	10 (254)	7/8 (22)
	INCONEL 622	0.062 (1.6)	DCEP	260	31-32	10 (254)	7/8 (22)

are less prone to absorb moisture compared to agglomerated SAW fluxes.

FILLER METAL

Filler metals for submerged-arc welding are the same as those used for gas metal-arc welding. Wire diameters in the range of 0.045 to 0.093 in (1.1 to 2.4 mm) are used. The 0.062 in (1.6 mm) diameter is generally preferred. Small-diameter wire is useful for welding this material, and the 0.093 in (2.4 mm) diameter wire is used for heavy sections.

CURRENT

Direct current with either straight (DCEN) or reverse polarity (DCEP) is used. Reverse polarity is preferred for butt welds because it produces flatter beads with deeper penetration at low arc voltage (30-33 V). Straight polarity is preferred for overlaying because it gives a slightly higher deposition rate and less penetration. Straight polarity requires a deeper flux burden which results in increased flux consumption. Straight polarity is best used with an oscillating technique for overlaying. Depositing stringer beads with straight polarity is not recommended due to poor wetting and "ropy" bead shape and the resulting lack of fusion defects.

WELDING PROCEDURE

Recommended joint designs for submerged-arc butt welding are shown in Figure 4 (page 5). Typical con-

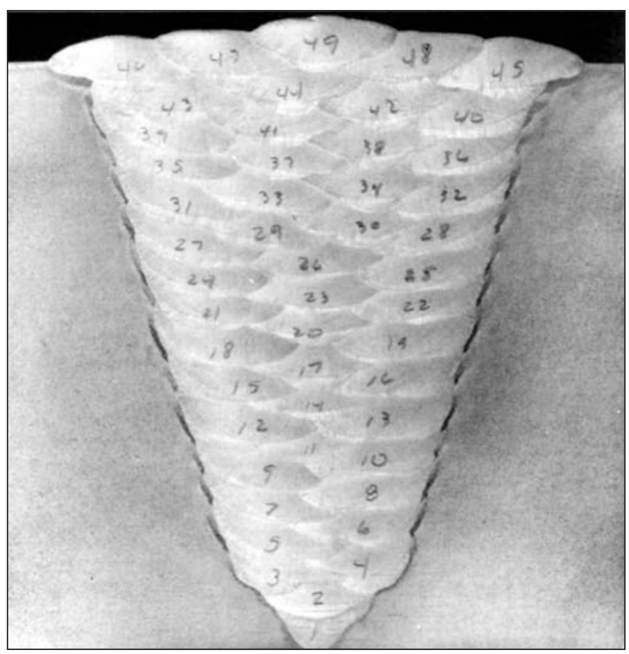


Figure 7. INCONEL alloy 600 joint 3-in (76-mm) thick completed with 0.062-in. (1.6-mm) diameter INCONEL Filler Metal 82 and INCOFLUX 4 Submerged Arc Flux (numerals indicate sequence of bead placement).

Table 6 - Typical Chemical Composition, % of All Weld Metal Samples from Groove Welds.

Flux Type	Filler Metal	Base Material	Ni	C	Mn	Fe	S	Si	Cu	Cr	Ti	Nb	Mo	W
4	INCONEL 82	INCONEL 600	Bal	0.07	3.21	1.75	0.006	0.40	–	19.25	0.17	3.38	–	–
5	MONEL 60	MONEL 400	Bal	0.06	5.0	3.5	0.013	0.90	26.0	–	0.48	–	–	–
	NI-ROD FC 55	Ductile Iron	50	1.0	4.2	44	–	0.60	–	–	–	–	–	–
6	Nickel 61	Nickel 200	89	0.07	0.4	8.5	0.004	0.65	–	–	1.7	–	–	–
&	NI-ROD 44	Ductile Fe	Bal	0.7	10	60	–	–	–	–	–	–	–	–
NT100	NI-ROD 99	Ductile Fe	83.5	0.01	0.26	14.9	0.005	0.40	–	0.01	0.03	–	0.01	–
	CF 36	NILO 36	36.0	0.2	1.5	60.8	–	–	–	–	–	1.5	–	–
	CF 42	NILO 42	42	0.2	1.5	Bal	–	–	–	–	–	1.5	–	–
7	INCONEL 625	INCONEL 625	60.15	0.02	0.74	0.75	0.001	0.29	–	21.59	0.13	3.29	8.60	–
8	MONEL 67	Cu-Ni	35	0.01	0.70	0.5	0.006	0.50	63	–	0.25	–	–	–
NT120	INCONEL C-276	INCONEL C-276	59	0.002	0.93	5.5	0.001	0.2	0.016	16	0.03	0.35	15	3.5
	INCO-WELD 686CPT	INCONEL 686	58	0.01	0.8	1.1	0.004	0.32	0.007	20	0.03	0.075	16.2	4.0
	INCONEL 622	INCONEL 622	59	0.005	0.75	0.75	0.001	0.25	0.008	20.4	0.03	0.27	14	3.3

Typical Mechanical Properties.

Flux Type	Filler Metal	Tensile Strength ksi (MPa)	Yield Strength 0.2% Offset, ksi (MPa)	Elongation %	Reduction of Area, %	Impact Strength CVN @ - 196° C ft-lb (J)	Impact Strength Room Temp. ft-lb (J)
4	INCONEL 82	97 (669)	55 (379)	35	–	70-80	–
5	MONEL 60	75 (517)	40 (276)	40	–	–	–
	NI-ROD FC 55	65-80 (450-550)	45-55 (300-380)	15-20	–	–	–
6	Nickel 61	68 (469)	38 (262)	32	38	–	–
	NI-ROD 44	92 (635)	58 (400)	26	42	–	–
	NI-ROD 99	65 (450)	45 (310)	10-15	20	–	–
	CF 36	71.5 (493)	49.8 (343)	29	–	–	72 (98)
	CF 42	–	–	–	–	–	–
7	INCONEL 625	107.7 (743)	63.8 (440)	40	39	73 (99)*	52.5 (71)*
8	MONEL 67	–	–	–	–	–	–
NT100	Nickel 61	68 (469)	38 (262)	32	38	–	–
	NI-ROD 44	92 (635)	58 (400)	26	42	–	–
	NI-ROD 99	65 (450)	45 (310)	10-15	20	–	–
	CF 36	71.5 (493)	49.8 (343)	29	–	–	72 (98)
	CF 42	71.5 (493)	49.8 (343)	29	–	–	–
NT120	INCONEL C-276	105.8 (729)	62 (427)	49.8	35.6	55 (75)	–
	INCO-WELD 686CPT	106.4 (734)	63.3 (436)	45.1	50	–	–
	INCONEL 622	99.8 (688)	56.2 (387)	51.2	43.5	–	–

* Impact values from 625 and INCOFLUX 7 on 9% Nickel Steel.

ditions for submerged-arc welding with various flux/filler-metal combinations are given in Table 5. Typical chemical compositions and mechanical properties of weld metal from submerged-arc groove welds are shown in Table 6.

Slag entrapment is a possibility during any welding operation involving flux. The problem can be controlled by the use of an appropriate joint design and proper bead placement. In a multipass welding, beads should be placed so as to provide an open or reasonably wide root for the next bead. Figure 7 illustrates bead placement in a 3-in (76-mm) thick groove weld in INCONEL alloy 600.

Bead contour is important. Slightly convex beads

Table 7 - Chemical Composition, %, at Various Levels[a] of a 3-in (76-mm) Thick Joint in INCONEL alloy 600 Welded with INCONEL Filler Metal 82 and INCOFLUX 4 Submerged Arc Flux

Element	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
Nickel	73.6	73.5	73.6	73.5	73.7	73.6
Chromium	18.1	18.0	18.1	18.0	18.1	18.0
Niobium	3.61	3.71	3.59	3.67	3.50	3.60
Iron	0.86	0.87	0.88	0.88	0.87	1.00
Silicon	0.44	0.44	0.43	0.43	0.44	0.44
Carbon	0.05	0.05	0.05	0.05	0.05	0.05
Sulfur	0.003	0.003	0.003	0.003	0.003	0.003

(a) Approximately 1/2 in (13 mm) intervals beginning at top surface.

are essential. Flat or concave beads are prone to centerline cracking. Bead contour is most effectively controlled by voltage and travel speed. Higher voltage and travel speed results in flatter beads.

By the use of proper welding procedures, excellent results are attainable when submerged-arc welding heavy sections of nickel alloy products. Six inch (150 mm) INCONEL alloy 600 plates have been successfully welded from one side (single U-joint design) in the fully restrained condition with INCOFLUX 4 Submerged-Arc Flux and INCONEL Filler Metal 82.

Weld composition remains essentially constant through the thickness of heavy section weldments with no accumulation of flux components. Table 7 lists compositions of samples removed at 1/2-in (13-mm) intervals from the top surface of a 3-in (76-mm) thick weld.

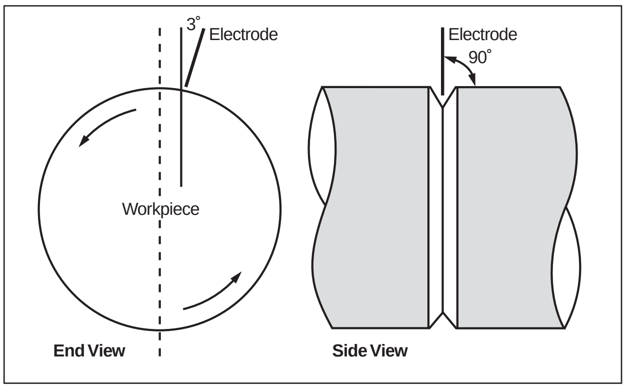


Figure 8. Optimum electrode position for submerged-arc circumferential welding.

Circumferential welding of groove joints in pipe is performed with the same procedures used for groove joints in plate. The degree of difficulty increases as the pipe diameter decreases. Welding parameters must be adjusted accordingly. Six-inch (150-mm) diameter is the practical minimum that may be readily welded. The major difficulty in pipe welding is preventing the molten slag from flowing either into or away from the weld metal as the pipe is rotated. The electrode position can be used to control weld-metal dilution and bead shape (Figure 8). Pipe diameter and joint design influence the operable electrode positions. Better control of fusion and penetration can be achieved by the use of the gas tungsten-arc process for the root pass.

Plasma-Arc Welding

The plasma-arc process can be used to advantage for joining nickel alloys in thicknesses from 0.1 to 0.3 in. Thicknesses outside that range can be plasma-arc welded, but better results can usually be obtained with other welding processes.

An important application of the plasma-arc process is the welding of thicknesses up to 0.3 in. without the use of filler metal. That thickness is significantly greater than the limiting thickness for autogenous welding by the gas tungsten-arc process. Filler metal is normally required for gas tungsten-arc welding of material greater than 0.1 in. thick.

The following discussion applies specifically to automatic welding by the "keyhole" method of operation and with a transferred arc. With the keyhole method, the plasma stream completely penetrates the joint, and fusion occurs at the trailing edge of the keyhole-shaped penetrated area resulting from movement of the torch along the joint.

GAS

The orifice gas has a significant effect on the depth of penetration and the configuration of the penetration pattern. Argon or a mixture of argon and 5 to 8% hydrogen gives good results in autogenous keyhole welding. Starting of the torch becomes more difficult as hydrogen is added to the gas. The same gas supply is normally used for both the orifice and outer-shield gas.

CURRENT

Power sources for plasma-arc welding are similar to those for gas tungsten-arc welding. Straight-polarity direct current is used.

WELDING PROCEDURE

The joint surfaces must permit a tight fit with no gaps. Sheared or saw-cut edges are usually adequate. Clamping fixtures must be used to maintain joint fit-up. The backup bar should have a 3/4-in. relief for venting of the plasma gas. The weld root should be protected by inert gas introduced through the backup bar.

Typical welding conditions for various thicknesses of several alloys are given in Table 8. Amperage, gas flow, and travel speed must be in the proper relation to provide consistent keyholing. Turbulence in the weld puddle can result from an unstable keyhole. One indication of a proper keyhole is a consistent stream of plasma gas flowing from the bottom of the joint. Figure 9 shows the relation of travel speed to amperage. Excessive travel speeds can cause undercutting and should be avoided.

Undercutting can also be caused by an inclined

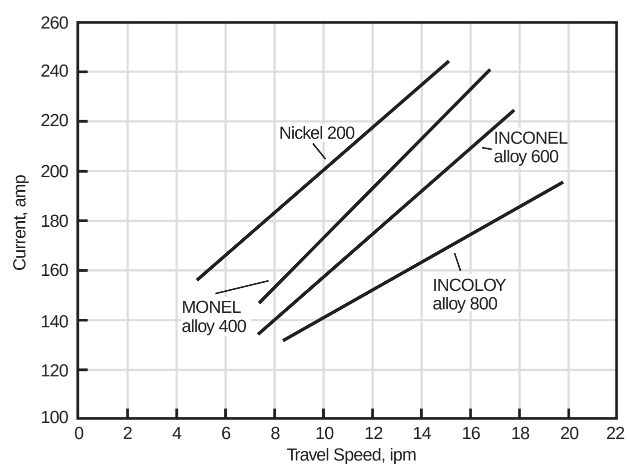


Figure 9. Travel speed and amperage required for keyholing.

torch and by joint mismatch. The torch must be maintained perpendicular to the joint in both longitudinal and transverse directions. The torch must also be kept on the joint centerline. A deviation of 0.040 in. can be sufficient to cause lack of fusion.

Torch-to-work distances are normally 1/8 to 3/16 in. Longer distances result in porosity; shorter distances can result in spatter accumulation on the orifice.

A small amount of filler metal can be added during welding by the keyhole method. The amount is limited by the ability of the puddle's surface tension to support additional molten metal.

Joints in material over 0.3 in. thick can be plasma-arc welded by use of the keyhole method, without filler metal, for the root pass, followed by a non-keyholing pass with filler metal added.

Overlaying

Nickel-base, corrosion-resistant alloys are needed in many applications to provide protection from corrosive environments. However, in many cases, the comparative high cost of these base materials makes the weld deposit of a protective layer on less expensive load-bearing mild or low alloy steel the most realistic financial alternative.

Nickel-alloy weld metals are readily applied as overlays on most structural grades of steel. For best results, iron dilution must be kept at minimum levels. Excessive amounts of iron in the overlay compromise the corrosion resistance of the overlay and can cause weld cracking.

The same welding processes used for joining alloy components can also be used for overlaying. However, submerged-arc welding is the process most commonly used for overlaying.

As with all nickel-alloy welding applications, base metal cleanliness is essential. All oxides and foreign material must be removed from the surface to be overlaid. The procedures and precautions discussed under "Surface Preparation" should be carefully followed.

Cracking can sometimes occur in the first layer of nickel-base overlays on grades of steel that contain high levels of sulfur. When this occurs, the cracked overlay should be removed and a buffer layer of carbon-steel weld metal deposited onto the sulfur-bearing steel base material. The nickel-alloy overlay can then be redeposited.

Nickel-alloy overlays can be applied to some grades of iron castings. To determine if the casting is weldable, a trial overlay should be attempted. If the casting skin or as-cast surface is not removed, then a flux containing NI-ROD 99X or NI-ROD 55 Welding Electrode will aid in removing deleterious elements on the surface of the casting. For higher production rates for unprepared casting surfaces, NI-ROD FC55 should aid in removing any casting skin issue to produce sound weld deposits. When overlays are applied directly to cast iron without a barrier layer, amperage should be kept at a minimum to keep dilution at the lowest level possible.

SHIELDED METAL-ARC OVERLAYS

Because of the versatility and portability of the process, shielded metal-arc welding is often used for in-situ overlay steel components. Applications such as facing on vessel outlets and trim on valves are common. SMAW is also well suited for overlay of cast iron parts. NI-ROD and NI-ROD 55 Welding Electrodes deposit a sound buffer layer that can be used as a base for other alloy overlays.

The procedures outlined for shielded metal-arc joining are equally applicable for overlaying. Special care must be taken to control iron dilution of the overlay. Excessive dilution can compromise weld properties and soundness as well as corrosion resistance. Welds with too much iron are generally incapable of passing bend qualification tests (Figure 10).

The current for weld overlay with SMAW should be in the lower half of the recommended range for the electrode. The arc force should be directed at the fusion line of the previous bead so that the weld metal will spread onto the steel with only minimum weaving of the electrode. If deposits with thin feather edges are

Table 8 - Typical Conditions for Plasma-Arc Welding

Alloy	Material Thickness (in)	Orifice Diameter (in)	Orifice Gas[a] Flow (cfh)	Current (amps)	Voltage (volts)	Travel Speed (ipm)
Nickel 200	0.325	0.136	10.0	310	31.5	9
	0.287	0.136	10.0	250	31.5	10
	0.235	0.136	10.0	245	31.5	14
	0.125	0.136	10.0	160	31.0	20
MONEL alloy 400	0.250	0.136	12.5	210	31.0	14
INCONEL alloy 600	0.260	0.136	12.5	210	31.0	17
	0.195	0.136	12.5	155	31.0	17
INCOLOY alloy 800	0.325	0.155	14.0	270	31.5	11
	0.230	0.136	12.5	185	31.5	17
	0.125	0.136	10.0	115	31.0	18

(a) Orifice and outershield gas: 95% argon, 5% hydrogen. Outershield flow rate: 45 cfh.

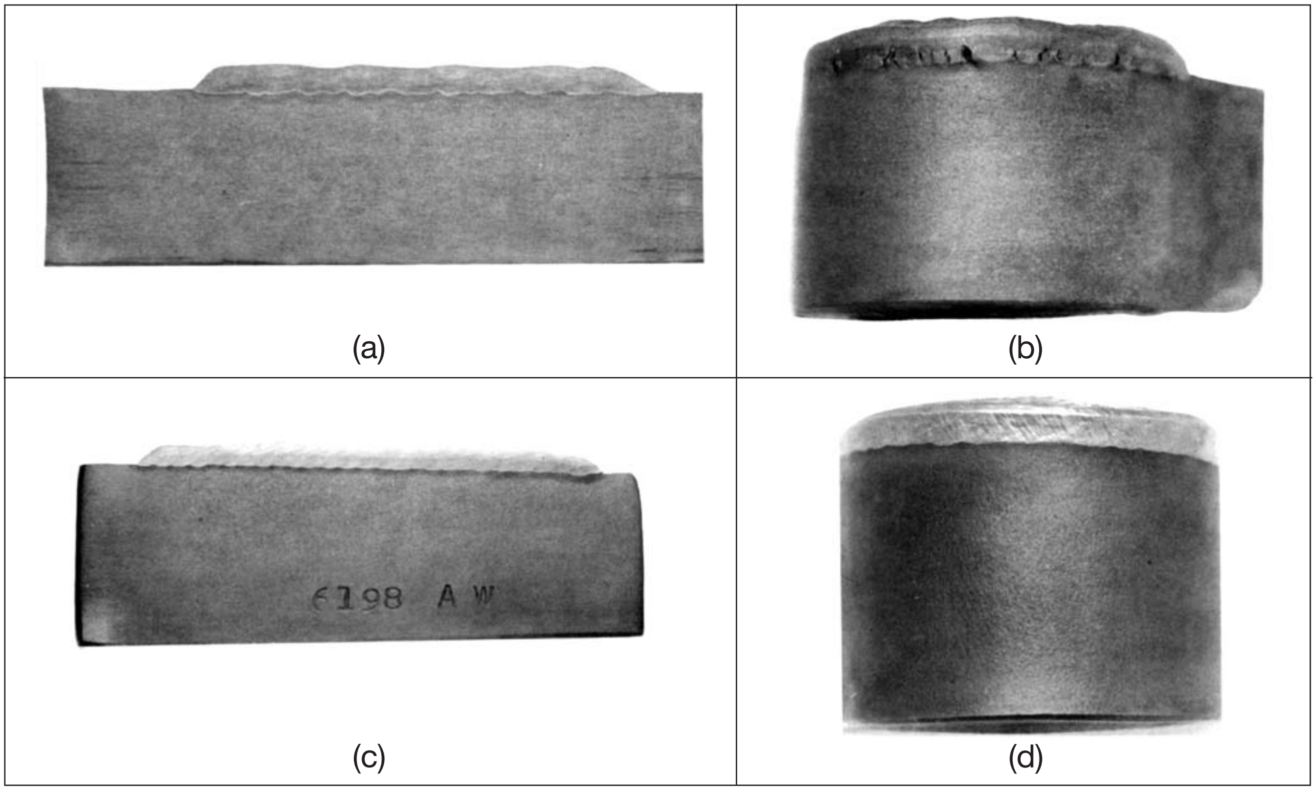


Figure 10 - Manual shielded-metal-arc overlays. (a) Overlay with scalloped underbead contour.
(b) Bend-test specimen with cracks caused by improper underbead contour.
(c) Overlay with smooth underbead contour.
(d) Bend-test specimen from overlay shown in (c).

applied, more layers will be required and the possibility of excessive dilution will be greater. The penetration pattern or underbead contour of the overlay should be as smooth as possible.

GAS METAL-ARC OVERLAYS

Gas metal-arc welding with spray transfer is often used for high-deposition overlaying of steel components with nickel-alloy filler metals. The overlays are usually produced with mechanized equipment and with oscillation of the electrode.

Pure argon is often used as a shielding gas. The addition of 15 to 25% helium has been found to be beneficial for overlays of nickel and nickel-chromium welding products. Beads become wider and flatter with reduced penetration as the helium content is increased to about 25%. Gas-flow rates are influenced by welding technique and will vary from 25 to 100 ft^3/h (0.99 to 2.83 m^3/h). As welding current is increased, the weld puddle will become larger and, thus, larger gas cups are required for protection. The cup should be large enough to deliver an adequate quantity of gas under low velocity to the overlay area. When oscillation is used, a trailing shield may be necessary for adequate protection. It also must be considered that when air-cooled torches designed to use carbon dioxide shielding gas are used with inert gas shielding, the duty cycle of the torch must be derated due to the decreased thermal conductivity of the inert gases.

The chemical compositions of automatic gas metal-arc overlays are shown in Table 9 (page 18). The overlays were produced with the following welding parameters and conditions:

- Torch gas, 50 ft^3/h (1.4 m^3/h) argon
- Trailing shield, 50 ft^3/h (1.4 m^3/h) argon
- Electrode extension, 3/4 in (19 mm)
- Power source, reverse-polarity (DCEP)
- Oscillation frequency, 70 cycles/min
- Oscillation width, 7/8 in (22 mm)
- Bead overlap, 1/4 to 3/8 in (6.4 to 9.5 mm)
- Travel speed, 4 1/2 in/min (114 mm/min)

When nickel-copper or copper-nickel overlays are to be applied to steel by GMAW, a barrier layer of Nickel Filler Metal 61 must be applied first. The nickel weld metal will tolerate greater iron dilution without fissuring than will the copper-bearing welding products.

GAS METAL-ARC WELDING PULSING TRANSFER

When a single pass overlay is being considered or when overlays are applied manually, the iron content of the first bead will be considerably higher than that of subsequent beads. The first bead should be applied using a low energy process such as pulsed-arc at a reduced travel speed to dissipate much of the digging

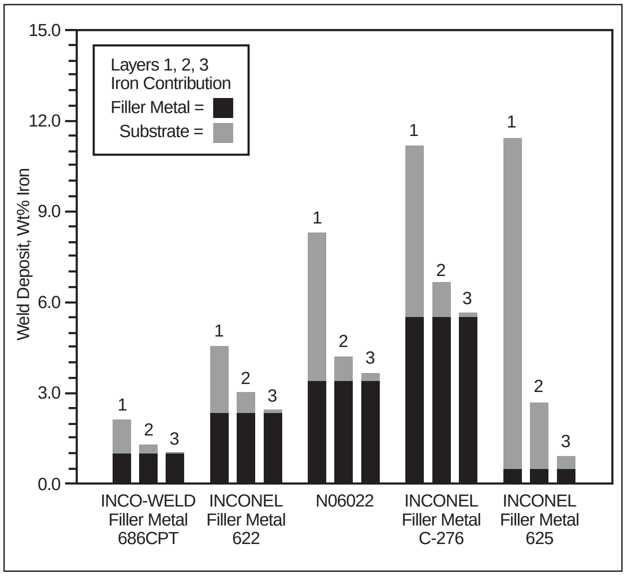


Figure 11. - Wt% Iron vs. Layer No. & Alloy Ni-Cr-Mo overlay on mild steel P-GMAW-pulsing transfer, 100% helium, 0.045 in (1.1 mm) diameter.

force of the arc and, thus, reduce the iron content of that bead. The iron content and surface contour of subsequent beads of the overlay can be controlled by use of the stringer bead technique and directing the arc at the edge of the preceding bead. Such a procedure will result in a 50% overlap of beads without excessive arc impingement. The welding gun should be inclined up to 5 degrees away from the preceding bead so that the major force of the arc impinges on the preceding bead, not on the steel being overlaid.

Solid State Pulsed Gas Metal Arc Welding (P-GMAW) has helped nickel base filler metals for low heat input welding application. Low heat input P-GMAW maximizes the corrosion resistance of the as-deposited weld, for not only joining, but also weld overlaying of stainless and steel pipe, vessels, heat exchanger tube-sheets and water-wall tubes. Solid state P-GMAW power sources can offer a stable arc with high helium levels with argon and in some cases pure helium can be used allowing for improved wetting while maintaining low amperage weld deposits with a significantly lower potential for weld toe lack of fusion defects. One of the primary filler metal properties that has a significant effect on the P-GMAW welding parameters, as well as weld deposit dilution, is the "burn-off" rate. Each filler metal composition will have a unique burn-off rate based on the composition of the filler metal. Figure 11 illustrates how different burn-off properties of various Ni-Cr-Mo filler metals can affect the P-GMAW weld deposit iron dilution from the steel sub-

Table 9 - Chemical Composition of Gas-Metal-Arc Overlays on Steel[a]

Filler Metal	Current, A	Voltage, V	Chemical Composition, %, of Deposited Weld Metal														
			Layer	Ni	Fe	Cr	Cu	C	Mn	S	Si	Mg	Ti	Al	Nb+Ta	Mo	W
Nickel Filler Metal 61	280-290	27-29	1	71.6	25.5	–	–	0.12	0.28	0.005	0.32	–	2.08	0.06	–	–	–
			2	84.7	12.1	–	–	0.09	0.17	0.006	0.35	–	2.46	0.07	–	–	–
			3	94.9	1.7	–	–	0.06	0.09	0.003	0.37	–	2.76	0.08	–	–	–
MONEL Filler Metal 60[b]	280-300	27-29	2	66.3	7.8	–	19.9	0.06	2.81	0.003	0.84	0.008	2.19	0.05	–	–	–
			3	65.5	2.9	–	24.8	0.04	3.51	0.004	0.94	0.006	2.26	0.04	–	–	–
MONEL Filler Metal 67[b]	280-290	27-28	2	41.1	11.5	–	45.8	0.04	0.53	0.007	0.14	–	0.83	–	–	–	–
			3	35.6	3.1	–	60.1	0.01	0.61	0.006	0.08	–	0.43	–	–	–	–
INCONEL Filler Metal 82	280-300	29-30	1	51.3	28.5	15.8	0.07	0.17	2.35	0.012	0.20	0.017	0.23	0.06	1.74	–	–
			2	68.0	8.8	18.9	0.06	0.040	2.67	0.008	0.12	1.015	0.30	0.06	2.27	–	–
			3	72.3	2.5	19.7	0.06	0.029	2.78	0.007	0.11	0.020	0.31	0.06	2.38	–	–
INCONEL Filler Metal C-276	n/a	n/a	1	54.9	11.2	15.0	–	0.008	0.382	–	0.021	–	–	–	–	14.4	3.51
			2	58.0	6.5	15.8	–	0.007	0.388	–	0.020	–	–	–	–	15.2	3.70
			3	58.5	5.7	16.0	–	0.005	0.393	–	0.019	–	–	–	–	15.3	3.73
INCONEL Filler Metal 622	n/a	n/a	1	57.4	4.5	20.0	–	0.004	0.212	–	0.027	–	–	–	–	14.0	3.29
			2	57.5	3.0	20.0	–	0.002	0.213	–	0.027	–	–	–	–	14.0	3.30
			3	58.7	2.5	20.5	–	0.002	0.212	–	0.026	–	–	–	–	14.2	3.35
INCONEL Filler Metal 686CPT	n/a	n/a	1	56.9	2.0	20.3	–	0.006	0.227	–	0.019	–	–	–	–	16.2	3.89
			2	57.3	1.3	20.4	–	0.004	0.229	–	0.019	–	–	–	–	16.3	3.91
			3	57.5	1.1	20.5	–	0.004	0.230	–	0.020	–	–	–	–	16.3	3.91
UNS N06022 Filler Metal	n/a	n/a	1	54.5	8.3	20.2	–	0.008	0.224	–	0.033	–	–	–	–	12.6	2.96
			2	57.0	4.3	21.1	–	0.002	0.222	–	0.032	–	–	–	–	13.2	3.10
			3	57.4	3.7	21.2	–	0.002	0.222	–	0.032	–	–	–	–	13.2	3.12

(a) Automatic overlays with 0.062-in (1.6-mm) dia. filler metal on SA 212 Grade B steel. See text for additional welding conditions.
(b) First layer applied with Nickel Filler Metal 61.

strate. INCO-WELD 686CPT filler metal has a higher burn-off rate due primarily to the high level of refractory elements in its chemical composition.

P-GMAW also offers excellent low heat input out of position welding of thin sheet materials for cladding applications (wallpapering). Seal welds and attachment welds are required when lining mild steel and/or stainless steel structural components for service in highly corrosive wet environments.

SUBMERGED-ARC OVERLAYS

The submerged arc process produces high quality nickel-alloy overlays on carbon steel and low-alloy steel. The process offers several advantages over gas-metal arc overlaying:

1. Higher deposition rates, 25-50% increase with 0.062 in (1.6 mm) diameter filler metal and the ability to use larger electrodes.
2. Fewer layers are required for a given overlay thickness. For example, with 0.062 in (1.6 mm) filler metal, two layers applied by the submerged-arc process have been found to be equivalent to three layers applied by the gas metal arc process. The chemical composition of submerged-arc over lays are found in Table 10.
3. The welding arc is much less affected by minor process variations such as wire condition and electrical fluctuations.
4. As-welded surfaces smooth enough to be dye-penetrate-inspected with no special surface preparation other than wire brushing.
5. Direct applications of nickel-copper alloy on steel without a nickel barrier layer.

Table 10 - Typical Chemical Composition of Submerged Arc Overlays on Steel[a]

Flux Type	Filler Metal	Wire Diameter in (mm)	Layer	Ni	C	Mn	Fe	S	Si	Cu	Cr	Ti	Nb	Nb + Ta	Mo	W
4	INCONEL 82	0.062 (1.6)	1	63.5	0.07	2.95	12.5	0.008	0.40	–	17.00	0.15	–	3.4	–	–
			2	70.0	0.07	3.00	5.3	0.008	0.40	–	17.50	0.15	–	3.5	–	–
			3	71.5	0.07	3.05	2.6	0.008	0.40	–	18.75	0.15	–	3.5	–	–
5	MONEL 60	0.062 (1.6)	1	60.6	0.06	5.00	12.0	0.014	0.90	21.0	–	0.45	–	–	–	–
			2	64.6	0.04	5.50	4.5	0.015	0.90	24.0	–	0.45	–	–	–	–
6	Nickel 61	0.062 (1.6)	2	88.8	0.07	0.40	8.4	0.004	0.64	–	–	1.70	–	–	–	–
	INCONEL 82	0.062 (1.6)	2	68.6	0.04	3.00	7.2	0.007	0.37	–	18.50	–	–	2.2	–	–
	INCONEL 625	0.062 (1.6)	2	61.0	0.06	0.34	6.1	–	0.30	–	20.4	–	3.1	–	8.4	–
7	INCONEL 625	0.062 (1.6)	1	60.2	0.02	0.74	3.6	0.001	0.29	–	21.6	0.13	–	3.29	8.60	–
8	MONEL 67[b]	0.062 (1.6)	-	27.5	0.03	1.10	8.0	–	0.02	63.3	–	–	–	–	–	–
NT 100	NICKEL 61	0.062 (1.6)	2	88.8	0.07	0.40	8.4	0.004	0.64	–	–	1.70	–	–	–	–
	INCONEL 82	0.062 (1.6)	2	68.6	0.04	3.00	7.2	0.007	0.37	–	18.50	–	–	2.2	–	–
	INCONEL 625	0.062 (1.6)	2	61.0	0.06	0.34	6.1	–	0.30	–	20.4	–	3.1	–	8.4	–
NT110	MONEL 60	0.062 (1.6)	FM	64.99	0.047	3.62	0.66	–	0.95	27.70	–	–	–	–	–	–
			1	48.19	0.036	5.28	23.83	–	0.67	21.48	–	–	–	–	–	–
			2	57.15	0.027	5.46	11.13	–	0.68	25.02	–	–	–	–	–	–
			3	62.38	0.024	5.65	3.83	–	0.69	26.95	–	–	–	–	–	–
			4	63.84	0.029	5.02	1.47	–	0.85	27.92	–	–	–	–	–	–
	MONEL 67[b]	0.062 (1.6)	FM	30.21	0.008	0.75	0.49	–	0.10	68.07	–	–	–	–	–	–
			1	30.27	0.003	0.84	1.77	–	0.02	65.46	–	–	–	–	–	–
NT 120	INCONEL C-276	0.062 (1.6)	FM	58.89	0.004	0.39	5.55	0.001	0.009	0.020	15.98	0.02	0.09	–	15.36	3.76
			1	46.67	0.007	0.91	22.4	0.0003	0.136	0.014	13.41	0.016	0.146	–	12.46	3.57
			2	53.90	0.013	0.94	12.59	0.005	0.165	0.010	15.02	0.023	0.323	–	13.68	3.23
			3	56.74	0.006	0.95	8.05	0.003	0.180	0.180	15.73	0.025	0.331	–	14.44	3.43
			4	57.75	0.002	0.93	6.47	0.0001	0.168	0.006	15.75	0.03	0.348	–	14.95	3.49
	INCO-WELD 686CPT	0.062 (1.6)	FM	57.88	0.004	0.220	1.07	0.001	0.010	0.010	20.31	0.05	0.060	–	16.28	3.90
			1	46.80	0.007	0.819	18.42	0.0001	0.321	0.004	17.19	0.02	0.477	–	13.45	3.38
			2	53.97	0.007	0.747	4.81	0.0001	0.344	0.003	18.82	0.03	0.482	–	16.04	4.23
			3	55.68	0.007	0.697	2.24	0.0001	0.333	0.003	19.09	0.03	0.445	–	16.45	4.26
			4	55.97	0.007	0.711	1.42	0.0001	0.349	0.002	19.11	0.03	0.476	–	16.83	4.26
	INCONEL 622	0.062 (1.6)	FM	59.06	0.001	0.23	2.4	0.001	0.02	0.01	20.45	0.05	0.0l	–	14.38	3.39
			1	40.48	0.026	0.852	31.76	0.001	0.196	0.009	15.04	0.02	0.213	–	9.28	2.04
			2	50.48	0.007	0.722	13.90	0.001	0.182	0.007	18.78	0.03	0.257	–	12.21	3.10
			3	54.58	0.004	0.739	7.20	0.0003	0.189	0.006	19.93	0.03	0.285	–	13.52	3.22
			4	56.50	0.005	0.711	4.33	0.001	0.243	0.008	20.34	0.03	0.269	–	14.05	3.36

(a) Overlays on ASTM SA 212 Grade B steel or A36 carbon steel.
(b) When overlaying steel with MONEL 67 a barrier layer of NICKEL 61 is required.

6. The increased control provided by the submerged arc overlaying process generally yields fewer defects and repairs along with no arc flash and little smoke.

In addition, the increased control provided by the submerged-arc process generally yields fewer defects and repairs.

Typical conditions for submerged arc overlaying with various flux/filler metal combinations are given in Table 11. Chemical compositions of overlay deposits are shown in Table 9 (page 18).

The recommended power supply for all overlays applied by oscillating techniques is constant-voltage direct current with straight polarity (DCEN). Straight polarity produces a less-penetrating arc that reduces dilution. Reverse polarity, however, should be used for stringer-bead overlays to minimize the possibility of slag inclusions. When the stringer bead technique is used, it is essential to use 50% bead overlap to control dilution. To maintain-

Table 11 - Typical Welding Parameters Submerged Arc for Overlaying

Flux Type	Filler Metal	Wire Diameter in (mm)	Polarity	Current (Amps)	Voltage (V)	Travel Speed in/min (mm/min)	Electrode Extension in (mm)	Oscillation Frequency cycles/min	Oscillation Width in (mm)
4	INCONEL 82	0.062 (1.6)	DCEN	240-260	32-34	3.5-5 (89-130)	7/8-1 (22-25)	45-70	7/8-1.5 (22-38)
		0.093 (2.4)	DCEN	300-400	34-37	3-5 (76-130)	1 1/8-2 (29-51)	35-50	1-2 (25-51)
5	MONEL 60	0.062 (1.6)	DCEN	260-280	32-35	3.5-6 (89-150)	7/8-1 (22-25)	50-70	7/8-1.5 (22-38)
		0.093 (2.4)	DCEN	300-400	34-37	3-5 (89-130)	1 1/8-2 (29-51)	35-50	1-2 (25-51)
		0.062 (1.6)	DCEP	260-280	32-35	7-9 (180-230)	7/8-1 (22-25)	–	–
		0.093 (2.4)	DCEP	300-350	35-37	8-10 (200-250)	1.25-1.5 (32-38)	–	–
	NI-ROD FC 55	–	–	–	–	–	–	–	–
6	NICKEL 61	0.062 (1.6)	DCEN	250-280	30-32	3.5-5 (89-130)	7/8-1 (22-25)	50-70	7/8-1.5 (22-38)
	INCONEL 82	0.062 (1.6)	DCEN	240-260	32-34	3-5 (76-130)	7/8-1 (22-25)	45-70	7/8-1.5 (22-38)
		0.093 (2.4)	DCEN	300-400	34-37	3-5 (76-130)	1 1/8-2 (29-51)	35-50	1-2 (25-51)
	INCONEL 625	0.062 (1.6)	DCEN	240-260	32-34	3.5-5 (89-130)	7/8-1 (22-25)	50-60	7/8-1.5 (22-38)
	NI-ROD 44	0.062. (1.6)	DCEP	250	32-34	4.5 (114)	1 (25)	60	1 1/8 (29)
	NI-ROD 99	0.035 (0.9)	DCEN	160-200	27-30	4-6 (100-150)	1/2-1 (13-25)	50-80	1/2-1 1/4 (13-32)
		0.035 (0.9)	DCEP	160-200	27-30	9-11 (230-280)	1/2-1 (13-25)	–	–
		0.045 (1.1)	DCEN	200-240	30-33	4-6 (100-150)	3/4-1 1/8 (19-29)	50-80	1/2-1 1/4 (13-32)
		0.045 (1.1)	DCEP	200-240	30-33	9-11 (230-280)	3/4-1 1.8 (19-29)	–	–
		0.062 (1.6)	DCEN	240-260	32-34	4-6 (100-150)	3/4-1 1/8 (19-29)	50-80	1/2-1/1/4 (13-32)
		0.062 (1.6)	DCEP	240-260	32-34	10-12 (250-300)	3/4-1 1/8 (19-29)	–	–
	CF 36	–	–	–	–	–	–	–	–
	CF 42	–	–	–	–	–	–	–	–
7	INCONEL 625	0.062 (1.6)	DCEN	250-260	32-33	5-6 (130-150)	0.75-1 (19-25)	60-80	0.75 (19)
		0.093 (2.4)	DCEN	300-320	32-33	5-6 (130-150)	0.75-1 (19-25)	50-70	0.875 (22)
8	MONEL 67	0.062 (1.6)	DCEN	280-300	32-35	3.5-6 (89-150)	7/8-1 (22-25)	50-70	7/8-1.5 (22-38)
NT100	NICKEL 61	0.062 (1.6)	DCEN	250-280	30-32	3.5-5 (89-130)	7/8-1 (22-25)	50-70	7/8-1.5 (22-38)
	INCONEL 82	0.062 (1.6)	DCEN	240-260	32-34	3-5 (76-130)	7/8-1 (22-25)	45-70	7/8-1.5 (22-38)
		0.093 (2.4)	DCEN	300-400	34-37	3-5 (76-130)	1 1/8-2 (29-51)	35-50	1-2 (25-51)
	INCONEL 625	0.062 (1.6)	DCEN	240-260	32-34	3/5-5 (89-130)	7/8-1 (22-25)	50-60	7/8-1.5 (22-38)
	NI-ROD 44	0.062 (1.6)	DCEP	250	32-34	4.5 (114)	1 (25)	60	1 1/8 (29)
	NI-ROD 99	0.035 (0.9)	DCEN	160-200	27-30	4-6 (100-150)	1/2-1 (13-25)	50-80	1/2-1 1/4 (13-32)
		0.035 (0.9)	DCEP	160-200	27-30	9-11 (230-280)	1/2-1 (13-25)	–	–
		0.045 (1.1)	DCEN	200-240	30-33	4-6 (100-150)	3/4-1 1/8 (19-29)	50-80	1/2-1 1/4 (13-32)
		0.045 (1.1)	DCEP	200-240	30-33	9-11 (230-280)	3/4-1 1/8 (19-29)	–	–
		0.062 (1.6)	DCEN	240-260	32-34	4-6 (100-150)	3/4-1 1/8 (19-29)	50-80	1/2-1 1/4 (13-32)
		0.062 (1.6)	DCEP	240-260	32-34	10-12 (250-300)	3/4-1 1/8 (19-29)	–	–
	CF 36	–	–	–	–	–	–	–	–
	CF 42	–	–	–	–	–	–	–	–
NT 110	MONEL 60	0.062 (1.6)	DCEP	240-290	32-35	7-9 (178-229)	7/8-1 (22-25)	–	–
		0.093 (2.4)	DCEP	300-400	35-37	8-10 (203-254)	1.25-1.5 (32-38)	–	–
	MONEL 67	0.062 (1.6)	DCEP	240-290	32-35	7-9 (178-229)	7/8-1 (22-25)	–	–
		0.093 (2.4)	DCEP	300-400	35-37	8-10 (203-254)	1.25-1.5 (32-38)	–	–
NT 120	INCONEL C-276	0.062 (1.6)	DCEP	235-245	33-34	4 (102)	7/8 (22)	30	1.5 (38)
	INCO-WELD 686 CPT	0.062 (1.6)	DCEP	235-245	33-34	4 (102)	7/8 (22)	30	1.5 (38)
	INCONEL 622	0.062 (1.6)	DCEP	235-245	33-34	4 (102)	7/8 (22)	30	1.5 (38)

constant dilution, it is sometimes desirable to apply the first bead on a “waste strip” or by using a lower dilution process such as pulsed GMAW.

The most efficient use of the submerged-arc process for overlaying requires equipment capable of oscillating the electrode. Pendulum oscillation is characterized by a slight hesitation at both sides of the bead. It produces slightly greater penetration and somewhat higher iron dilution at those points.

Straight-line oscillation gives approximately the same results as pendulum oscillation. Straight-line constant-velocity oscillation produces the lowest level of iron dilution. It provides for movement on a horizontal path so that the arc is maintained constant. The optimum movement is that which is programmed to have no end dwell, so that the deeper penetration at either side resulting from hesitation is eliminated. Figure 12 illustrates bead shapes resulting from various oscillation techniques.

Iron dilution is influenced by oscillation width as well as by current, voltage, and travel speed. Generally, iron dilution will decrease as oscillation width is increased with oscillating overlays. Only enough overlap to produce a smooth top surface is required. Usually smooth tie-ins are produced using 1/8-inch overlap and 0.1 secs dwell at the previous bead edge.

Non-oscillating techniques are sometimes used for making narrow overlays in inaccessible areas where oscillation is not practical. Bead placement is of the utmost importance. Iron dilution and surface contour are controlled by positioning the electrode 1/16 in (1.6 mm) away from the fusion line of the previous bead to yield 50% bead overlap. The major reason for bend test failure in stringer bead weld overlay qualification tests is deeply scalloped penetration patterns as shown in Figure 10 (page 17). This is caused by locating the subsequent beads too far from the existing bead.

The flux depth should be sufficient only to prevent arc breakthrough. The depth required will vary with voltage and electrode diameter. As the voltage is increased, the amount of flux overburden and the amount of molten flux should be increased. Use of the proper flux is essential. As with groove welding, a fluxburden of about 3/4 - 7/8 in. is optimum. The use of flux-delivery systems that direct the flux onto the arc are not recommended.

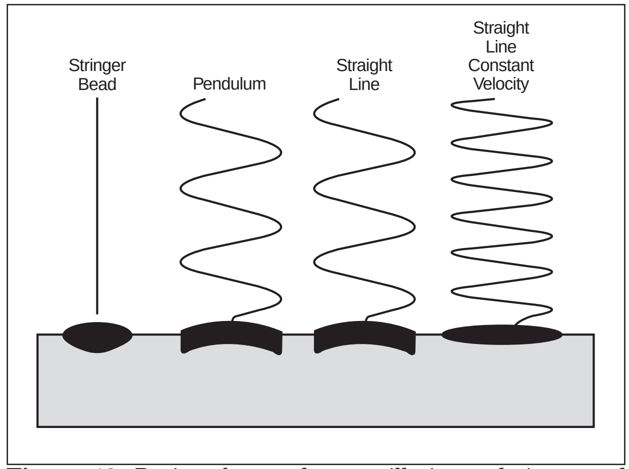


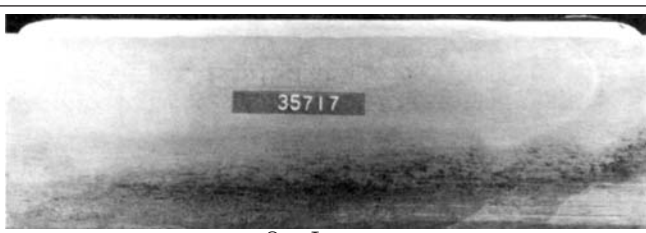
Figure 12. Basic submerged-arc oscillation techniques and bead configurations.

Stress relieving of overlays is usually not required. However, specifications may require stress relieving of the steel being overlaid. A stress relief of 1150°F (620°C) for 1 hr or more for each inch of thickness is often sufficient. However, the requirements of welding specification should be considered as controlling.

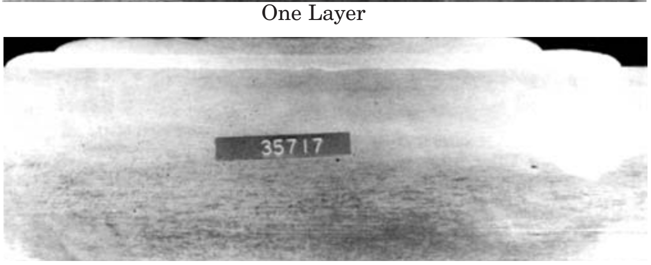
HOT-WIRE PLASMA-ARC OVERLAYS

High-quality overlays can be produced at high deposition rates with the hot-wire plasma-arc process. The process offers precise control of dilution. Dilution rates as low as 2% have been obtained. However, for optimum uniformity and control over lack of fusion defects, a dilution rate of 5 to 10% range is recommended.

The highest deposition rates are produced by feeding two filler-metal wires which are resistance-heat-



One Layer



Two Layers

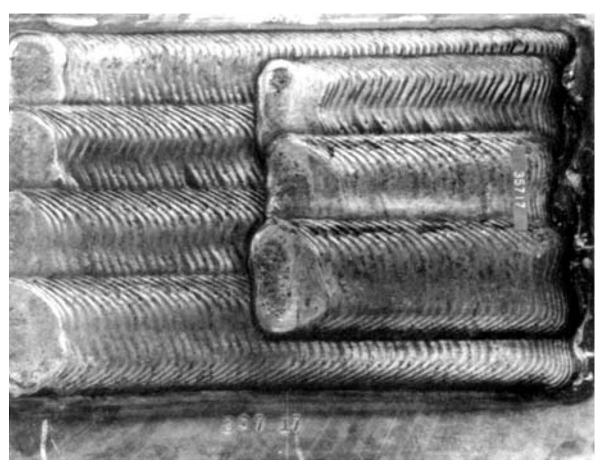


Figure 13. - Cross sections and surface of hot-wire plasma-arc overlays of INCONEL Filler Metal 82 on steel.

ed by a separate AC power source. The filler metal is nearly molten when it enters the weld puddle. Deposition rates for nickel-alloy welds are 35-40 lb/h (16-18 kg/h), approximately double those obtained with submerged-arc overlaying.

Figure 13 shows the surface and cross section of a hot-wire plasma-arc overlay made with INCONEL Filler Metal 82. Side-bend tests performed on the overlay showed no fissures.

Weld parameters for hot-wire plasma-arc overlaying with INCONEL Filler Metal 82 and MONEL Filler Metal 60 are given in Table 12. Chemical compositions of two-layer overlays made with those filler metals are listed on Table 13.

STRIP WELDING OVERLAYS

Strip welding overlays can be produced with the Electroslag Strip Surfacing (ESS) process and the Submerged-Arc Strip Surfacing (SAS) process. The ESS welding process is similar to the SAS welding process except the nature of the ESS flux prevents the formation of an arc. With the ESS welding process the electrical resistivity of the molten slag provides the heat source to melt the strip as opposed to melting by electric arc as occurs with the SAS welding process.

The ESS and SAS processes utilize identical equipment. Both processes offer high deposition rates (35-50 lbs/hr). Both processes are limited to use in the flat (1G) position. However, the ESS process results in 50% less dilution than the SAS process. Weldstrip alloys and suggested parameters are presented in Tables 14 and 15.

Welding Procedure

The strip should be cut on a 30 degree angle. The point of the strip should be brought into contact with the workpiece. The strip stick-out (distance from the contact tip to the workpiece) is normally 1-2 inches (25-50 mm). The recommended flux burden is 0.5 - 1.0 inch (13 - 25 mm) deep and should initially surround the strip. During ESS welding, the flux should be distributed to the leading edge of the strip and the coverage should be maintained uniformly. When SAS welding is used the flux should be distributed to both sides of the strip. Excessive flux burden should beavoided during both ESS and SAS welding; exces-sive flux and slag weight tends to deform the weld surface.

Table 12 - Conditions for Hot-Wire Plasma-Arc Overlaying

	MONEL Filler Metal 60	INCONEL Filler Metal 82
Filler Metal Diameter, in (mm)	0.062 (1.57)	0.062 (1.57)
Plasma-Arc Power Source	Straight-Polarity DCEN	Straight-Polarity DCEN
Plasma-Arc Current, A	490	490
Plasma-Arc Voltage, V	36	36.5
Hot-Wire Power Source	AC	AC
Hot-Wire Current, A	200	175
Hot-Wire Voltage, V	17	23.5
Plasma Gas and Flow Rate	75% He, 25% A; 55 ft^3/h (1.6 m^3/h)	75% He, 25% A; 55 ft^3/h (1.6 m^3/h)
Outershield Gas and Flow Rate	Argon; 40 ft^3/h (1.1 m^3/h)	Argon; 40 ft^3/h (1.1 m^3/h)
Trailing Shield Gas and Flow Rate	Argon; 45 ft^3/h (1.3 m^3/h)	Argon; 45 ft^3/h (1.3 m^3/h)
Torch-to-Work Distance, in (mm)	13/16 (21)	13/16 (21)
Travel Speed, in/min (mm/min)	7-1/2 (190)	7-1/2 (190)
Oscillation Width, in (mm)	1-1/2 (38)	1-1/2 (38)
Oscillation Frequency, cycles/min	44	44
Deposit Width, in (mm)	2 (51)	2-3/16 (56)
Deposit Thickness, in (mm)	3/16 (4.8)	3/16 (4.8)
Deposit Rate, lb/h (kg/h)	40 (18)	40 (18)
Preheat, °F (°C)	250 (120)	250 (120)

Table 13 - Chemical Composition, %, of Hot-Wire Plasma-Arc Overlays on Steel[a]

Filler Metal	Layer	Ni	Fe	Cr	Cu	C	Mn	S	Si	Ti	Al	Nb+Ta
MONEL Filler Metal 60	1	61.1	5.5	–	27.0	0.07	3.21	0.006	0.86	2.14	0.05	–
	2	63.1	1.5	–	28.2	0.07	3.32	0.006	0.88	2.25	0.04	–
INCONEL Filler Metal 82	1	68.3	8.3	18.4	0.05	0.02	2.67	0.010	0.16	0.24	–	2.16
	2	73.2	1.7	20.2	0.02	0.01	2.86	0.010	0.17	0.24	–	2.31

(a) Overlay on ASTM A 387 Grade B steel made with 0.062 in (1.6 mm) diameter filler metal.

Table 14 - Typical Parameters for Electroslag Strip Surfacing

Flux Type	Weldstrip	Welding Process	Wire Size in (mm)	Polarity	Current (Amps)	Voltage (V)	Travel Speed in/min (mm/min)	Strip Speed in/min (mm/min)	Strip Stick-out in (mm)	Flux Burden in (mm)
ESS1	82	ESW	1.2 (30)	DCEP	600-800	24-25	5-8 (127-203)	60-70 (1524-1778)	1-2 (25-50)	0.5-1 (13-25)
		ESW	2.4 (60)	DCEP	1100-1300	24-25	5-8 (127-203)	60-70 (1524-1778)	1-2 (25-50)	0.5-1 (13-25)
	625	ESW	1.2 (30)	DCEP	600-800	24-25	5-8 (127-203)	60-70 (1500-1800)	1-2 (25-50)	0.5-1 (13-25)
		ESW	2.4 (60)	DCEP	1100-1300	24-25	5-8 (127-203)	60-70 (1500-1800)	1-2 (25-50)	0.5-1 (13-25)
	686 CPT	ESW	1.2 (30)	DCEP	600-800	24-25	5-8 (127-203)	60-70 (1500-1800)	1-2 (25-50)	0.5-1 (13-25)
		ESW	2.4 (60)	DCEP	1100-1300	24-25	5-8 (127-203)	60-70 (1500-1800)	1-2 (25-50)	0.5-1 (13-25)
ESS2	52SCC	ESW	1.2 (30)	DCEP	600-700	23-24	6-7 (150-180)	65-70 (1650-1800)	0.75-1 (19-25)	0.75-1.5 (19-38)
		ESW	2.4 (60)	DCEP	1100-1300	23-24	6-7 (150-180)	65-70 (1500-1800)	0.75-1 (19-25)	0.75-1.5 (19-38)

Typical Chemical Compositions

Flux Type	Weldstrip	Base Material	Joint Configuration	Layer	C	Mn	Si	Cr	Mo	Nb	Fe	Ni	W
ESS1	82	Steel	Overlay	Weldstrip	0.047	2.92	0.11	20.07	–	2.42	1.23	72.74	–
				1	0.046	3.07	0.32	20.24	–	2.03	3.26	70.79	–
				2	0.045	3.05	0.24	20.95	–	2.08	1.63	71.93	–
				3	0.04	3.05	0.24	21	–	2.03	1.53	72.05	–
ESS1	625	Steel	Overlay	Weldstrip	0.011	0.05	0.07	21.5	8.84	3.45	3.87	61.7	–
				1	0.024	0.5	0.24	21.44	8.12	3.02	7.96	58.4	–
				2	0.021	0.49	0.27	22.02	8.45	3.07	4.67	60.6	–
				3	0.021	0.44	0.25	22.08	8.66	3.13	4.17	60.81	–
ESS1	686 CPT	Steel	Overlay	Weldstrip	0.002	0.25	0.01	20.4	16.27	0.02	0.36	58.65	3.88
				1	0.0009	0.57	0.06	19.75	14.99	0.03	5.28	54.71	3.88
				2	0.0001	0.56	0.07	20.27	15.72	0.03	1.51	56.8	3.88
				3	0.0001	0.57	0.07	20.39	15.95	0.03	0.57	57.36	3.88
ESS2	52SCC	Steel	Overlay	Weldstrip	0.03	0.14	0.07	30.01	–	0.01	9.11	59.58	–
				1	0.02	1.48	0.27	29.0	–	1.2	10.3	57.3	–
				2	0.02	1.38	0.27	29.5	–	1.2	8.9	58.4	–

Table 15 - Typical Parameters for Submerged-Arc Strip Surfacing

Flux Type	Weldstrip	Welding Process	Wire Size in (mm)	Polarity	Current (Amps)	Voltage (V)	Travel Speed in/min (mm/min)	Electrode Extension in (mm)	Flux Burden in (mm)
SAS1	82	SAW	1.2 (30)	DCEP	300-450	25-28	4-5 (102-127)	3/4-1 (19-25)	1-2 (25-50)
		SAW	2.4 (60)	DCEP	700-900	25-28	4-5 (102-127)	3/4-1 (19-25)	1-2 (25-50)
	625	SAW	1.2 (30)	DCEP	300-450	25-28	4-5 (102-127)	3/4-1 (19-25)	1-2 (25-50)
		SAW	2.4 (60)	DCEP	700-900	25-28	4-5 (102-127)	3/4-1 (19-25)	1-2 (25-50)
SAS2	52SCC	SAW	2.4 (60)	DCEP	700-900	25-28	4-5 (102-127)	3/4-1 (19-25)	1-2 (25-50)

Typical Chemical Compositions

Flux Type	Weldstrip	Base Material	Joint Configuration	Layer	C	Mn	Si	Cr	Mo	Nb	Fe	Ni
SAS1	82	Steel	Overlay	Weldstrip	0.047	2.92	0.11	20.07	–	2.42	1.23	72.74
				1	0.040	3.10	0.30	17.86	–	1.95	14.9	64.1
				2	0.037	3.25	0.38	19.84	–	2.01	2.87	71.16
				3	0.037	3.35	0.38	19.92	–	2.05	1.57	71.27
SAS1	625	Steel	Overlay	Weldstrip	0.026	0.08	0.09	21.52	9.02	3.45	0.75	64.02
				1	0.037	0.91	0.39	18.51	7.76	2.78	13.15	55.92
				2	0.036	0.86	0.40	20.71	8.58	2.99	3.05	62.45
				3	0.028	0.85	0.41	20.84	8.79	3.03	1.30	63.36
SAS2	52SCC	Steel	Overlay	2	0.01	0.83	0.25	29.05	–	0.82	9.32	57.35

Welding Nickel Alloy Clad Steel Plate

When only a thin section of a nickel alloy is required to protect a component from corrosion, significant savings are possible by fabricating it from alloy clad steel plate instead of solid alloy plate. By the use of clad steel plate, the steel substrate meets the structural requirements while the thin cladding of alloy protects the components from corrosive attack. Alloy clad steel plate typically costs half the price of solid alloy plate.

Alloy clad steel plates are readily joined by conventional welding processes and procedures using standard nickel alloy welding products. Welding procedures must be designed to maintain the integrity and corrosion resistance of the alloy cladding as well as the strength of the steel substrate. This requirement influences welding product selection, joint design, and welding technique. Dilution of iron into the alloy weldment is to be avoided as the content of iron compromises the weld's corrosion resistance and mechanical properties.

The choice of welding products for joining alloy clad steel plate is critical. Due to the propensity for iron dilution of the weldment, it is suggested that a welding product more highly alloyed than the cladding material be used to offset the effects of iron dilution commonly encountered when welding clad steel plate. For example, INCONEL alloy C-276 clad steel plate is best joined with INCO-WELD 686CPT welding products.

Thinner section clad steel plates (3/16 to 3/8 inch steel backing plate) are normally joined with full alloy welds. It may be more economical when welding heavier plate to weld most of the steel section with steel welding products and only the alloy cladding and a small portion of the steel backing with the more expensive nickel alloy welding products. Depositing steel weld metal over nickel alloy weld or base metal is not recommended as diluting the alloy constituents into the steel weld metal can cause excessive hardness and cracking.

Clad steel plates are joined by techniques in which welding takes place from only the steel side, only the alloy side, or both sides. Accessibility and plate thickness will generally dictate the welding scenario to use. It is generally best to weld from both sides of the clad steel plate when possible.

Thin section clad steel plate is best joined by welding from both sides with the first weld pass being deposited on the cladding side by a technique such that it does not fully penetrate the alloy cladding. In this manner, the weld does not penetrate into the steel substrate and iron dilution is avoided. The steel substrate is then back chipped and the weld completed with the alloy welding product (Figure 14).

Joining heavy section clad steel plate from both sides is preferable so that the steel substrate can be welded with economical steel welding products. Prepared joints should be used when possible. Figures 15a and 15b shows recommended designs for two thickness ranges. The preferred scenario is that the steel portion of the clad steel plate is welded first from the steel side with the steel welding product appropriate for the specific grade of steel. It is important to avoid penetration of the cladding by the first welding pass as dilution of nickel and other alloying elements into the steel weld can cause excessive hardness and cracking. Also penetration of the cladding with the steel weld compromises the corrosion-resistance of that portion of the cladding. The joint designs in Figures 15a and 15b include a small steel land to help avoid penetration of the steel weld into the nickel alloy cladding. After welding of the steel substrate is completed, a joint on the clad side of the plate should be prepared by machining, grinding, or chipping, as appropriate, and a weld deposited with the desired alloy welding product. The service weld on the clad side of the plate will be somewhat

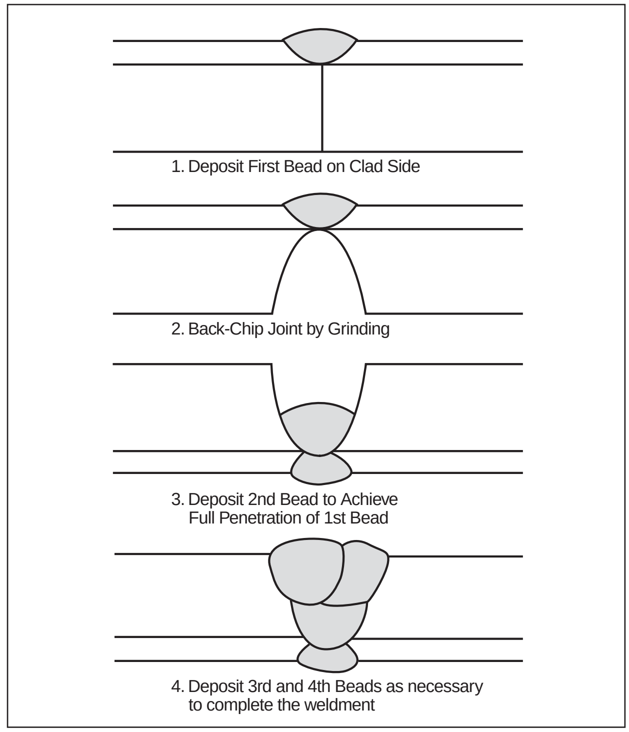
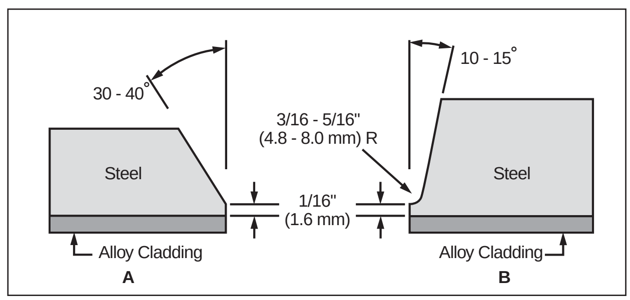


Figure 14. Welding Alloy Clad Steel Plate – The above bead sequence is typical for clad plate compromised of 1/16" alloy cladding on 1/4" steel backing. An over-alloyed welding product is recommended.



Figures 15a & 15b. Joint designs for clad steel.
(A) Material 3/16 to 5/8 in. (4.8 to 16 mm) thick.
(B) Material 5/8 to 1 in. (16 to 25 mm) thick.

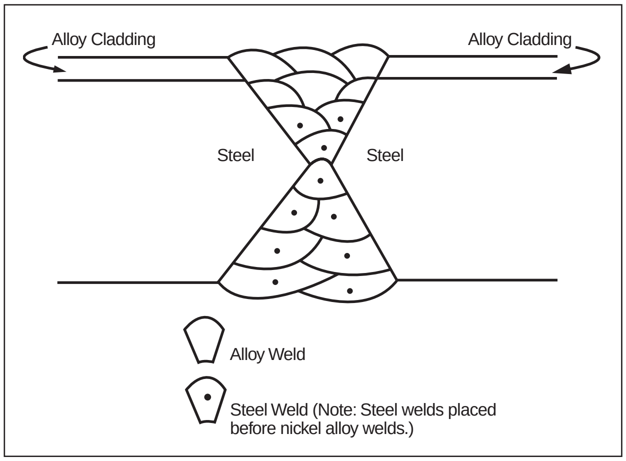


Figure 15c. Double "V" joint.

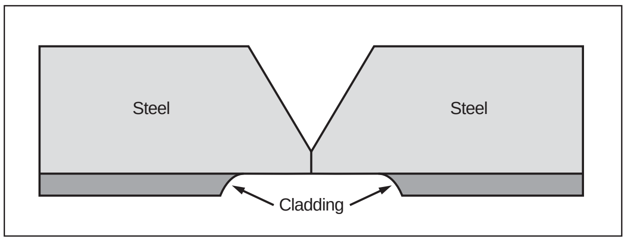


Figure 16. Strip-back method of joint preparation.

diluted with iron from the steel weld and backing. To maintain corrosion resistance, at least two (preferably three or more layers) should be deposited in making the cladding weld. Also, the use of highly alloyed welding products is suggested. When welding must be done from only one side, conventional joint designs are used. If welding is done from the alloy side, the steel backing may be welded with steel welding products with only the cladding and steel interface being joined with the alloy welding product. If welding must be done from the steel side only, the complete joint should be deposited with the alloy welding product. It must be considered that the welds deposited from only one side will to some degree be diluted with iron. Thus, their corrosion resistance will be accordingly reduced. To offset the effects of dilution highly alloyed overmatching welding products should be used.

To better control residual stresses and minimize distortion when welding heavy sections of alloy clad steel plate, a double "V" joint such as is seen in Figure 15c or a double "U" or double "J" joint may be preferred when both sides of the weld joint are accessible. With this joint configuration, one side will be welded with steel welding products. Depending on the thickness of the plate being welded, the other side of the joint may be deposited with alloy welding products or it may be partially welded with steel welding products and only the top layers of the joint deposited with the more costly alloy welding products. The welding engineer is cautioned to be sure that the effects of iron dilution are considered when determining what portion of the weldment to make with alloy welding products. As above, the use of overmatching welding consumables is encouraged.

The "strip-back" technique is sometimes used when joining heavy section clad steel plate. With this method the cladding adjacent to the weld joint is removed as shown in Figure 16. The steel substrate is then welded using a standard joint design and welding product. After the steel weld is completed, the integrity of the cladding is restored by a weld overlaying technique. The main advantage of the strip-back method is that it eliminates the possibility of cracking caused by penetration of the steel weld metal into the cladding.

Welding Metallurgy and Design

Nickel-alloy joining procedures must reflect any special metallurgical aspects of the operation. And, since many of the high performance alloys utilize rather complex phenomena in developing high levels of strength and corrosion-resistance, the welding engineer must thoroughly understand the metallurgy of the base metal and the welding product.

Metallurgical factors strongly influence procedures for welding dissimilar materials and precipitation-hardenable alloys. Any welded joint can undergo metallurgical changes when subjected to cold work and heat treatment. For high-temperature service, both metallurgical and design considerations are important in obtaining life in fabricated equipment.

WELDABILITY

In developing a welding procedure, the engineer must first affirm that the products of interest are indeed weldable. The alloy's composition, structure, and thermal mechanical history all affect its response to welding.

Wrought alloys generally exhibit better weldability than castings. The dendritic structure of castings often exhibits severe elemental segregation. Also, castings often contain significant additions of silicon for fluidity. Silicon can compromise the hot-cracking resistance of some alloys and, thus, their weldability.

Materials with a coarse grain structure (ASTM Number 5 or coarser) are generally found to be less weldable than those with finer grain structures. Coarse grain material are particularly prone to base metal microfissuring. Grain size can restrict the use of processes having high energy input (e.g., GMAW in the spray mode of transfer and electron beam welding). Table 16 illustrates the effect of grain size on selection of welding processes for several alloys. Alloys are best welded in the annealed condition. Alloys with high levels of residual stress due to rolling, drawing, or forming can be prone to cracking. Alloy products annealed at lower temperatures (mill anneal) generally exhibit finer grain structures than those annealed at higher temperatures (solution anneal) and, thus, are found to offer a better welding response. Some alloys must be solution annealed prior to final heat treatment (e.g., precipitation hardenable alloys) or being placed into high temperature service conditions (e.g., INCONEL alloy 601 or 617 or

Table 16 - Effect of Grain Size on Recommended Welding Processes[a]

Alloy	Grain Size[b]	Gas Metal Arc[c]	Electron Beam	Gas Tungsten Arc	Shielded Metal Arc
INCONEL alloy 600	Fine	X	X	X	X
	Coarse	–	–	X	X
INCONEL alloy 617	Fine	X	X	X	X
	Coarse	–	–	–	X
INCONEL alloy 625	Fine	X	X	X	X
	Coarse	–	–	X	X
INCONEL alloy 706	Fine	–	X	X	X
	Coarse	–	–	–	X
INCONEL alloy 718	Fine	–	X	X	X
	Coarse	–	–	–	X
INCOLOY alloy 800	Fine	X	X	X	X
	Coarse	–	X	X	X
AISI Type 316	Fine	–	–	X	X
	Coarse	–	–	X	X
AISI Type 347	Fine	X	X	X	X
	Coarse	–	–	X	X

(a) Processes marked X are recommended.
(b) Fine grain is smaller than ASTM Number 5, coarse grain ASTM Number 5 or larger.
(c) Spray transfer.

INCOLOY alloy 800HT or 803). If possible, such alloys should be welded after a mill anneal and prior to the solution anneal.

DISSIMILAR WELDING

The information presented here can be used as a general guideline in the selection of a welding product for a dissimilar joint. The effects of mixing dissimilar materials are too complex to permit prediction of results with absolute certainty in all cases. However, with an accurate estimate of dilution rates, the procedures outlined will eliminate needless trials by showing which electrodes and filler metals have a high probability for success.

1) General Guidelines

Dissimilar welding often involves complex metallurgical considerations. The composition of the weld deposit is controlled not only by the electrode or filler metal but also by the amount of dilution of elements from the two base metals joined. The amount of dilution varies with the welding process, the operator technique, and the joint design. All of these influence the selection of a joining method and a welding material that will produce a welded joint having the properties required by the application.

Some Special Metals welding products are especially applicable to dissimilar joining applications. Welding product recommendations for many frequently encountered dissimilar joints are given in Table 17 (pages 30 and 31). For more specific recommendations, contact Special Metals Welding Products Company or visit the website, **www.specialmetalswelding.com**. The nickel-chromium electrodes and filler metals, INCO-WELD A, B, C, and 686CPT Electrodes, INCONEL Welding Electrodes 112, 122 and 182, INCONEL Filler Metals 82, 622 and 625, and INCO-WELD 686CPT Filler Metal are particularly versatile materials for dissimilar welding. They can tolerate dilution from a variety of base metals without becoming crack-sensitive.

In many cases, more than one welding product will satisfy the requirement of metallurgical compatibility. The selection of the optimum product will be determined by the requirements for strength, rigors of the service environment, and economics. In general, the weld should be at least as strong at the operating temperature as the weakest material in the dissimilar joint. Corrosion resistance to the service environment is critical. For example, INCOLOY alloy 825 may in theory be welded with either INCO-WELD A Welding Electrode or INCONEL Welding Electrode 112. If the weldment is to be exposed to a corrosive environment, Welding Electrode 112 will likely be preferred because of its superior corrosion resistance. However, if a low carbon steel beam is to be welded to the exterior of an alloy 825 vessel for structural reinforcement, INCO-WELD A might be preferred. It meets the strength requirement for joining steel to alloy 825 (it is stronger than the low carbon steel beam) and it is lower in cost than Welding Electrode 112.

Sometimes the suitable welding product for a dissimilar joint is not evident. Potential electrodes and filler metals must be evaluated on the basis of their ability to accept dilution from the two base metals without the resulting weld being crack sensitive or unsuitable in some other way. For a weld between a nickel-base alloy and another material, the best results will usually be obtained with a high nickel alloy welding product.

2) Dilution Rates

Dilution rate resulting from a set of welding conditions (welding process, technique, joint design, etc.) can be accurately determined by chemical analysis of a deposited bead. The dilution rate can also be determined by an area comparison on a joint cross section. As shown in Figure 17, the rate is calculated from measurements of the final weld-metal area and the area of original base metal included in it.

Dilution rates for shielded metal-arc welding are well established. Also, welder technique has less effect on dilution rate with shielded metal-arc welding than with other welding processes. For flat-position shielded metal-arc welding, a dilution rate of 30% is typical and may be used to calculate weld deposit composition. A 30% dilution rate means that 70% of the complete weld bead is supplied by the electrode, and 30% is supplied by the base metals with 15% coming from each dissimilar member. For other welding processes, dilution rates are dependent upon the specific welding technique and can vary widely. Dilution rates with the gas-metal arc process usually range from as little as 10% to over 50%, depending upon the type of metal

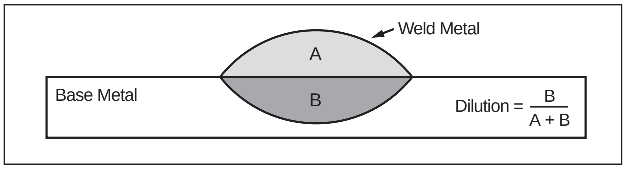


Figure 17. Calculation of dilution rate from cross-sectional area of weld bead.

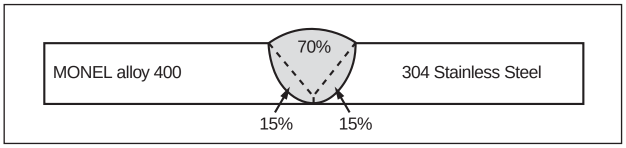


Figure 18. Weld metal contributed by each source in a dissimilar weld.

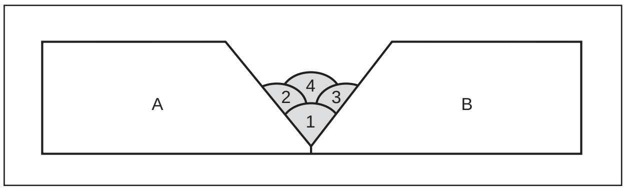


Figure 19. Multiple-pass dissimilar weld. Bead 1 is 15% A, 15% B, 70% filler metal. Bead 2 is 15% A, 15% Bead 1, 70% filler metal. Bead 4 is 15% Bead 2, 15% Bead 3, 70% filler metal.

transfer and torch manipulation. The highest dilution rates are encountered with spray transfer and the lowest with short-circuiting transfer. Large variations in dilution rate are also found with the gas tungsten-arc process. Dilution rates can range from about 20% to over 80% depending on the technique and the amount of filler metal added. The dilution rate in a joint between MONEL alloy 400 (67% Ni, 32% Cu) and Type 304 stainless steel (8% Ni, 18% Cr, 74% Fe) made with INCO-WELD A Electrode (70% Ni, 15% Cr, 8% Fe) would be composed of 15% MONEL alloy 400, 15% Type 304 stainless steel, and 70% INCO-WELD A Electrode. Figure 18 shows the relative amounts of each material in the weld bead. The amount of major elements contributed by each source can be calculated as follows:

Contribution of INCO-WELD A Electrode:
70% x 70% Ni = 49% Nickel
70% x 15% Cr = 10.5% Chromium
70% x 8% Fe = 5.6% Iron

Dilution by MONEL alloy 400:
15% x 67% Ni = 10% Nickel Dilution
15% x 32% Cu = 4.8% Copper Dilution

Dilution by Type 304 stainless steel:
15% x 8% Ni = 1.2% Nickel Dilution
15% x 18% Cr = 2.7% Chromium Dilution
15% x 74% Fe = 11.1% Iron Dilution

The electrode contribution added to base-metal dilution is the calculated composition of the weld deposit: 60.2% nickel (49% + 10% + 1.2%), 13.2% chromium (10.5% + 2.7%), 16.7% iron (5.6% + 11.1%), and 4.8% copper.

In a multiple-pass weld, composition remains constant along each bead in a macro or bulk sense but varies with bead location. The root bead is diluted equally by the two base metals. As shown in Figure 19, subsequent beads may be diluted partially by a base metal and partially by previous bead or entirely by previous beads.

3) Dilution Limits

Once the potential chemical composition of dissimilar weldment is determined, it becomes necessary to determine whether that composition is acceptable. This can in general be done by use of the following dilution limits. It is to be noted that these values are general in nature and no warranty is made as to their absolute accuracy. Also, the cracking tendency of a weld will also be influenced by its configuration, size, residual stresses, the welding process being used, etc.

The elements normally of concern in considering dilution of nickel alloy welding products are copper, chromium, and iron. All of the products can accept unlimited dilution by nickel without detriment.

Dilution limits given in the following discussion apply only to solid solution weld metal and wrought base materials. The values should be considered as guidelines. Questionable cases may require that a trial joint be evaluated. When a weld metal will be diluted by more than one potentially detrimental element (e.g., Pb, Sn, or Zn), allowance should be made for possible additive or interactive affects.

***Nickel Welding Products*.**

Nickel Welding Electrode 141 and Nickel Filler Metal 61 have high solubility limits for a variety of elements, and, from the standpoint of dilution tolerance, they are excellent dissimilar-welding materials. Use of the products for dissimilar welding, however, is often limited by their lower strength, in comparison with other nickel-alloy welding products.

The following dilution limits do not apply to NI-ROD and NI-ROD 55 Welding Electrodes. Those electrodes are specifically formulated for the welding of cast iron.

The nickel welding products have complete solubility for copper and can accept unlimited dilution by that element.

Chromium dilution of Filler Metal 61 and Welding Electrode 141 should not exceed 30%.

Nickel Welding Electrode 141 can tolerate up to about 40% iron dilution. Filler Metal 61, however, should not be diluted with more than 25% iron.

MONEL (Ni-Cu & Cu-Ni) Welding Products.

The nickel-copper and copper-nickel welding products (MONEL Welding Electrodes 190 and 187, MONEL Filler Metals 60 and 67) can tolerate unlimited dilution by copper.

Nickel-copper weld deposits can be diluted with up to about 8% chromium.

Copper-nickel deposits (Filler Metal 67 and Welding Electrode 187) should not be diluted with more than 5% chromium.

Iron dilution limits for deposits of MONEL Filler Metal 60 are influenced by the welding process used. If the deposit is applied by submerged-arc welding, it can tolerate up to about 22% iron dilution. With a gas-shielded process, the deposit can only be diluted by up to 15% iron without loss of mechanical properties.

If a joint involving steel is to be welded by a gas-shielded process with Filler Metal 60, a barrier layer of Nickel Filler Metal 61 should first be applied to the steel. Shielded metal-arc deposits of MONEL Welding Electrode 190 can be diluted with up to about 30% iron.

Iron dilution of copper-nickel weld deposits (MONEL Filler Metal 67 and Welding Electrode 187) should not exceed 5%.

INCONEL (Ni-Cr, Ni-Cr-Mo, Ni-Cr-Co-Mo) Welding Products.

The INCONEL nickel-chromium welding products are the most widely used materials for dissimilar welding. The products produce high-strength weld deposits, and the deposits can be diluted by a variety of dissimilar materials with no reduction of mechanical properties. Included in the nickel-chromium group of welding products is INCO-WELD A Electrode, which has exceptional dissimilar-welding capability.

Copper dilution of INCONEL welding products should not exceed about 15%.

The maximum total chromium content in the completed weld can be up to 30%. Since the welding products contain 15-20% chromium, dilution by chromium must be kept below 15%.

SMAW deposits of nickel-chromium from flux coated electrodes can accept up to about 50% iron dilution. Iron dilution of nickel-chromium filler metals, however, should not exceed 25%.

Silicon dilution of nickel-chromium deposits should also be considered, especially if the joint involves a cast material. Total silicon content in the weld deposit should not exceed about 0.75%.

4) Dissimilar Welding Products.

Environmental requirements of some welds will necessitate that they be deposited with non-matching weld metal. Iron castings are usually welded with nickel and nickel-iron (NI-ROD and NI-ROD 55) welding electrodes for strength, ductility, machinability, and other properties of interest. Nickel steels for cryogenic service (e.g. 9% Ni steel for liquid natural gas service) are often welded with INCONEL welding products because of their tensile strength and toughness at low temperatures. MONEL alloy 400 for service in hot saline is welded with INCONEL Welding Electrode 112 and INCONEL Filler Metal 625 to avoid preferential attack of the welds due to galvanic corrosion of the welds.

Super-Austenitic Stainless Steels (typically, Fe-25% Ni-20% Cr-6% Mo-0.2% N) are usually welded with INCONEL Welding Electrodes 112 and 122, INCONEL Filler Metals 625 and 622 or products that contain higher molybdenum contents. This is to provide welds that exhibit corrosion resistance equal to or better than the base metal. Over-alloyed welds are needed to offset the elemental segregation that occurs during solidification of the weld. These examples are by no means exhaustive but are intended to illustrate the versatility of nickel alloy weld metals in solving specific weld metal requirements in dissimilar metals welding applications.

Some general guidelines for selection of welding products for dissimilar joining applications are found in Table 17.

5) Thermal Expansion and Melting Point

In addition to weld-metal dilution, differences in thermal expansion and melting point can influence the selection of filler metal for dissimilar joints, especially when the welded parts will be exposed to high service temperatures.

Expansion differences in pieces to be joined can result in significant stresses in the joint area and a resulting reduction in fatigue strength. If one of the base metals is of lower strength, a filler metal that has an expansion rate near that of the weaker base metal should be selected. The stress resulting from unequal expansion will then be concentrated on the stronger side of the joint.

Joining pieces of austenitic stainless steel and mild steel illustrates the importance of thermal expansion considerations. The expansion rate of mild steel is lower than that of stainless steel. From the standpoint of dilution, either a stainless-steel electrode or an INCONEL nickel-chromium welding product would be suitable. The stainless electrode has an expansion rate near that of wrought stainless steel. Thus, if the joint is welded with a stainless steel product, both the weld metal and the stainless base metal expand in a similar manner to concentrate stresses along the weaker (mild-steel) side of the joint. If the joint is welded with an INCONEL welding product, the stress resulting from unequal expansion will be confined to the stronger, stainless steel side of the joint. An example of this principle is dissimilar joints in power generation boiler tubes. T-11 (1.25% Cr-0.5% Mo) and T-22 (2.25% Cr-1% Mo) waterwall tubes are welded to 304 stainless steel superheater tubes. Welds made with INCO-WELD A Welding Electrode or INCONEL Filler Metal 82 provide service life 5-7 times that of 309 stainless steel weldments.

Differences in melting point between two base metals or between the weld metal and base metal can during welding result in rupture of the material having the lower melting point. Solidification and contraction of the material with the higher melting point focuses stresses on the lower melting point material while it is in a weak, incompletely solidified condition. The problem can often be eliminated by the application of a layer of weld metal on the low-melting-point base metal before the joint is welded. Thus, a lower stress level is present during application of the weld-metal layer. During completion of the joint, the previously applied weld metal serves to reduce the melting-point differential across the weld joint.

Carbon migration can be an important consideration in the selection of a filler metal for a dissimilar joint with carbon steel. Nickel-alloy weld metals are effective barriers to carbon migration. For example, in joining carbon steels to stainless steels, high-nickel weld materials are sometimes used to prevent undesirable carbon migration from the carbon steel into the stainless steel where it might cause sensitization by combining with chromium and weakening of the depleted carbon steel.

Welding Product Selection

The selection of the optimum welding product is essential to the success of a joining application. In addition to the alloys being joined, many factors including strength, corrosion resistance, physical and mechanical properties, and anticipated weld metal dilution must be considered. However, as a general rule it is best to select a welding product that produces a weldment with strength and corrosion resistance superior to that of the material (or materials) being joined.

It is acknowledged that this is a complex subject requiring a thorough evaluation of the required properties of the joint. However, some general guidelines are presented in Table 17 (page 30 & 31) to assist the welding engineer. Designers may also wish to contact Special Metals Welding Products Company in Newton, NC for consultation and visit the website at **www.specialmetalswelding.com.**

Corrosion Resistance

The welding process and procedure and choice of welding product can greatly affect the corrosion resistance of the component being fabricated. Thus, the welding engineer must be cognizant of these effects and design accordingly. In general, it is best to join materials with over-matching composition (more highly alloyed, more corrosion-resistant) welding products. A comprehensive discussion of corrosion mechanisms is found in publication number SMC-026, "Special Metals: High-Performance Alloys for Resistance to Aqueous Corrosion".

Aqueous corrosion takes place as a flow of electric current between an anode and a cathode. Corrosion occurs at the anode. The relative sizes of the anode and the cathode can significantly affect the corrosion rate. If the cathode is significantly larger than the anode, the rate can be significantly increased. Thus, when designing a welded structure it is best that the weld metal be cathodic to the base metal. In other words, the weld should be more corrosion-resistant than the base metal. Since the weld is generally much smaller in area than the base metal, were the weld to be anodic, disastrous consequences could result. For example, the weld could simply corrode away preferentially to the base metal. As an example, for service in a marine environment, INCOLOY alloy 825 is best joined with INCONEL alloy 625 welding products - INCONEL Welding Electrode 112 or Filler Metal 625. Or, for service in flue gas desulfurization systems, INCONEL alloy C-276 is joined with INCO-WELD 686CPT welding products.

The idea of using over-matching composition welding products is particularly important when joining nickel-chromium-molybdenum corrosion-resistant alloys. Elements with relatively high melting points (e.g. molybdenum and tungsten) tend to segregate. Welding products with over-matching composition are often chosen for welding corrosion-resistant alloys. For example, 316 and 317 grades of stainless steel, 6% molybdenum super-austenitic stainless steels, duplex stainless steels, INCOLOY alloy 825, and INCONEL alloy G-3 are often joined with INCONEL alloy 625 welding products - INCONEL Welding Electrode 112 and INCONEL Filler Metal 625. More highly alloyed corrosion-resistant materials such as INCONEL alloys 625, 622, and C-276 are welded with the INCONEL alloy 686 welding products, INCO-WELD 686CPT Welding Electrode and Filler Metal. More information on the use of INCO-WELD 686CPT products for over-matching welding is included in publication SMC-024, "INCONEL alloy 686", on our website, **www.specialmetals.com**.

Welding Precipitation – Hardenable Alloys

The ability of precipitation-hardenable alloys to be strengthened by heat treatment results from their complex chemical composition and intricate metallurgical reactions that must take place in a very exact manner. Thus joining such alloys must be done exactly according to complex welding and heat treating procedures.

The precipitation-hardenable alloys produced by SMC are strengthened by two hardening systems. One is the nickel-aluminum-titanium system, which includes DURANICKEL alloy 301, MONEL alloy K-500, and INCONEL alloy X-750. The other is the nickel-niobium (columbium)-aluminum-titanium system, which includes INCONEL alloys 706, 718 and 725.

Figure 20. Failure in INCONEL alloy X-750 induced by residual welding stress at a 2-in. (51-mm) thick joint which was welded in the age-hardened condition and re-aged at 1300ÞF (705ÞC) for 20 h after welding.

Table 17 - Suggested Nickel Alloy Welding Products

Welding Electrodes for SMAW (below highlighted diagonal)

Filler Metals for GMAW, GTAW, & SAW (above highlighted diagonal)

	Nickel 200	MONEL alloy 400	INCONEL alloy 600	INCONEL alloy 625	INCONEL alloy 686	INCOLOY alloys 803, 800H/HT and 800	INCOLOY alloy 825	Carbon, Low alloy & Nickel Steels	3 - 30% Chromium Steels	Austenitic Stainless Steels	Duplex and Super Duplex Stainless Steels	Cast high-temperature alloys	Copper-Nickel alloys
Nickel 200	Nickel 61 Nickel 141	MONEL 60 Nickel 61	INCONEL 82 Nickel 61	INCONEL 625 INCONEL 82 Nickel 61	I-W 686CPT INCONEL 622 INCONEL 82 Nickel 61	INCONEL 82 Nickel 61	INCONEL 625 INCONEL 82 Nickel 61	INCONEL 82 Nickel 61	INCONEL 82 Nickel 61	INCONEL 82 Nickel 61	I-W 686CPT INCONEL 82 Nickel 61 INCONEL 622	INCONEL 82 Nickel 61	MONEL 60 MONEL 67 Nickel 61
MONEL alloy 400	MONEL 190 Nickel 141	MONEL 60 INCONEL 625 INCONEL 112 MONEL 190	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82 Nickel 61	I-W 686CPT INCONEL 625 INCONEL 82 INCONEL 622	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82 MONEL 60	INCONEL 625 INCONEL 82 MONEL 60	INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 625 INCONEL 82 INCONEL 622	INCONEL 625 INCONEL 82	MONEL 60 MONEL 67 Nickel 61
INCONEL alloy 600	INCO-WELD A INCONEL 112 INCONEL 182 Nickel 141	INCO-WELD A INCONEL 112 INCONEL 182	INCONEL 82 INCO-WELD A INCONEL 182	INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 625 INCONEL 82 INCONEL 622	INCONEL 617 INCONEL 625	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82	INCONEL 617 INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 82 INCONEL 622	INCONEL 617 INCONEL 625 INCONEL 82	INCONEL 82 Nickel 61
INCONEL alloy 625	INCO-WELD A INCONEL 112 INCONEL 182 Nickel 141	INCO-WELD A INCONEL 112 Nickel 141	INCO-WELD A INCONEL 112 INCONEL 182	INCONEL 625 INCONEL 112	I-W 686CPT INCONEL 62 INCONEL 622	INCONEL 617 INCONEL 625 INCONEL 82	INCONEL 625	INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 622	INCONEL 617 INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82 Nickel 61
INCONEL alloy 686	INCO-WELD A I-W 686CPT Nickel 141	I-W 686CPT INCO-WELD A INCONEL 112	INCO-WELD A INCONEL 82 I-W 686CPT	I-W 686CPT INCONEL 112	I-W 686 CPT INCONEL 622 I-W 686CPT	I-W 686CPT INCONEL 617 INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 625	I-W 686CPT INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 625 INCONEL 82	I-W 686CPT	I-W 686CPT INCONEL 617 INCONEL 82	I-W 686CPT INCONEL 625 Nickel 61
INCOLOY alloys 800, 800H/HT and 803	INCO-WELD A INCONEL 112 INCONEL 182 Nickel 141	INCO-WELD A INCONEL 112 INCONEL 182	INCO-WELD A INCONEL 112 INCONEL 117	INCO-WELD A INCONEL 112 INCONEL 117 INCONEL 182	INCO-WELD A I-W 686CPT INCONEL 122	INCONEL 617 INCONEL 82 INCO-WELD A INCONEL 117	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82	INCONEL 617 INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 82 INCONEL 622	INCONEL 617 INCONEL 625 INCONEL 82	INCONEL 82 Nickel 61
INCOLOY alloy 825 & Super Austenitic Stainless Steel	INCO-WELD A Nickel 141	INCO-WELD A INCONEL 112 INCONEL 182	INCO-WELD A INCONEL 112 INCONEL 182	INCONEL 112 INCONEL 122 I-W 686CPT	I-W 686CPT INCONEL 112 INCONEL 122	INCO-WELD A INCONEL 112	INCONEL 625 I-W 686CPT INCONEL 112 I-W 686CPT	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82 INCONEL 622	I-W 686CPT INCONEL 625	INCONEL 625 INCONEL 82	INCONEL 82 Nickel 61
Carbon, Low alloy & Nickel Steels	INCO-WELD A INCONEL 112 INCONEL 182 Nickel 141	INCO-WELD A INCONEL 112 INCONEL 182 MONEL 190	INCO-WELD A INCONEL 112 INCONEL 182	INCONEL 112 INCO-WELD A	INCO-WELD A I-W 686CPT INCONEL 122 INCONEL 182	INCO-WELD A INCONEL 117	INCO-WELD A INCONEL 112 INCONEL 182	INCONEL 625 INCONEL 82 INCO-WELD A INCONEL 112	INCONEL 625 INCONEL 82	INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 82 INCONEL 622	INCONEL 625 INCONEL 82	INCONEL 82 Nickel 61
3 - 30% Chromium Steels	INCO-WELD A INCONEL 112 INCONEL 182 Nickel 141	INCO-WELD A INCONEL 112 INCONEL 182	INCO-WELD A INCONEL 112 INCONEL 117	INCONEL 112 INCO-WELD A	INCO-WELD A I-W 686CPT INCONEL 122 INCONEL 182	INCO-WELD A INCONEL 117	INCO-WELD A INCONEL 112 INCONEL 182	INCO-WELD A INCO-WELD 112	INCONEL 625/52 INCONEL 82 INCONEL 82 INCONEL 112/152	INCONEL 625 INCONEL 82	I-W 686CPT INCONEL 625 INCONEL 82 INCONEL 622	INCONEL 625 INCONEL 82 INCONEL 617	INCONEL 82 Nickel 61
Austenitic Stainless Steels	INCO-WELD A INCONEL 112 INCONEL 182 Nickel 141	INCO-WELD A INCONEL 112 INCONEL 182 MONEL 190	INCO-WELD A INCONEL 112 INCONEL 117 INCONEL 182	I-W 686CPT INCONEL 112	INCO-WELD A I-W 686CPT INCONEL 122 INCONEL 182	INCO-WELD A INCONEL 112 INCONEL 117	INCO-WELD A INCONEL 112 INCONEL 182	INCO-WELD A INCONEL 112 INCONEL 182	INCO-WELD A INCONEL 112 INCONEL 182	I-W 686CPT INCONEL 82/625 I-W A/686CPT INCONEL 112	I-W 686CPT	INCONEL 82 INCONEL 82 INCONEL 622	INCONEL 82 Nickel 61
Duplex and Super Duplex Stainless Steels	I-W 686CPT INCO-WELD A Nickel 141 INCONEL 122	I-W 686CPT INCO-WELD A INCONEL 122	I-W 686CPT INCO-WELD A INCONEL 122	I-W 686CPT INCONEL 112 INCONEL 122	I-W 686CPT INCONEL 122	I-W 686CPT INCO-WELD A INCONEL 122	I-W 686CPT INCONEL 112 INCONEL 122	I-W 686CPT INCO-WELD A INCONEL 122 INCONEL 182	I-W 686CPT INCO-WELD A INCONEL 122	I-W 686CPT INCO-WELD A INCONEL 122	I-W 686CPT INCONEL 622 INCONEL 122 I-W 686CPT	I-W 686CPT INCONEL 82 INCONEL 622	I-W 686CPT INCONEL 82 INCONEL 622
Cast high-temperature alloys	INCO-WELD A INCONEL 112 INCONEL 182	INCO-WELD A INCONEL 112 INCONEL 182	INCO-WELD A INCONEL 117	INCO-WELD A INCONEL 117	I-W 686CPT INCONEL 117 INCONEL 122	INCO-WELD A INCONEL 117	INCO-WELD A INCONEL 112	INCO-WELD A INCONEL 112 INCONEL 182	INCO-WELD A INCONEL 112 INCONEL 117	INCO-WELD A INCONEL 112 INCONEL 117	I-W 686CPT INCO-WELD A INCONEL 122	INCONEL 617 INCONEL 82 INCO-WELD A INCONEL 117	INCONEL 82 Nickel 61
Copper-Nickel alloys	Nickel 141 MONEL 187 MONEL 190 Nickel 141	MONEL 190 MONEL 187 MONEL 190 Nickel 141	INCO-WELD A INCONEL 182 Nickel 141	INCO-WELD A INCONEL 112 Nickel 141	I-W 686CPT Nickel 141 INCONEL 122	INCO-WELD A INCONEL 182 Nickel 141	INCO-WELD A INCONEL 182 Nickel 141	INCO-WELD A INCONEL 182 MONEL 190 Nickel 141	INCO-WELD A INCONEL 182 Nickel 141	INCO-WELD A INCONEL 182 Nickel 141	I-W 686CPT INCO-WELD A INCONEL 122	INCO-WELD A INCONEL 182 Nickel 141	MONEL 67 MONEL 187

Both types of alloy systems are weldable. The most significant difference between the two systems is the rate at which precipitation occurs. Precipitation of the strengthening constituents in aluminum-titanium-niobium hardened alloys occurs more slowly. The delayed precipitation reaction enables the alloys to be welded and directly aged with less possibility of cracking.

Cracking can occur when high residual welding stresses are present during the aging treatment as shown in Figure 20. Cracking takes place in the base metal near the heat-affected zone, the area of highest stress. Stress relief occurs very slowly at aging temperatures. Thus, high residual welding stresses in conjunction with stresses resulting from aging can exceed the rupture strength of the base metal and the material cracks.

Precipitation-hardenable alloys are best joined by processes which induce the least stresses in the weldment. The gas tungsten-arc welding process is generally preferred. Ideally, matching composition welding products are used. If similar composition products are not available, a welding product of an alloy with properties similar to the alloy is used. When a dissimilar welding product must be used, it is critical that a product with similar aging constituents be chosen.

GENERAL WELDING PROCEDURES

Heat input during welding should be kept as low as practical. For multiple-bead or multiple-layer welds, several small beads should be used instead of a few large, heavy beads.

Aluminum and titanium readily form high melting oxide compounds. Even under ideal welding conditions, aluminum and titanium oxides form and float to the top of the molten weld puddle. When depositing multiple pass weldments, the oxide particle can accumulate to the point that a scale is formed. The oxide scale can inhibit proper fusion. Also, flakes of the oxide scale can become entrapped in the weldment. The trapped oxide particles can act as mechanical stress raisers and significantly reduce joint efficiency and service life. The oxide film should be removed by abrasive blasting or grinding when it becomes heavy enough to be visually apparent on the weld surface. Wire brushing is not recommended for this purpose as it does not actually remove the oxide film but only polishes it, thus hiding it from sight.

Rigid or complex structures must be assembled and welded with care to avoid excessively high stress levels. Fabricated parts or subassemblies should be given sufficient annealing treatments to ensure a low level of residual stress before they are precipitation heat treated. Any part that has been significantly worked by bending, drawing or other forming operations should be annealed prior to welding. Heat treating should be done in furnaces with an atmosphere controlled to limit oxidation and, thus, minimize subsequent cleaning operations. If a thermal treatment has been performed on material containing partially filled weld grooves, the oxide should be removed from the welding area by grinding or abrasive blasting before welding is resumed.

ALUMINUM-TITANIUM HARDENING SYSTEM

Because of their rapid aging response, alloys hardened by the aluminum-titanium precipitation reaction are susceptible to weld-associated base-metal cracking when they are welded and aged. Thus, special attention is required when preparing a welding/heat treating procedure.

Welding of aluminum-titanium hardened alloys is best accomplished after the component has been annealed or solution annealed prior to welding. Components welded in the aged condition should not be subsequently heat treated or exposed to service temperatures in the aging range (>1000°F).

Weldments age hardenable by the aluminum-titanium reaction should be solution-treated prior to precipitation heat treating. It is important that the thermal treatment be carried out with a fast, uniform rate of heating to avoid prolonged exposure to temperatures in the precipitation-hardening range. The best method to attain this high heating rate is to charge the weldment directly into a furnace preheated to the appropriate temperature. If the mass of the part is large in relation to furnace area, it may be necessary to preheat the furnace to 200-500°F (110-280°C) above the annealing temperature.

It is sometimes impractical to anneal a part after welding. Preweld heat treatments may be helpful in such cases. Two procedures that have been used successfully for INCONEL alloy X-750 are:

Heat at 1550°F (845°C)/16 hrs., air-cool, and weld, or
Heat at 1950°F (1065°C) 1 hr., furnace-cool at a rate of 25-100°F (15-55°C)/h to 1200°F (650°C),air-cool and weld.

ALUMINUM-TITANIUM-NIOBIUM (COLUMBIUM) HARDENING SYSTEM

The addition of niobium (columbium) to the aluminum-titanium reduces the rate of the precipitation reaction. This reduces the tendency of the alloy to cracking during heat treatment.

Aluminum-titanium-niobium hardened alloys such as INCONEL alloys 706, 718, and 725 are best welded in the annealed or solution-treated condition. If complex units must be annealed in conjunction with welding or forming operations, the annealing temperature should be consistent with the specification and end-use requirements. The alloys have good resistance to postweld cracking. Pierce-Miller weld-patch tests have shown that annealed alloy 718 sheet can under some conditions be welded and directly aged without-cracking. However, direct aging of highly restrained sheet that has been welded in the aged condition can result in base metal cracking. Highly restrained or complicated structures should be annealed after welding and prior to age hardening to avoid base metal cracking. Rapid heating as described above for aluminum-titanium hardened alloys is also recommended for aluminum-titanium-niobium hardened alloys as well.

Fabricating Nickel-Alloy Components for High Temperature Service

Equipment and components for service at high temperatures are often fabricated from nickel-chromium and iron-nickel-chromium alloy (e.g., INCONEL alloys 600, 601, and 617 and INCOLOY alloys 800HT and 803) because of their excellent heat resistance. The severe demands imposed by high temperatures must be considered in equipment design and welding procedures.

DESIGN FACTORS

Weldments sometimes have lower stress-rupture ductility and/or resistance to thermal fatigue than wrought products. Proper design of welded structures can minimize the effects of these reduced properties.

Equipment should be designed so that welds are located where the effects of reduced rupture ductility will not be detrimental. Generally, this involves placing the welds in areas where minimum deformation at high temperatures occurs. For example, a horizontal pipe supported at its ends and having a longitudinal weld should be turned to locate the weld at the top rather than at the bottom. Thus, the elongation that occurs when the pipe sags during high-temperature service takes place in the wrought portion of the pipe.

To minimize the effects of thermal or mechanical fatigue, welds should be located in areas of low-stress concentration. Corners and changes in shape and dimensions can tend to concentrate stresses. thus, welds should, when possible, be located elsewhere. Butt joints are preferred because the stresses act axially rather than eccentrically as in corner and lap joints. Figure 21 shows some examples of design modifications that locate welds in areas of low stress. Full penetration weldments are best and a backing weld should be applied when the root side of the joint is accessible.

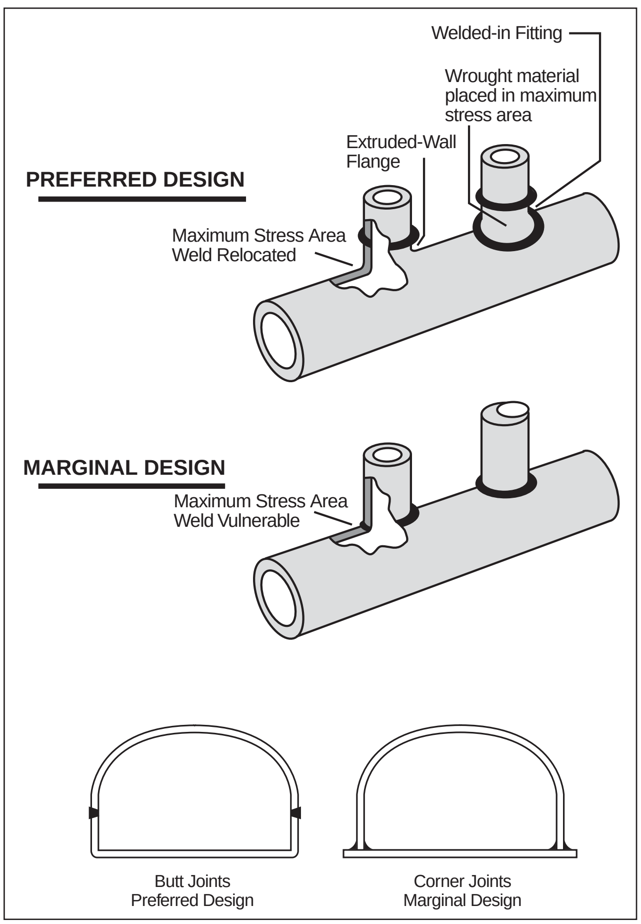


Figure 21. Designs for high-temperature service.

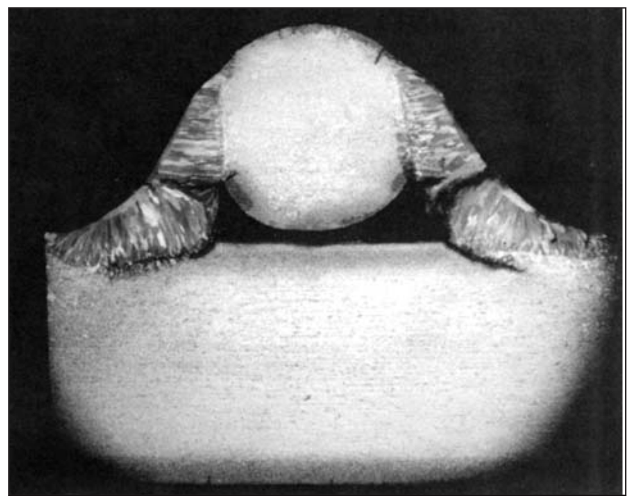


Figure 22. Thermal-fatigue cracking emanating from incomplete welds.

WELDING PROCEDURE

The weld should completely penetrate or close the joint. Lack of fusion and penetration should be avoided. Thermal-fatigue failures can often be traced to incomplete welds that create stress concentrations. Figure 22 shows an example. Some joint designs that facilitate complete penetration are shown in Figure 23.

If a joint must be located near dimension or shape changes, careful welding procedures are required to minimize the inherent stress concentrations. It is important to avoid undercutting, lack of penetration, weld craters, and excessive weld reinforcement. If a joint in rod or bar stock cannot be completely penetrated, the weld metal should be continuous and seal the joint so that none of the process atmosphere can enter. Figure 24 shows two joint types that can be completely sealed with weld metal.

Welds of heat treating apparatus fabricated of round or flat stock should be smoothly flared into the base metal without undercut. When heat treating equipment is to be exposed to cyclic heating and quenching, wrap-around or loosely riveted joints are sometimes desirable as they provide some freedom for movement.

When SMAW or SAW is employed for fabrication of alloy parts or equipment for high temperature service, it is essential that all welding slag be removed from completed joints prior to exposing them to elevated temperatures. Chromium-bearing nickel alloys exhibit heat resistance because they form a protective oxide layer on their surface which prevents corrodents (oxygen, sulfur, carbon, nitrogen, etc.) from penetrating into the alloy interior. Any slag remaining from welding becomes molten when exposed to elevated temperatures. The slag reduces the oxide layer on the surface of the alloy part allowing corrosion to progress quickly through the alloy section (Figure 25). Many types of slag contain fluoride and other compounds which are themselves corrosive and can attack the alloy component. Under reducing conditions, the slag can absorb and concentrate sulfur and other deleterious elements and compounds and accelerate attack. For example, it was found that when an alloy component that was contaminated with weld slag was exposed in an atmosphere containing 0.01% sulfur, the slag which originally contained only 0.05% sulfur was found to contain 1.6% after only a one month exposure. Increased sulfur content in the slag can also depress its melting temperature, causing it to melt and become corrosive at lower temperatures.

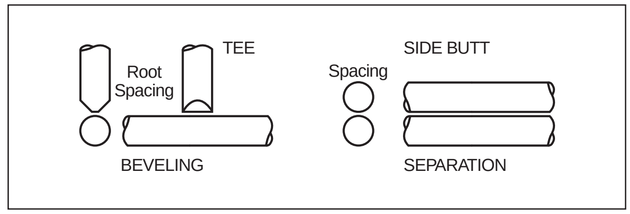


Figure 23. Designs for achievement of completely penetrated weld (high-temperature service).

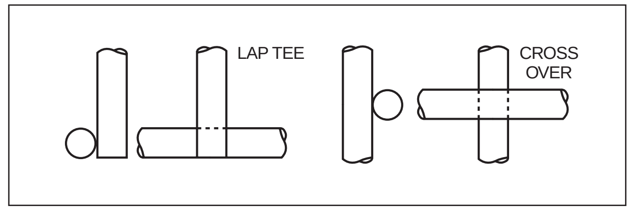


Figure 24. Designs for sealed joints by weld-all-around techniques (high-temperature service).

Figure 25. Attack by molten welding flux.

Testing and Inspection

Nickel alloy welds are normally tested and inspected by procedures similar to those used for carbon and stainless steel welds. Typical inspection techniques include visual examination, radiography, mechanical testing (e.g., tensile and impact), and metallography. Magnetic-particle inspection may be used to inspect welds in pure nickel products (e.g., Nickel 200 and 201). However, nickel alloys are non-magnetic under most conditions so magnetic particle inspection is not possible. Liquid penetrant inspection is widely used to locate small surface defects.

BEND TESTING

Bend testing is often used to evaluate the soundness and ductility of welded joints. Both free and guided bend tests are used. Specimens may be tested with the weld oriented either transverse or longitudinal.

Transverse specimens are commonly used for weld qualification. However, variations in properties across the weld can yield confusing results leading to the rejection of acceptable welds. A transverse bend test specimen contains several distinct zones which may have quite different properties. This can result in uneven deformation of the sample during testing. For example, if the weld metal is somewhat weaker than the base metal (e.g., as when two pieces of cold worked material are joined) deformation during bending will largely take place in the weld. While the weld may be sound and have excellent ductility, it may rupture during bending because of preferential deformation in the weld as compared to the stronger base metal.

The effect is more pronounced in dissimilar joints in which one member is lower in strength than the other. Figure 26 shows a transverse face-bend specimen of a joint between Nickel 200 and carbon steel. Almost all elongation took place on the Nickel 200 side of the joint. Average elongation measured in a gauge length spanning the entire joint may be 20%. However, the elongation occurring preferentially on the Nickel 200 side of the joint may be 40% or more.

A longitudinal bend test specimen in which the weld is in the center and parallel to the long edge deforms more evenly, thus yielding more reliable test

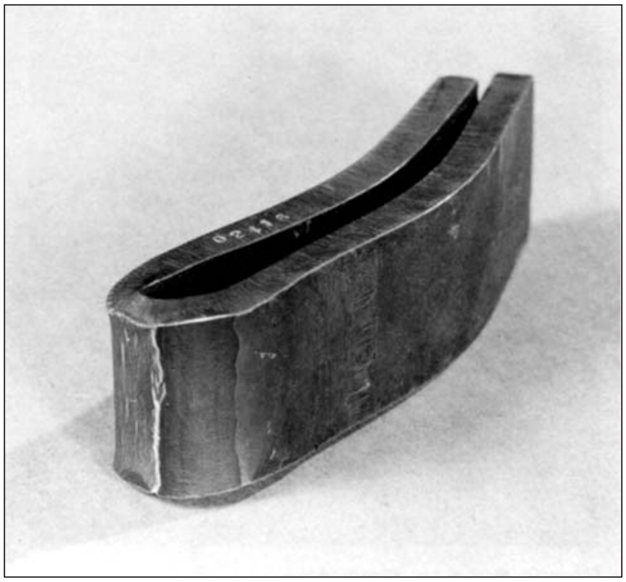


Figure 26. Transverse face-bend specimen.

Figure 27. Longitudinal bend-test specimen in which weld runs central and parallel to the long edge.

Table 18 - Macroetching Solutions for Weld Metals

Weld Metal	Etchant	Etchant Preparation
Nickel Welding Electrode 141	A	Etchant A 1 part H_2O_2 (30%) 2 parts HCl 3 parts H_2O Must be freshly mixed. Use hot H_2O to speed reaction. Immerse specimen 30-120 sec. Etchant B (Lepito's Solution) 1. Dissolve 15 gm $(NH_4)_2SO_4$ in 75 cc of H_2O 2. Dissolve 250 gm $FeCl_3$ in 100 cc of HCl 3. Mix 1 and 2 and add 30 cc of HNO_3 (concentrated). Swab on specimen. Heat specimen to speed reaction. Etchant C 1 part H_2O_2 (30%) 4 parts HCl Must be freshly mixed. Heat specimen to speed reaction. Immerse specimen 30-120 sec.
Nickel Filler Metal 61	A	
MONEL Welding Electrode 187[a]	A	
MONEL Welding Electrode 190[a]	A	
MONEL Filler Metal 60[a]	A	
MONEL Filler Metal 67[a]	A	
INCONEL Welding Electrode 112	C	
INCONEL Welding Electrode 132	A or B	
INCONEL Welding Electrode 182	A or B	
INCO-WELD A Electrode	A or B	
INCONEL Filler Metal 62	A or B	
INCONEL Filler Metal 82	A or B	
INCONEL Filler Metal 92	A or B	
INCONEL Filler Metal 601	A or B	
INCONEL Filler Metal 625	C	
INCONEL Filler Metal 718[a]	B	
INCOLOY Welding Electrode 135	A or B	
INCOLOY Filler Metal 65	A or B	

(a) Heat specimen to 200ÞF (95ÞC) before etching.

results. As shown in Figure 27, all areas of the joint must elongate at the same rate regardless of differences in strength. While they require a greater amount of welding for preparation of a specimen, longitudinal bend tests give the inspector a much more realistic assessment of the quality of a weldment.

Just as the results of transverse bend tests can be misleading, tensile tests pulled transverse to the direction of welding can give equally misleading results for the same reasons. Longitudinal tensile tests are preferred for determining weld metal strength and ductility.

VISUAL EXAMINATION OF ETCHED WELD SPECIMENS

Certainly the most widely used method of weld inspection is simple visual examination. Visual inspection can be enhanced by etching the specimen to be examined to better define details of the weld structure. The surface of a sample to be etched should be prepared by grinding. Rough grinding on an abrasive wheel or emery-cloth belt is usually adequate. Etching solutions for weldments deposited with various welding products are described in Table 18.

Brazing

Introduction

Brazing is a popular method of joining materials in which the bond is made without melting of the base metal. The filler metal wets the base metal by capillary flow. Thus, it is essential that the pieces to be joined are properly cleaned. They must be free of any external dirt and significant oxide films or scales must be removed. Brazing filler metals melt at temperatures below the melting point of the alloys being joined so the effect of the heat on the properties of the alloys are minimized. Furnace brazing is particularly popular for joining large numbers of small components. When properly designed and produced, the strength of a brazement approaches that of a weld.

Most nickel and nickel alloy products can be joined by brazing. General procedural information is presented here. However, for more detailed information on procedures and the alloys used as filler metals for brazing, the reader should contact the brazing filler metal manufacturer for specific recommendations. There are many proprietary brazing alloys available for which information is only available from the manufacturer.

Brazing may be performed manually by heating with an oxy-fuel torch and by automated means such as furnace brazing. Brazing is also possible with high technology heat sources such as LASER.

Four factors are important in achieving high strength: joint design, close control of joint clearances, elimination of flux inclusions and unfused areas, and effective wetting of the base material by the brazing alloy. All these factors must be addressed in a brazing procedure regardless of the heat source.

For development of maximum bond strength, the joint clearance should be small. Another approach is to make the lap joint three times the thickness of the thinner member. With this design, slightly larger clearances and some defects such as flux inclusions and incomplete brazed areas can be tolerated.

Parts to be brazed should be designed to be self-locating. If holding is required, some mechanical means such as riveting, staking, bolting, or spot welding should be used.

In all brazing operations, it is essential that the base material be clean. Common contaminants such as shop dirt, oil, grease, cutting fluid, marking compounds, etc. may be removed by chemical cleaning with solvents. Oxide and other surface scales and films, especially those on age-hardenable alloys (e.g., INCONEL alloys 718, 725 and X-750) and other alloys containing aluminum and/or titanium (e.g., INCONEL alloy 601), may require grinding. When brazing such alloys it may also be helpful to use a flux to reduce the oxide, plate the parts to be brazed with nickel or copper prior to brazing, or braze them in a furnace with a highly reducing atmosphere, or a vacuum chamber. The information on cleaning and surface preparation of components for welding presented earlier in this bulletin pages 2 and 3 is also applicable to brazing.

Parts which have been brazed must be thoroughly cleaned before welding (e.g., weld repair of a brazed part). All brazing alloy must be removed. Contamination of the weld with the braze alloy will almost certainly cause weld cracking because of the low melting metals inherent in braze filler metals.

BRAZING ALLOYS

Several different types of braze filler metals may be used to braze nickel alloys. The choice of the optimum product will be dependent upon economics, the temperature to which the braze will be exposed, the alloy being brazed, and the brazing process to be employed.

Brazing alloys that contain significant levels of phosphorus (e.g., ASTM BCuP-5) should never be used with any nickel alloy. The brittle nickel phosphide layer that forms at the bond line can fracture under impact or bending.

Precipitation-hardenable alloys are normally aged after brazing. Thus, brazing alloys with melting temperatures above the aging temperatures must be used.

Stress Cracking (Liquid Metal Embrittlement)

Before discussing brazing alloys and techniques, it is first necessary that the reader be warned about a catastrophic problem that can result from improper brazing procedures. Caution is advised when brazing nickel alloys with silver brazing alloys and other brazing materials containing low melting metals which can induce base metal cracking (Figure 28). This phenomenon is a type of stress-corrosion cracking often referred to as liquid metal embrittlement. It is encountered when brazing high-strength alloys with annealing temperatures above the melting temperature of the brazing alloy. Cracking occurs instantaneously at the brazing temperature and is usually detectable by visual examination.

Liquid metal cracking occurs by the action of a corrosive medium (silver and/or other low melting metals in the molten brazing alloy) in conjunction with stresses in the part being brazed. Both the corrosive medium and stress must be present for the phenomenon to occur. Stresses can be induced by metallurgical or mechanical mechanisms. Residual stresses in precipitation-hardenable alloys can result from the age hardening heat treatment. Cold forming (rolling, drawing, bending, spinning, etc.) can produce enough internal stresses to cause cracking during brazing. Improper restraint can also create excessive stresses. Stress can be induced when a fixture does not provide proper alignment of parts or the parts are clamped too tightly. When socket joints in tubing are being brazed, ovality (out-of-roundness) of both the tube and fitting must be at a minimum. Otherwise, stress will develop when the tube is forced into the socket. Unequal, rapid heating can also cause sufficient stress to cause cracking. If heavy parts are heated so rapidly that the outside surfaces become hot without appreciable heating of the center, thermal stresses can result and stress cracking may occur.

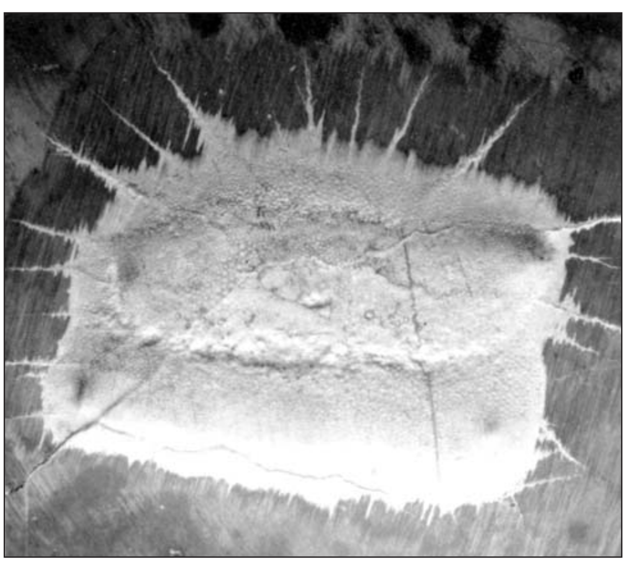


Figure 28. Specimen of silver-brazed INCONEL alloy 718 showing stress-corrosion cracking.

The precipitation-hardenable alloys must be brazed only in the annealed condition as the aging treatment stresses the material. While aged INCONEL alloy 718 is less sensitive than the other precipitation-hardenable alloys to stress-corrosion cracking during brazing, more reliable results will be obtained by brazing the alloy in the annealed condition.

Stress-corrosion cracking can usually be eliminated by a change in procedure, such as:

- Using annealed rather than hard-temper material.
- Annealing cold-worked parts before brazing.
- Eliminating externally applied stress.
- Heating at a slower, more uniform rate.
- Using a braze alloy with a higher melting point. Thus, some stress relief of the base material occurs during heating before the brazing alloy melts.
- In torch brazing, heating the fluxed and assembled parts to a high temperature (1600°F) and then cooling to the appropriate temperature before applying the brazing alloy.
- Using an alloy not containing silver or cadmium (Cadmium does not cause cracking by itself but can aggravate conditions conducive to cracking.)

Silver Brazing

Silver brazing alloys are popular because of their excellent flow characteristics and ease of usage. However, their cost is quite high. As noted on the prior page, silver brazing alloys readily cause liquid metal embrittlement of stressed alloy components.

Properly made silver braze joints will have the strength near that of annealed alloys at room-temperature. The strength of silver brazements drops rapidly as the temperature exceeds 300°F with 400°F being the maximum service temperature for highly stressed joints. If design stresses are sufficiently low, somewhat higher temperatures can be tolerated. Special alloys are available for service temperatures up to approximately 750°F.

SILVER BRAZING ALLOYS

Even though their main constituents are copper and zinc, brazing alloys containing only a small percentage of silver carry the silver designation. Examples are shown in Table 19. There are many silver brazing alloys manufactured under various proprietary trade names.

ASTM BAg-2, BAg-1, and BAg-1a are low-melting-temperature materials commonly used with nickel alloys. Brazing alloys ASTM BAg-4 and BAg-3 will fill wide clearances and produce large fillets because they are more viscous and sluggish when molten.

FLUXES

Fluxes for use with silver brazing are mixtures of fluorides and borates that melt below the melting temperature of the brazing alloys.

Standard fluxes are used on most alloys not containing aluminum. Special fluxes are available for aluminum-containing alloys (e.g., MONEL alloy K-500 and INCONEL alloys 718 and X-750. There are also fluxes designed to have long life during extended heating cycles.

Proper safety procedures must be followed during the preparation or use of fluxes. Fume control is essential.

JOINT DESIGN

Some of the joint designs commonly used in silver brazing are shown in Figure 29. Lap joints are preferred to butt joints. As shown in Figure 29, rings and washers of brazing alloy are often used. In some designs, vents must be provided for the escape of air or steam from the flux. Application of the brazing alloy should be taken into consideration when parts are designed.

HEATING METHODS

Any means of heating may be used that will bring the parts up to brazing temperature in a reasonable length of time and hold them there long enough for the alloy to flow. The joint must be uniformly heated. Torch heating with oxyacetylene, oxy-hydrogen, oxy-gas, or air-gas is commonly used. A large, soft, reducing flame will minimize oxidation.

Induction heating is an excellent way to heat a large number of small parts. Resistance heating is appropriate for brazing small parts and assembling small parts to large ones if pressure on the parts can be tolerated.

Salt bath brazing is feasible but seldom used with nickel alloys. Metal-bath brazing is used for fine wire and very small parts.

Electric or oil- or gas-fired furnaces are satisfactory. Temperature control is important especially because flow of the brazing alloy cannot be observed.

Surrounding the work with an oxygen-free gas will help extend the life of the flux during long heating cycles. Combusted city gas, nitrogen, hydrogen, and other gases have been used when heating at elevated temperatures for short times.

ATMOSPHERES

Furnace brazing without flux can be in a vacuum, a reducing atmosphere of dry hydrogen, dissociated ammonia, or combusted city gas when proper procedures are followed. Brazing alloys that contain low-vapor-pressure materials (e.g., cadmium, zinc, lithium) are not suitable for use with vacuum brazing.

A hydrogen atmosphere must be dry for successful brazing. The dew point required will depend on the

Table 19 - Silver Brazing Alloys

Nominal Composition, %				AWS Designation (Specification A5.8)	SAE Specification	Solidus[a] (Melting Point), ÞF	Liquidus[a] (Flow Point), ÞF
Silver	Copper	Zinc	Others				
15	80	–	5 P	BCuP-5	–	1190	1475
35	26	21	18 Cd	BAg-2	AMS-4768	1125	1295
40	30	28	2 Ni	BAg-4	–	1240	1435
45	15	16	24 Cd	BAg-1	AMS-4769	1125	1145
50	15-1/2	16-1/2	18 Cd	BAg-1a	AMS-4770	1160	1175
50	15-1/2	15-1/2	16 Cd, 3 Ni	BAg-3	AMS-4771	1170	1270
60	25	15	–	–	–	1245	1325
63	28-1/2	–	6 Sn, 2.5 Ni	–	AMS-4774	1275	1475
72	28	–	–	BAg-8	–	1435	1435

(a) Approximate temperatures, consult manufacturer for exact values.

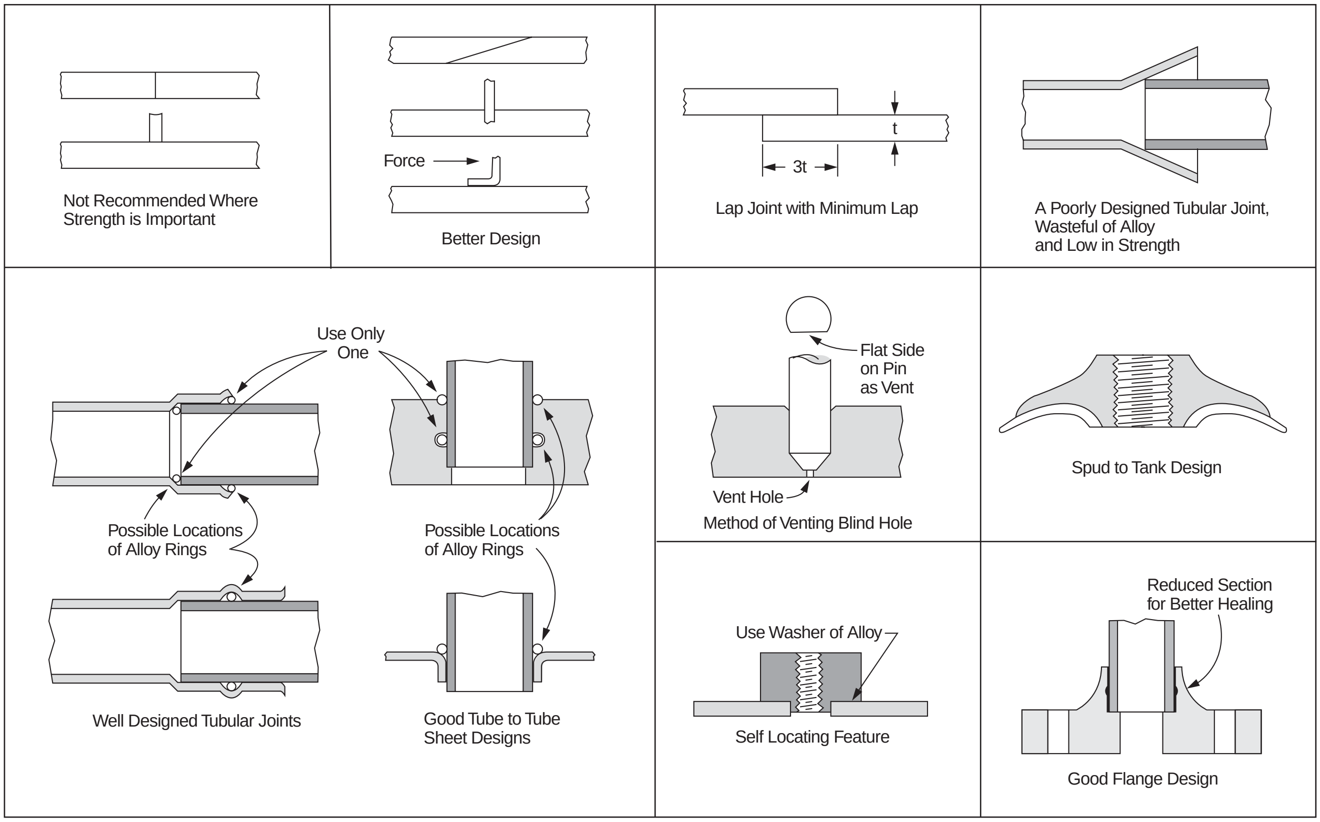


Figure 29. Some joint designs for silver brazing.

brazing temperature and the composition of the alloy to be brazed. Figure 30 (page 40) can be used as a guide in determining the dew point necessary for a brazing operation. The curves show the temperatures and dew points at which pure metals are at equilibrium with their oxides in hydrogen atmospheres. Conditions represented by the area above and to the left of an equilibrium curve are oxidizing to the metal; conditions below and to the right of a curve are reducing. For brazing, the dew point must be such that the atmosphere is reducing to the metal at brazing temperatures.

The plots in Figure 30 are for pure metals. For alloys, the curve representing the most difficult-to-reduce element present in an amount over 1% should be selected as the controlling curve. In practice, the dew point must be somewhat lower than the indicated equilibrium point, and a continuous flow of hydrogen is required.

PROCEDURE

The flux is generally applied by brush or swab. It is good practice to apply a generous coating to the parts prior to assembly and to assemble while the flux is wet. More flux can be applied to the finished assembly with particular attention paid to coating any pre-placed brazing alloy. If parts to be heated are covered by flux, oxidation will be prevented, and there will be no need for a subsequent oxide-removal treatment.

The flux should be allowed to dry prior to application of heat. Heating while the flux is wet often results in sputtering of the flux as the water is driven off.

When torch heating, the flame is played on the work prior to applying the brazing alloy so that the joint area comes up to a uniform temperature of 50° to 100°F higher than the melting temperature of the brazing alloy. The brazing alloy will flow to the hottest area if the parts are properly cleaned.

Care must be taken not to overheat the part. Overheating, evidenced by a lacy fillet instead of the shiny appearance of normal molten brazes, is a common source of trouble as the fluxes break down and excessive oxidation occurs.

Hand feeding of the brazing alloy is satisfactory for torch heating. However, since the amount of alloy used is a matter of operator judgement, it is usually not as economical as other methods. Brazing alloy rings, shapes, foil, or powder mixed in flux are generally more economical methods.

If torch brazing is employed, pre-placed braze filler metal should not be in the open where it might be melted prematurely. A neat joint with uniform filler will not result. Where inspection of the brazed joint will be difficult (such as the inside of a tube), it is advisable to place the insert away from the outer surface. Then a continuous fillet on the outside of the brazed joint will be a good indication of complete penetration. If washers or strips of brazing alloy are used, the parts must be free to move together as the alloy melts and flows.

When the alloy has flowed completely, the flame

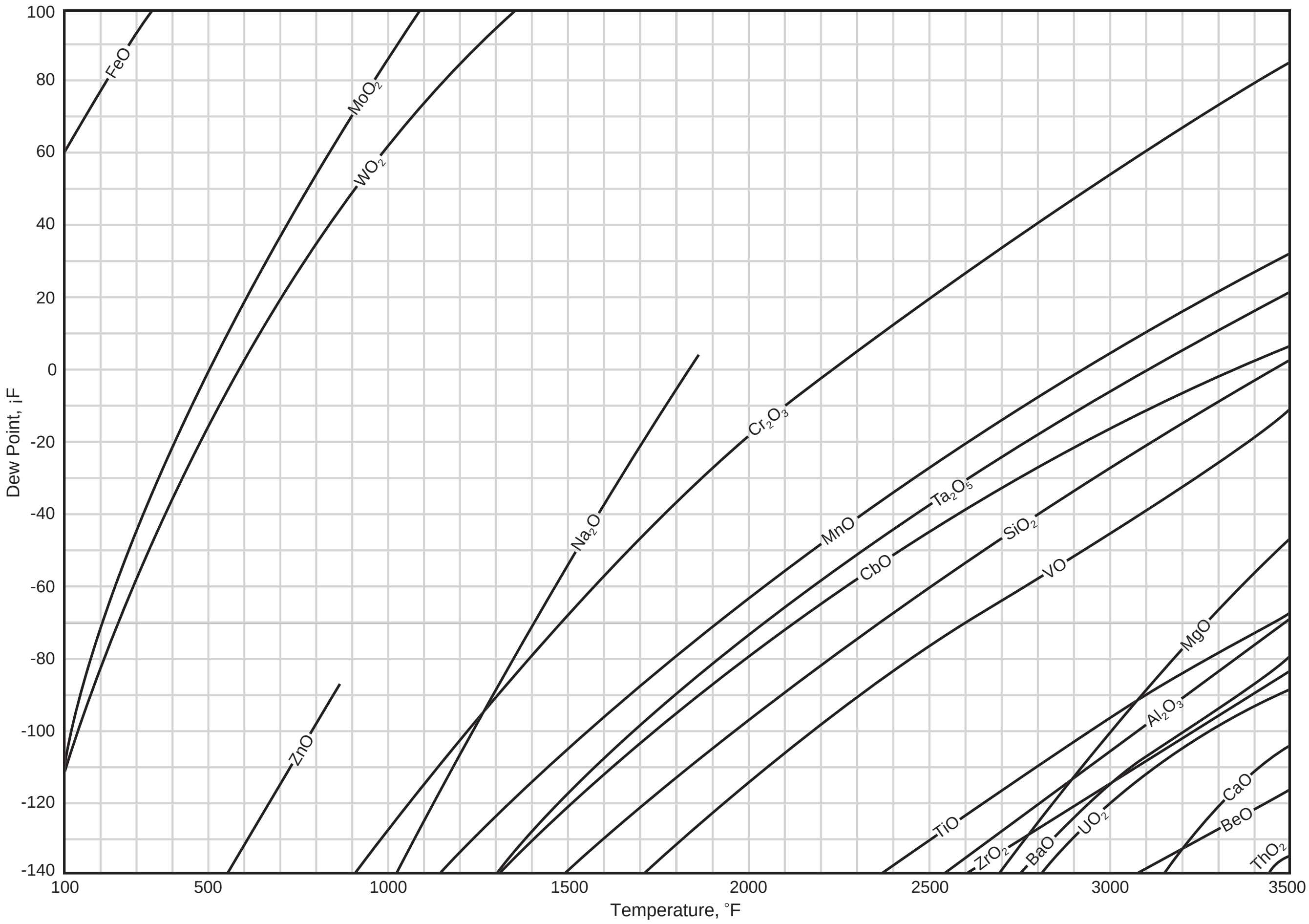


Figure 30. Metal/metal-oxide equilibria in pure hydrogen atmospheres. Metals easier to reduce than those plotted are Ni, Au, Pt, Ag, Pd, Ir, Cu, Pb, Co, Sn, Os, and Bi. La is more difficult to reduce than those plotted.

should be removed and the joint allowed to cool undisturbed. A sudden change from a very shiny to a dull surface appearance indicates solidification.

POSTBRAZING TREATMENT

After brazing, the flux must be removed as it will be corrosive to some materials. If the parts are quenched in water from about 700°F, most of the flux will be broken off by the thermal shock. The balance will wash off in hot water or steam and water. Flux residue is soluble in hot water, but considerable soaking time may be required for the removal of thick, fused material.

If oxidation has occurred, a pickling operation may be required to clean the assembly. An anodic treatment in 25% sulfuric acid is sometimes helpful for postbraze cleaning.

Heat treating of precipitation-hardenable alloys is best performed in two steps:

1. Solution anneal before brazing.
2. Age harden after brazing.

Copper Brazing

Copper brazing is normally used for joining components to be used at service temperatures up to 950°F. At higher temperatures copper brazements exhibit a drastic loss of strength and oxidize rapidly.

Nickel alloys can normally be copper-brazed with the same equipment used with steels. Minor changes in procedure may be necessary due to their special characteristics. Brazing temperatures range from 1850° to 2100°F; most operations are done at 2050°F.

A slightly rough or lightly etched surface is preferred for the optimum flow of copper braze alloys. Such a surface will be wet with copper for relatively large distances from actual joints. Polished surfaces will resist the flow of copper brazing metals.

Elements such as chromium, aluminum, and titanium form refractory oxides in a normal copper brazing atmosphere. Therefore, such alloys as INCONEL alloys 718 and X-750 and MONEL alloy K-500 will be more difficult to braze than Nickel 200 and MONEL alloy 400. To prevent the formation of these refractory oxides, the parts may be copper- or nickel-plated prior to brazing. Before plating, the material should be thoroughly cleaned and then given an anodic-cathodic strike treatment in a nickel chloride bath. During the anodic (reverse current) treatment oxides present on the material will be removed. The plating may then be applied with conventional current flow. While either nickel or copper will help prevent the refractory oxides from forming, but copper will, in addition, become the brazing alloy. About 0.003 in. of copper is usually adequate. If desired, the flash may be pickled off after brazing.

COPPER BRAZING ALLOYS

Commercially pure grades of copper are commonly used as brazing filler metals. Tough-pitch copper containing as much as 0.04% oxygen is used. However, it is generally believed that oxygen-free copper will produce joints having somewhat greater strength and ductility.

Alloys may be pre-placed in the form of wire, strips, slugs, plating, or powder. Powder may be applied as a slurry. The vehicles or binders most frequently used are methyl cellulose and acrylic resins whose products of combustion are gases that will not interfere with the brazing operation. They are preferred to such binders as machine oil, glycerin, and varnish, which leave a carbonaceous residue. A fairly thin mix will be required for dipping, brushing, or spraying. A stiffer mix may be used in a grease-gun-like manner.

FLUXES

Fluxes for brazing with copper filler metals are similar to those used for oxy-fuel welding. Mixtures of chloride salts (calcium, sodium, and barium) and fluoride salts (barium) in an appropriate binder are suitable. The addition of hematite and wetting agents may be required for brazing the age hardenable alloys. The flux mixture will become glass-like after cooling and is insoluble in water. Common methods of removal are abrasive blasting, chipping, and grinding.

JOINT DESIGN

Joint designs for copper-brazing nickel alloys are similar to those used for steel. Tolerances for assembly range from a light press fit to 0.002 in. maximum clearance. Butt-brazed joints will have strengths approaching those of annealed wrought alloy products.

HEATING METHODS AND ATMOSPHERES

Copper brazing is usually limited to furnace heating because of the atmosphere requirements. Heating may be electric, gas, or oil as long as the atmosphere can be maintained within desired limits. In some special cases, other means such as induction or resistance heating can be used, but only for highly specialized brazing of relatively small parts.

An atmosphere of combusted gas (containing not more than 20 grains sulfur per 100 cu ft) is satisfactory for MONEL alloy 400 and Nickel 200 but not INCONEL alloy 600. Dissociated ammonia can be used with alloy 400 and Nickel 200 and also for INCONEL alloy 600 if the dew point is low (-80°F or lower).

PROCEDURE

Copper brazing materials rapidly alloy with MONEL alloy 400 and Nickel 200. The braze metal should be placed as closely adjacent to the joint as possible. There should be sufficient metal to fill the joint. Excessive copper braze metal, however, can create excessive alloying with the nickel-chromium base metals.

Depth of alloying (penetration) is a function of brazing-alloy flow, quantity of brazing alloy, and time at temperature. When copper flows over the base metal, it can erode the surface. On heavy sections this effect may not be significant. However, when joining thin sections even shallow penetration may be serious. This problem can be partially overcome by limiting the amount of brazing alloy and reducing brazing time.

Excessive oxygen and moisture in the brazing atmosphere will impede or prevent flow of the copper brazing alloy. The surface of the part will appear dark and oxidized rather than bright. A positive pressure should be maintained in the furnace to prevent air from entering. Improper drying of the combustion gas before it enters the furnace can result in excessive oxidation.

POST-BRAZING TREATMENT

Copper-brazed parts usually require no post-brazing treatment. They should appear bright when they are removed from the furnace. Copper flash can be removed, either in a bath of 20 parts household ammonia and 1 part hydrogen peroxide or a solution of 15 gal. water, 1 gal. sulfuric acid, and 80 lb. of chromic acid. Immersion time depends on thickness of copper to be removed. One hour (or more) immersion time may be needed to remove a heavy flash.

Precipitation-hardenable alloys may be heat treated (age hardened) after brazing.

Flux must be removed from brazed parts by abrasive blasting, grinding, or chipping. It’s especially critical that parts for high-temperature service be thoroughly cleaned.

Nickel Brazing

Nickel brazing alloys produce joints with strength and oxidation resistance for service at temperatures up to 2000°F. While the brazements have good strength (often approaching that of the base metal), they generally exhibit only moderate ductility.

Table 20 - Strength of Butt Joints in Nickel-Chromium-Cobalt Alloy S-590 (AMS 5570) Brazed with Nickel-Chromium-Boron-Silicon Brazing Alloy (AMS 4775)

Test Temperature °F	Tensile Strength, psi	
	Brazed Joint	Base Metal
Room Temperature	119,230	134,500
800	100,150	103,230
1200	91,300	94,880
1400	69,250	70,850
1500	–	53,600
1600	41,730	39,280
1700	–	35,100
1800	23,280	23,600
1900	–	18,650
2000	13,790	13,810

Table 21 - Nickel-Base Brazing Alloys

Nominal Composition, %							Solidus, °F	Liquidus, °F	Brazing Range, °F	AWS Class.	AMS Spec.	Remarks
Ni	Cr	B	Si	Fe	C	P						
73.25	14	3.5	4	4.5	0.75 max	–	1790	1900	1950-2200	BNi-1	4775	High strength and heat-resistant joints.
82.4	7	3.1	4.5	3	–	–	1780	1830	1850-2150	BNi-2	4777	Similar to BNi-1. Lower brazing tempera ture.
90.9	–	3.1	4.5	1.5	–	–	1800	1900	1850-2150	BNi-3	4778	Good flowing characteristics.
92.5	–	1.5	3.5	1.5	–	–	1800	1950	1850-2150	BNi-4	4779	Useful for large, ductile fillets.
70.9	19	–	10.1	–	–	–	1975	2075	2100-2200	BNi-5	4782	Can be used for nuclear applications.
89	–	–	–	–	–	11	1610	1610	1700-1875	BNi-6	–	Extremely free flowing.
77	13	–	–	–	–	10	1630	1630	1700-1900	BNi-7	–	Useful for heat-resistant joints in thin sec tions.
70	16.5	3.75	4	4	0.95	–	1740	1950	–	–	4575A	Good high-temperature corrosion resist ance.
70	16.5	3.75	4	4	0.6 max	–	1740	1950	–	–	4776	Low-carbon version of 4575A.

Brazing with nickel-base filler metals is particularly useful for nickel-chromium superalloys such as INCONEL alloys 718 and X-750 and many of the NIMONIC and UDIMET alloys. Typical properties are shown in Table 20.

NICKEL BRAZING ALLOYS

Nickel brazing alloys typically contain 70 to 95% nickel. Some of these alloys are shown in Table 21. They are often produced in the form of powder (200 mesh or finer). They are also available as powder-impregnated sheets that can be cut or formed into rings, washers, and other shapes.

Powder can be applied directly to the parts to be to joined by placing it in adjacent holes. More often, it is applied as a slurry by brushing, spraying, dipping, or extruding. The slurry should be allowed to thoroughly dry before heating. The binder chosen for the slurry should leave no residue after brazing. Acrylic resins are flammable but have good characteristics for this purpose. Water-base methyl cellulose binders are also satisfactory.

FLUXES

Brazing can be accomplished using protective fluxes. Fluoride-base fluxes are popular. It is imperative that all residue be removed after brazing to avoid corrosive attack of the base metal. Flux residue is generally glass-like and quite tenacious, requiring grinding, chipping, or abrasive blasting for removal. Any fluxes that leave residues should not be used with joints that are inaccessible after assembly. In such cases, fluxes that are highly volatile and are expended during the brazing cycle are preferred.

JOINT DESIGN

Joint designs with nickel brazing alloys are the same as those used for silver brazing. Clearance should be maintained between 0.0005 and 0.005 in.

HEATING METHODS AND ATMOSPHERES

Nickel brazing is often performed in a furnace with highly reducing atmospheres. Base metals containing elements that form the most refractory oxides

Table 22 - Suggested Atmospheres for Brazing

Element[a]	Type of Atmosphere							Flux
	Combusted Fuel Gas (Exothermic)	Combusted Fuel Gas Exothermic (CO_2 Removed and Gas Dried, Exothermic)	High-Purity Cylinder Hydrogen	Dissociated (Cracked) Ammonia	Purified Inert Gas	Deoxidized and Dried High-Purity Hydrogen	Vacuum	
AWS Brazing Atmosphere Type No.	2	3	6	5	9	7	10	–
Copper, Cobalt, Nickel, Iron	X	X	X	X	X	X	X	X
Chromium	–	–	–	X	X	X	X	X
Silicon	–	–	–	–	–	X	X	X
Titanium	–	–	–	–	–	–	X	X
Aluminum	–	–	–	–	–	–	X	X

(a) More than 0.5%.

require the most stringent atmospheres. For many applications, dry hydrogen (at least -80°F dew point) is satisfactory. Table 22 shows suggested guidelines for atmospheres for use when either the base material or the brazing alloy contains the listed elements. However, the choice of atmosphere may be influenced by other factors in the manufacturing process. Also, if elements such as lithium are present, they may act as deoxidizers and permit the use of a less reducing atmosphere.

Alloys containing aluminum and titanium (e.g., precipitation hardenable alloys such as INCONEL alloy X-750 and 718) require special atmospheres for successful brazing. Even a dry hydrogen atmosphere may not be satisfactory for prevention of oxide formation on alloys containing more than 0.5% aluminum and/or titanium.

Nickel brazing can also be accomplished in a vacuum. A vacuum of at least 0.76 µ Hg is suggested. After evacuation, the chamber is sometimes backfilled with dry argon.

Bell-type furnaces are often used for furnace brazing with nickel-base filler metals because of their ability to satisfy the stringent atmosphere requirements. A standard copper-brazing furnace can be used for nickel-brazing. However, if low dew point hydrogen is to be used, it may be necessary to use a special retort to hold the work. Combusted city gas or dissociated ammonia may be used to surround the retort and protect the heating elements. There should be a slight positive pressure in the retort and it should be well sealed (sand seals containing alumina or mechanical seals, for example). To insure against an explosion, it should be thoroughly purged of air.

Oxyacetylene torch brazing can also be accomplished with nickel-base braze metals. This is best accomplished using the powder form of the brazing alloy mixed with a special high-temperature flux and a liquid vehicle to form a slurry. The brazing mixture is then brushed onto the joint.

PROCEDURE

Because it is difficult to obtain wetting on alloys containing more than about 0.5% aluminum and/or titanium, such alloys are often nickel-plated prior to brazing. The thickness of the plate required is dependent upon the brazing time and temperature. In general, however, a plate 0.0005 to 0.0015 inch is usually sufficient.

Interalloying has a very pronounced effect on the melting characteristics of the nickel brazing alloys. At brazing temperatures, the brazing alloy diffuses into the base metal. As diffusion occurs, the melting point of the remaining alloy increases. This coupled with vaporization of volatile elements can result in a significant increase in the melting temperature of the brazement. In service it will have useful strength at temperatures up to and even exceeding the original brazing temperature. Interalloying can be somewhat controlled by adjustment of time and temperature and quantity of brazing alloy.

Heating the part to be brazed too slowly through the melting range will cause the lower melting constituents of the alloy to become fluid and flow before the higher melting point elements. A "skull" of the higher melting constituents will remain solid. This material may not melt and flow even at the maximum brazing temperature. Because only part of the brazing alloy has been used, incomplete filling may result. The braze composition will also be altered and there will be elemental segregation. This undesirable situation can be avoided, particularly when joining thin sections, by using a high heating rate and brazing temperature and a shortened brazing time. If the braze alloy is brought to temperature fast enough, it will not separate.

POST-BRAZING TREATMENT

If good brazing practices are followed, parts should emerge from the furnace bright and scale-free, such that no post-brazing treatment is required. Precipitation hardenable materials may be heat-treated in the brazing furnace if desired. If flux has been used, any residue must be removed.

Other Brazing Alloys

Gold brazing alloys are used in jewelry manufacture for their color. The base material of gold-filled articles is often nickel. Procedures used are much like those for silver brazing. Gold-copper and gold-silver alloys are sometimes used in electronic vacuum tubes. Gold-nickel alloys are finding increased use, particularly in gas turbine and rocket engines.

Nickel and nickel-copper alloys are used as brazing alloys in the electronics industry to join tungsten and molybdenum to themselves and to other materials. Heating for brazing is generally by induction in a hydrogen bell.

Palladium-bearing brazing alloys have been developed for electronic devices and also for some high-temperature applications. Joining of complex assemblies often requires they be brazed without a flux. Special procedures may be necessary. Palladium alloys are useful because they have low vapor pressures at operating temperatures and because they form a series of alloys with graded brazing temperatures so that a number of successive brazing operations can be carried out on a single assembly.. Nickel-palladium brazing alloys are used for high-temperature applications. Two of these are shown in Table 23.

Other alloys for high-temperature brazing contain gold, silver, platinum, palladium, and manganese.

Table 23 - Nickel-Palladium Brazing Alloys for High-Temperature Applications

Composition, %					Brazing	Shear Strength, psi	
Ni	Mn	Pd	Cr	Si	Temp, °F	Room Temp	1450°F
48	31	21	–	–	2060	49,300	22,400
38	–	25	33	4	2150	36,000	31,500

While they do not produce joints as strong as those made with nickel-chromium-boron alloys, they are less prone to interalloying with the base metal. Thus, they exhibit better flow characteristics without attacking the base metal.

At elevated temperatures palladium alloy brazements are lower in strength than nickel-chromium brazements. For example, a nickel-chromium-boron-silicon brazement deposited using AMS 4775 braze metal typically exhibits a tensile strength at 1400°F of about 70 ksi. A brazement of 38% nickel, 33% chromium, 25% palladium, and 4% silicon has a tensile strength under similar conditions of about 30 ksi. Such differences in strength must be considered in the part design.

AWS BAu-4, a brazing alloy of 18% nickel and 82% gold, can often be used to braze INCONEL alloys 600, X-750, and 718 and other high-temperature alloys. Some of its desirable characteristics are resistance to stress corrosion, ability to fill relatively large clearances, small tendency to erode base metal, ductility at all temperatures, and good oxidation resistance. However, the brazements are not as strong as those made with nickel-chromium-boron-silicon brazing alloys.

Inspection of Brazements

To verify the quality of brazements, they must be inspected after deposition. While some inspection techniques for brazements are similar to those utilized for weld inspection, others are quite different.

All flux residue should be removed before visual inspection of brazed joints. Pinholes and unbrazed areas are often easily detected visually. If the brazing alloy has been preplaced so that it must flow completely through the joint to form a continuous fillet on the other side, visual inspection is usually sufficient to determine if the joint is sound and leaktight. However, visual inspection cannot ensure complete penetration.

A "lumpy" fillet-braze deposit not faired into the base metal indicates that insufficient heat was used. Too much heat may result in a fillet with a lacy appearance and pinholes.

Faulty joints that are clean may be refluxed and rebrazed. If serious oxidation has occurred, it is best to remove the braze, clean the joint, and rebraze.

Soldering

Introduction

Soldering may be used to join nickel-base alloys to themselves and other engineering materials if such requirements as strength and corrosion resistance will be met.

SOLDER ALLOYS

Common solders are composed of lead and tin. Solders with special properties may also contain antimony, silver, arsenic, bismuth, or indium.

Specifications for solder metals are shown in ASTM Specification B32.

FLUXES

Selection of the proper flux is an important criterion in achieving high quality solder joints in nickel and nickel alloys. Alloys to be soldered should be cleaned immediately before joining.

Zinc chloride-base fluxes are recommended for use with Nickel and MONEL alloys in conjunction with lead-tin or tin-lead solder. They may be purchased or made as shown below.

1. Zinc chloride.......................1 lb.
   Ammonium chloride..........1 lb.
   Glycerin..............................1 lb.
   Water.................................. 1 gal.
2. Neutralized acid (zinc added to hydrochloric acid until all effervescence stops and an excess of zinc exists). A small amount of ammonium chloride may be added.

Rosin-base fluxes can sometimes be used but generally only under very limited conditions. Special care is required to qualify the solder procedure to be sure that the flux is acceptable.

Stronger fluxes are required for nickel-chromium alloys such as INCONEL alloy 600. The commercially available fluxes designed for austenitic stainless steels are satisfactory. The following may also be satisfactory.

1. Neutralized acid plus 10% acetic acid.
2. Hydrochloric acid...............90 parts by weight
   Ferric chloride....................50 parts by weight
   Nitric acid...........................3 parts by weight

All of the above fluxes (except rosin-base) are strongly corrosive and must be carefully removed from the work after soldering. When washing after soldering is not possible, the following procedures may be substituted for those above.

For all nickel-base alloys, use one of the fluxes described above and precoat ("pre-tin") the parts. Wash them thoroughly. Use a non-corrosive rosin-base flux for final joining.

For Nickel 200 or MONEL alloy 400, use an organic acid flux (several proprietary fluxes are commercially available) that is corrosive at ambient temperatures but becomes non-corrosive when heated to soldering temperatures. All parts coated with flux must be heated to soldering temperature.

Proper safety procedures must be followed during the preparation and use of fluxes.

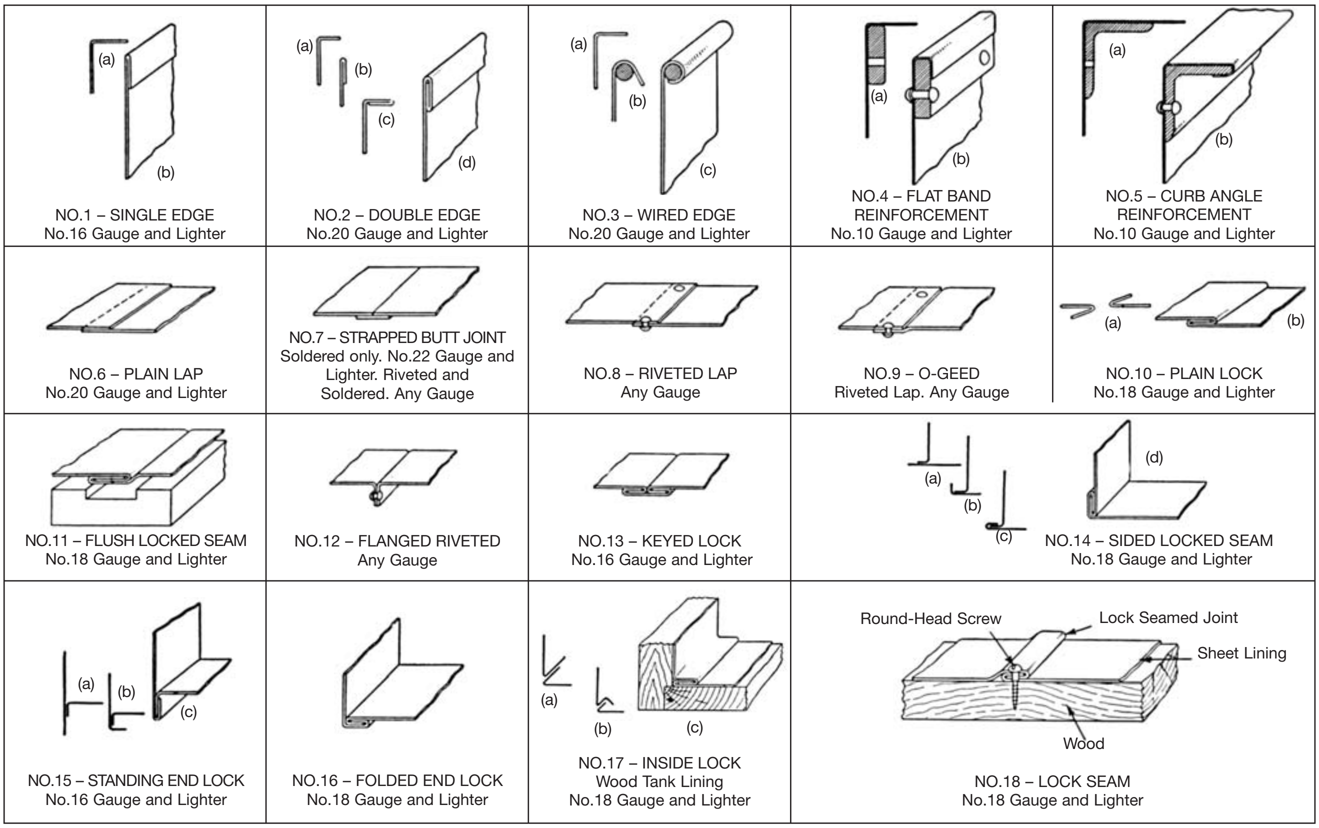


Figure 31. Mechanical joints and edge reinforcements used for joints to be soldered.

Joint Design

Joints that depend on solder alone for strength are relatively weak. They lose strength as the temperature increases, and some solders become brittle at low temperatures. Thus, solder alone cannot make a strong joint; it is used only to seal the joint. Joining techniques such as lock-seaming, riveting, spot welding, bolting should be incorporated to carry the structural load of the joint. Examples of reinforced joints are shown in Figure 31.

HEATING METHODS

The heating methods typically used for soldering are normally acceptable for use with nickel alloys. Heating procedures are also similar except that the lower thermal conductivity of some alloys may require slightly higher temperature, longer times, and/or more effective distribution of heat.

Overheating must be avoided, as it results in excessive oxide formation, carbonization of the flux, and poor joint quality.

PROCEDURES

Material to be soldered must be clean and free of foreign material. Surface preparation is discussed in detail in the front of this bulletin.

Joints with long laps, such as lock-seam joints and tubular joints, should be precoated (pre-tinned) prior to assembly with the same material to be used for soldering. Parts may be dipped in a molten solder bath or the surfaces may be heated and coated with flux and the solder flowed on. Excess solder is removed by shaking, wiping, or brushing while it is molten. Parts may also be protected by tin plating or hot tin dipping.

Precipitation-hardenable materials must be soldered after aging. Temperatures required for age hardening will melt most solders. Soldering temperatures will not significantly affect the properties of the aged alloys.

POST-SOLDERING TREATMENT

Most flux residues are hygroscopic. When they absorb moisture, they may become corrosive to nickel alloys. Even petroleum-base fluxes become corrosive as they oxidize with time. Residues, therefore, must be removed.

Washing in water or aqueous alkaline solutions (e.g., water containing ammonia or bicarbonate of soda) will remove most residues. If the flux binder contains oil or grease, the material must be degreased and then washed.

INSPECTION

Visual inspection is easily accomplished and usually gives one a good evaluation of the quality of a soldered joint. Fillets should be smooth and uninterrupted and should fair into the base material. Lumps are indicative of insufficient heat. Holes or discontinuities can be caused by dirty material or overheating and should be viewed with suspicion as possible leaks. Joints which must be leaktight should be pressure-tested.

Thermal Cutting

Introduction

Cutting Nickel Alloys

Many thermal processes can be used to successfully cut nickel-base alloy products. Determination of the optimum process is dependent upon the alloy, form, and thickness of the product being cut, the required tolerances and quality of cut, the cutting speed required, and whether the cutting operation will be automatic or manual.

Plasma-Arc Cutting

Cutting by the plasma-arc process is fast, versatile, and of the highest quality. High power and gas velocity are required for cutting so that the molten metal is blown out rather than allowed to solidify. When the proper procedures and modern equipment are used, little or no grinding of the cut surface is required prior to welding.

The energy required for cutting is generated by a high-velocity, constricted electric arc that passes between a tungsten electrode and the metal to be cut. Temperatures reach 10,000° to 40,000°F through the decomposition of superheated gas molecules into higher-energy ions and electrons or ion pairs.

In theory, several plasma-forming gases may be used. However, in general, nitrogen-hydrogen mixtures produce better results than argon-hydrogen mixtures. Cuts are cleaner and less sensitive to variations in settings. Cutting of very thick sections (over 5 in.), however, can best be done with the argon-hydrogen mixtures. While air and oxygen have been used, they are normally avoided because of short electrode life.

Most plasma-cutting systems use a dual flow of gases around the electrode and through the orifice. Nitrogen forms an inner stream to cool and protect the electrode and form an effective, efficient plasma column. An outer sheath of air or oxygen increases cutting efficiency.

Some conditions for plasma-arc cutting are shown in Table 24. Typical cuts are seen in Figure 32. Cuts up to 6 in. thick have been made in nickel alloys.

Table 24 -Conditions for Plasma-Arc Cutting

Material	Thickness (in)	Gas Flow (cfh)	Gas Type	Power (kw)	Speed (ipm)
Nickel 200	1-1/2	220	85% N_2, 15% H_2	95	25
	3	260	85% N_2, 15% H_2	138	6
	6	150	65% A, 35% H_2	104	5
MONEL alloy 400	2	270	85% N_2, 15% H_2	155	35
	2	260	85% N_2, 15% H_2	134	5
INCONEL alloy 600	1-3/4	220	85% N_2, 15% H_2	95	25
	3	260	85% N_2, 15% H_2	135	5
	6	150	65% A, 35% H_2	103	5
INCONEL X-750	2-1/2	270	85% N_2, 15% H_2	148	20
INCOLOY alloy 800	1-1/2	220	85% N_2, 15% H_2	92	20
	3	260	85% N_2, 15% H_2	163	5
	6	130	65% A, 35% H_2	98	5

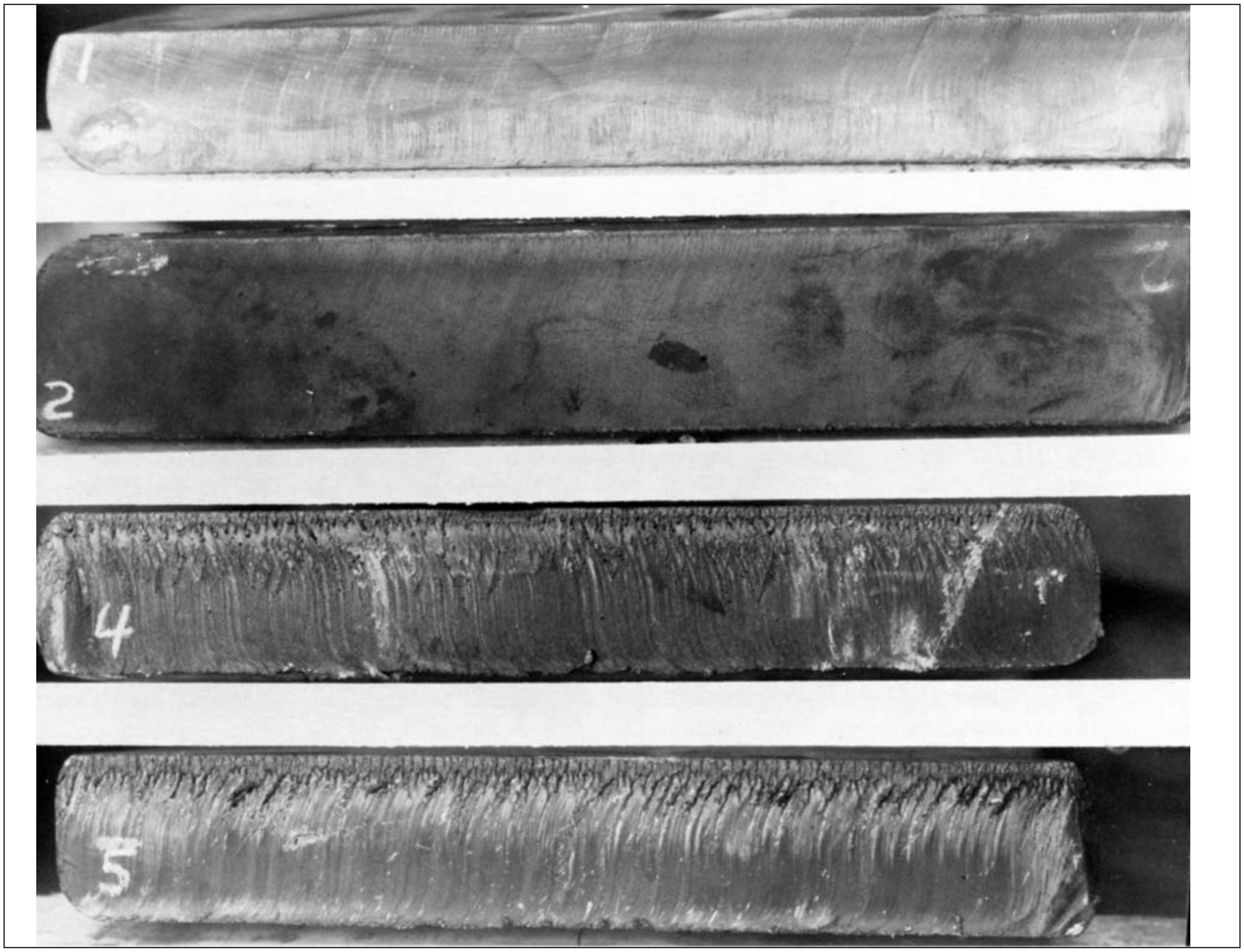


Figure 32. Cuts produced by plasma-arc process. (Top to bottom: Nickel 200, 1-1/2 in.; MONEL alloy 400, 2 in.; INCOLOY alloy 800, 1-1/2 in.; INCONEL alloy 600, 1-3/4 in).

Because of the restricted plasma column and the speed of the cutting process, heat-affected zones are usually quite narrow (0.010 to 0.015 inch wide). The cut surfaces of the thinner sections (3 inches and less) are very smooth and exhibit little or no dross. They are essentially square. For many applications little or no grinding is required.

Powder Cutting

Powder cutting, a variation of the gas cutting process, is based on the use of an oxygen jet into which is fed a fine metal powder. The powder initiates an exothermic reaction that supplies the necessary heat for cutting. Nickel alloys can be readily cut with a mixture of 70% iron and 30% aluminum. Table 25 shows data obtained from powder cutting.

Powder cutting results in the formation and accumulation of considerable amounts of oxide, dross, and burned material on the cut metal with the greatest buildup occurring on the top surface (Figure 33). This slag is more adherent on nickel-copper alloys than on nickel or nickel-chromium alloys. All adherent slag, powder, or dross must be removed prior to any further operation.

The heat-affected area from powder cutting is shallow. Corrosion resistance of the metal is not significantly affected if all discoloration is removed. However, tolerances of powder cuts are large such that powder cutting is limited more to severing of large sections as opposed to cutting of small parts requiring close tolerances.

Air Carbon-Arc Cutting and Gouging

The air carbon-arc process utilizes a graphite electrode that has been copper-coated to improve current-carrying characteristics and lengthen service life. Molten metal is blown away by a high-velocity stream of air flowing from the electrode holder. A standard constant-current SMAW power source is used.

The process is more effective for gouging operations rather than cutting and is widely used for back-gouging operations on welds and for the removal of fillet welds. By controlling the depth of the groove, limited thicknesses of material can be cut. While grooves up to 1 inch in depth can be made in a single pass, gouging in multiple increments of 1/4 in. depth yield optimum control. The width of the groove is determined primarily by the size of electrode. Torch

Table 25 - Powder Cutting Conditions						
Material	Thickness (in)	Speed (in/min)	Powder[a] Consumption (oz/min)	Oxygen Pressure (psi)	Nozzle Diameter (in)	Comments
Nickel 200	1/4	11.0	4.5	40	0.060	Good cut.
	1-5/16	4.5	9.0	65	0.100	Very rough cut
	1-5/16	4.0	9.0	65	0.100	Moderately rough cut, 500°F preheat.
	5	–	–	75	0.200	Would not cut.
MONEL alloy 400	1/4	11.0	4.5	40	0.060	Good cut.
	1/2	5.5	5.0-6.0	30	0.060	Good cut.
	1	4.6	6.0	65	0.100	Rough cut.
	1	4.4	6.0	65	0.100	Moderately rough cut, 500°F preheat.
	5	3.0	12.0	75	0.200	Fairly smooth cut, 700°F preheat.
INCONEL alloy 600	1/4	26.0	4.0-5.0	40	0.060	Good cut.
	5/8	7.0	9.0	65	0.080	Fairly smooth cut.

(a) 70% iron, 30% aluminum.

Figure 33. Iron oxide and burned material adhering to nickel alloy cut by powder-cutting process.

angle and speed affect the depth of the groove and the heat-affected zone.

Operating conditions must be carefully controlled to ensure that all molten metal is blown away from the workpiece. Air pressure and flow must be adequate. Arc voltage must be sufficiently high to develop a relatively long arc so that the air stream sweeps below the tip of the electrode. Under proper conditions, the surface of the groove will be smooth and the kerf will be small. Only light grinding is required to prepare the groove for welding.

Gas Tungsten-Arc Cutting

The gas tungsten-arc (GTA) process may be efficiently used to cut nickel alloys up to 1/8 inch in thickness. Under some conditions materials up to 2 inches thick may be cut. Cutting is accomplished by a constricted arc between a 1/8 or 5/32 in. diameter thoriated tungsten electrode and the workpiece. The cutting action is very fast.

For automatic cutting, the gas stream is 65% argon and 35% hydrogen. For manual cutting, a gas stream of 80% argon and 20% hydrogen is preferred. The stream should be of high velocity, with flow at about 70 cfh.

The GTA process requires a power supply capable of delivering 400 amperes at an arc voltage of 70-85 volts. Direct current - straight polarity (electrode negative) yields the best cutting results though the electrode life may be quite short.

Cuts in thinner material are smooth and have a good appearance. Cuts in thicker material may have more oxide and dross and may not be square. Bevel cuts can be made successfully. Typical cutting conditions are shown in Table 26.

An adherent metal dross normally forms on the bottom edge of the sections being cut. This layer can be minimized (or even eliminated) by clamping a sacrificial ("waster") plate of 3/16 or 1/4 inch mild steel to the bottom of the material to be cut.

Table 26 - Gas Tungsten-Arc Cutting Conditions (65% argon, 35% hydrogen gas at 70 cfh)					
Material	Thickness (in)	Cut	Current (amp)	Arc (volts)	Cutting Speed (ipm)
Nickel 200	3/8	Straight	430	70	60
MONEL alloy 400	3/8	Straight	430	70	60
MONEL alloy K-500	3/4	Straight	430	75	30
INCONEL alloy 600	3/8	Straight	430	70	60
	3/4	Straight	420	80	25
	1-1/4	Straight	500	85	20
	1-1/4	Bevel	450	90	15
	1-3/4	Straight	580	95	15
INCONEL alloy X-750	3/4	Straight	420	75	30
	3/4	Bevel	420	85	20
	1-1/8	Straight	400	80	25
	1-1//8	Bevel	400	85	15

The Special Metals Corporation trademarks include:

BRIGHTRAY®	INCOTHERM®	UDIMET®
CORRONEL®	INCO-WELD®	601GC®
DEPOLARIZED®	KOTHERM®	625LCF®
DURANICKEL®	MONEL®	686CPT®
FERRY®	NILO®	718SPF™
INCOBAR®	NILOMAG®	725™
INCOCLAD®	NIMONIC®	725NDUR ®
INCO-CORED®	NIOTHERM®	800HT®
INCOFLUX®	NI-ROD®	864™
INCOLOY®	NI-SPAN-C®	925™
INCONEL®	RESISTOHM®	956HT™
INCOTEST®	UDIMAR®	

Publication Number SMC-055

SPECIAL METALS

www.specialmetals.com

AFAQ ISO 9002

AFAQ ISO/TS 16949

LLOYD'S REGISTER QUALITY ASSURANCE ISO9002

ISO 9002 Certificate Number: 30125

TÜV CERT

UKAS TESTING 0281

NADCAP PERFORMANCE REVIEW INSTITUTE - Accredited -

U.S.A.
Special Metals Corporation

Billet, rod & bar, flat & tubular products
3200 Riverside Drive
Huntington, WV 25705-1771
Phone +1 (304) 526-5100
+1 (800) 334-4626
Fax +1 (304) 526-5643

Billet & bar products
4317 Middle Settlement Road
New Hartford, NY 13413-5392
Phone +1 (315) 798-2900
+1 (800) 334-8351
Fax +1 (315)798-2016

Atomized powder products
100 Industry Lane
Princeton, KY 42445
Phone +1 (270) 365-9551
Fax +1 (270) 365-5910

Shape Memory Alloys
4317 Middle Settlement Road
New Hartford, NY 13413-5392
Phone +1 (315) 798-2939
Fax +1 (315) 798-6860

United Kingdom

Special Metals Wiggin Ltd.
Holmer Road
Hereford HR4 9SL
Phone +44 (0) 1432 382200
Fax +44 (0) 1432 264030

Special Metals Wire Products
Holmer Road
Hereford HR4 9SL
Phone +44 (0) 1432 382556
Fax +44 (0) 1432 352984

China

Special Metals Pacific Pte. Ltd.
Room 1802, Plaza 66
1266 West Nanjing Road
Shanghai 200040
Phone +86 21 6288 1878
Fax +86 10 6288 1811

Special Metals Pacific Pte. Ltd.
Room 118, Ke Lun Mansion
12A Guanghua Road
Choa Yang District
Beijing 100020
Phone +86 10 6581 8396
Fax +86 10 6581 8381

France

Special Metals Services SA
17 Rue des Frères Lumière
69680 Chassieu (Lyon)
Phone +33 (0) 4 72 47 46 46
Fax +33 (0) 4 72 47 46 59

Germany

Special Metals Deutschland Ltd.
Postfach 20 04 09
40102 Düsseldorf
Phone +49 (0) 211 38 63 40
Fax +49 (0) 211 37 98 64

Hong Kong

Special Metals Pacific Pte. Ltd.
Room 1110, 11th Floor
Tsuen Wan Industrial Centre
220-248 Texaco Road, Tsuen Wan
Phone +852 2439 9336
Fax +852 2530 4511

India

Special Metals Services Ltd.
No. 60, First Main Road, First Block
Vasantha Vallabha Nagar
Subramanyapura Post
Bangalore 560 061
Phone +91 (0) 80 666 9159
Fax +91 (0) 80 666 8918

Italy

Special Metals Services SpA
Via Assunta 59
20054 Nova Milanese (MI)
Phone +390 362 4941
Fax +390 362 494224

The Netherlands

Special Metals Service BV
Postbus 8681
3009 AR Rotterdam
Phone +31 (0) 10 451 44 55
Fax +31 (0) 10 450 05 39

Singapore

Special Metals Pacific Pte. Ltd.
50 Robinson Road
06-00 MNB Building, Singapore 068882
Phone +65 6222 3988
Fax +65 6221 4298

Affiliated Companies

Special Metals Welding Products
1401 Burris Road
Newton, NC 28658, U.S.A.
Phone +1 (828) 465-0352
+1 (800) 624-3411
Fax +1 (828) 464-8993

Regal Road
Stratford-upon-Avon
Warwickshire CV37 0AZ, U.K.
Phone +44 (0) 1789 268017
Fax +44 (0) 1789 269681

Controlled Products Group
590 Seaman Street, Stoney Creek
Ontario L8E 4H1, Canada
Phone +1 (905) 643-6555
Fax +1 (905) 643-6614

A-1 Wire Tech, Inc.
A Special Metals Company
840 39th Avenue
Rockford, IL 61109, U.S.A.
Phone +1 (815) 226-0477
+1 (800) 426-6380
Fax +1 (815) 226-0537

Rescal SA
A Special Metals Company
200 Rue de la Couronne des Prés
78681 Epône Cédex, France
Phone +33 (0) 1 30 90 04 00
Fax +33 (0) 1 30 90 02 11

DAIDO-*SPECIAL METALS* Ltd.
A Joint Venture Company
Daido Building
7-13, Nishi-shinbashi 1-chome
Minato-ku, Tokyo 105, Japan
Phone +81 (0) 3 3504 0921
Fax +81 (0) 3 3504 0939