Welding
Nickel Alloys

Introduction

High-quality joints are readily produced in nickel alloys by commonly used welding processes. Some of the characteristics of nickel alloys result in somewhat different techniques than used for other materials, but the differences do not increase the difficulty of welding operations.

Special Metals Corporation manufactures companion welding products for the full range of its wrought alloys. The covered electrodes and bare filler wires are designed to match the high level of performance delivered by the alloys and to ensure single-source reliability in welded fabrications. The line of welding products also includes high-quality consumables for welding cast irons and for joining dissimilar metals. Descriptions and properties of the products are given in a separate publication.[1]

The choice of welding process should be based on (1) thickness of metal to be joined, (2) design of the unit, (3) design of the joint, (4) position in which the joint is to be made, (5) need for jigs or fixtures, (6) service conditions and corrosive environments to which the joint will be exposed, and (7) special shop or field-construction conditions.

Unless specifically noted otherwise, all procedures described in this publication are intended to be used with annealed base materials.

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, and essentially the same warping or distortion can be expected during welding.

All weld beads should have slightly convex contours. Flat or concave beads should be avoided.

Preheating is not required. If the base metal is cold, 35°F (2°C) or less, however, an area of about 12 in. (300 mm) surrounding the weld location should be warmed to 60°-70°F (16°-21°C) to prevent the formation of condensate. Moisture can cause porosity in the weld metal.

The properties of welded joints in nickel alloys are comparable to those of the base metals in the soft temper. No postweld treatment, either thermal or chemical, is needed to maintain or restore corrosion resistance. In most media, the corrosion resistance of the weld metal is similar to that of the base metal.

Postweld thermal treatment may be required for precipitation hardening. Postweld stress relief may be necessary to meet specification requirements or to avoid stress-corrosion cracking in applications involving hydrofluoric acid vapor or caustic.

Proper safety procedures [2, 3, 4] must be followed during all welding operations.

Values reported in this publication were derived from extensive testing and experience and will be typical of the subject discussed, but they are not suitable for specifications.

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Surface Preparation

Cleanliness is the single most important requirement for successful welding of nickel 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. 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 workpiece 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 not soluble in degreasing solvents may 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 manufacturers' 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 a 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.

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.

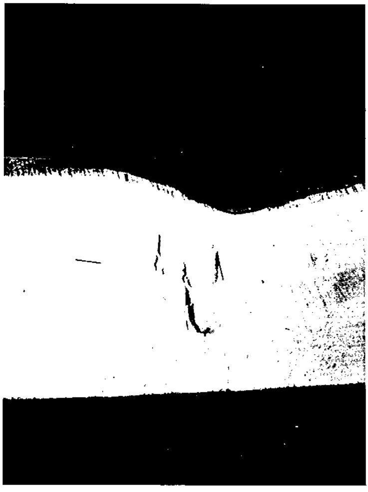


Figure 2. Typical effect of lead in MONEL alloy 400 welds.

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 (.0254 mm). However, the heavy oxide that forms during exposure to high temperatures (hot-working, heat-treating, or high-temperature service) must be removed.

Oxide must be removed primarily because it melts at a higher temperature 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 by grinding, abrasive blasting, machining, or pickling.

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.

Joint Design

Various joint designs are used for the nickel alloys. Some examples are shown in Figure 4. Approximate amounts of weld metal needed with those de-

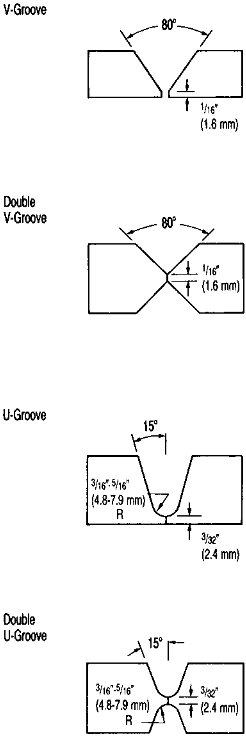
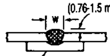
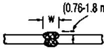
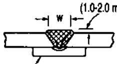
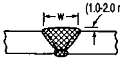
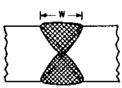
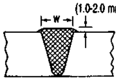
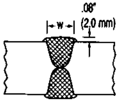


Figure 4. Typical joint designs.

signs are given in Table 1. The same basic designs are used for all welding processes. Modification of the designs in Figure 4, however, is required for submerged-arc and some gas-metal-arc welding.

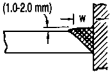
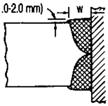
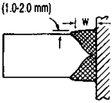
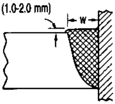
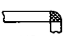
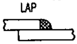
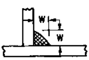
(continued on page 6)

Table 1 — Weld Metal Required for Various Joint Designs

Joint Type	Base Material Thickness		Width of Bead or Groove		Max. Root Spacing		Approx Amount of Metal Deposited				Approx Weight of Electrode Required.[a]	
	in.	mm	in.	mm	in.	mm	in³/ft	cm³/m	lb/ft	kg/m	lb/ft	kg/m
Square Butt Reinforcement .03"-.06" (0.76-1.5 mm) W  Removeable Copper Backing	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 Reinforcement .03"-.07" (0.76-1.8 mm) W 	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 Reinf. .04"-.08" (1.0-2.0 mm) W  Removeable Copper Backing	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 Reinf. .04"-.08" (1.0-2.0 mm) W  No Backing Used. Under Side of Weld Chipped and Welded	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
Double V Groove W 	1/2	12.7	0.40	10.2	1/8	3.18	2.65	142	0.89	1.32	1.16	1.73
	5/8	15.9	0.49	12.4	1/8	3.18	3.45	185	1.08	1.61	1.48	2.20
	3/4	19.1	0.62	15.7	1/8	3.18	4.60	247	1.46	2.17	2.00	2.98
	1	25.4	0.81	20.6	1/8	3.18	7.70	414	2.42	3.60	3.34	4.97
	1-1/4	3.18	1.03	26.2	1/8	3.18	9.26	498	2.92	4.35	4.00	5.95
U Groove Reinf. .04"-.08" (1.0-2.0 mm) W 	1/2	12.7	0.679	17.2	1/8	3.18	3.27	176	1.03	1.53	1.41	2.09
	5/8	15.9	0.745	18.9	1/8	3.18	4.37	235	1.38	2.05	1.90	2.83
	3/4	19.1	0.813	20.7	1/8	3.18	5.33	287	1.68	2.50	2.30	3.42
	1	25.4	0.957	24.3	1/8	3.18	8.35	449	2.63	3.91	3.60	5.36
	1-1/4	31.8	1.073	27.3	1/8	3.18	11.48	617	3.62	5.39	4.96	7.38
	1-1/2	38.1	1.215	30.9	1/8	3.18	15.16	815	4.79	7.13	6.55	9.74
	1-3/4	44.5	1.349	34.3	1/8	3.18	18.90	1016	5.98	8.90	8.19	12.1
	2	50.8	1.485	37.7	1/8	3.18	23.45	1261	7.40	11.0	10.12	15.1
Double U Groove Reinf. .08" (2.0 mm) W 	1	25.4	0.679	17.2	1/8	3.18	6.54	352	2.06	3.07	2.82	4.19
	1-1/4	31.8	0.745	18.9	1/8	3.18	8.74	470	2.76	4.11	3.80	5.66
	1-1/2	38.1	0.813	20.7	1/8	3.18	10.66	573	3.36	5.00	4.60	6.85
	2	50.8	0.957	24.3	1/8	3.18	16.66	896	5.26	7.83	7.20	10.7
	2-1/2	63.5	1.073	27.3	1/8	3.18	22.96	1234	7.24	10.8	9.92	14.8

[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 (95 g) of metal deposited (equivalent to 0.29 lb (130 g) of electrode).

Table 1 — Weld Metal Required for Various Joint Designs

Joint Type	Base Material Thickness		Width of Bead or Groove		Approx 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
Bevel Groove	1/4	6.35	0.125	3.18	0.22	11.8	0.07	0.104	0.09	0.134
Reinf. .04"-.08"	5/16	7.94	0.188	4.76	0.40	21.5	0.13	0.193	0.17	0.253
(1.0-2.0 mm)	3/8	9.53	0.250	6.35	0.61	32.8	0.19	0.283	0.26	0.387
	1/2	12.7	0.375	9.53	1.21	65.1	0.38	0.566	0.52	0.774
	5/8	15.9	0.500	12.7	1.98	106	0.63	0.938	0.86	1.28
	3/4	19.1	0.625	15.9	2.95	159	0.93	1.38	1.28	1.90
	1	25.4	0.875	22.2	5.57	299	1.77	2.63	2.42	3.60
Double J Groove	1	25.4	0.500	12.7	4.67	251	1.48	2.20	2.0	2.98
Reinf. .04"-.08"	1-1/4	31.8	0.563	14.3	6.90	371	1.90	2.83	2.6	3.87
(1.0-2.0 mm)	1-1/2	38.1	0.594	15.1	8.10	435	2.56	3.81	3.5	5.21
	1-3/4	44.5	0.625	15.9	9.83	528	3.11	4.63	4.3	6.40
	2	50.8	0.656	16.7	12.06	648	3.81	5.67	5.2	7.74
	2-1/4	57.2	0.688	17.5	14.29	768	4.51	6.71	6.2	9.23
	2-1/2	63.5	0.750	19.1	16.68	897	5.27	7.84	7.2	10.7
Double Bevel Groove	1/2	12.7	0.188	4.76	0.78	41.9	0.25	0.372	0.34	0.506
Reinf. .04"-.08"	5/8	15.9	0.250	6.35	1.24	66.7	0.39	0.580	0.54	0.804
(1.0-2.0 mm)	3/4	19.1	0.313	7.95	1.78	95.7	0.56	0.833	0.77	1.15
	1	25.4	0.438	11.1	3.13	168	0.99	1.47	1.36	2.02
	1-1/4	31.8	0.563	14.3	4.87	262	1.54	2.29	2.15	3.20
	1-1/2	38.1	0.688	17.5	7.00	376	2.21	3.29	3.03	4.51
	1-3/4	44.5	0.813	20.7	9.47	509	3.00	4.46	4.09	6.09
	2	50.8	0.938	23.8	12.33	663	3.90	5.80	5.35	7.96
J Groove	1	25.4	0.625	15.9	5.64	303	1.78	2.65	2.4	3.57
Reinf. .04"-.08"	1-1/4	31.8	0.719	18.3	7.91	425	2.50	3.72	3.4	5.06
(1.0-2.0 mm)	1-1/2	38.1	0.781	19.8	10.20	548	3.23	4.81	4.4	6.55
	1-3/4	44.5	0.875	22.2	12.95	696	4.09	6.07	5.6	8.33
	2	50.8	0.969	24.6	15.60	839	4.93	7.34	6.8	10.1
	2-1/4	57.2	1.031	26.7	18.35	987	5.80	8.63	8.0	11.9
	2-1/2	63.5	1.094	27.8	21.95	1180	6.94	10.3	9.5	14.1
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
LAP	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

Joint designs for submerged-arc welding are shown in Figure 5. Table 2 indicates the amounts of weld metal needed with compound-angle, single-U, and V joints. The double U-groove is the preferred design for all joints that permit its use. That design gives a lower level of residual stress from welding, and it can be completed in less time and with less filler metal.

The joint designs shown in Figure 4 are also used for gas-metal-arc welding, with one important exception. For globular, spray, and pulsing-arc welding, the U-groove design must be modified. The root radius should be decreased by about 50%, and the included angle should be doubled. With those processes, the use of high amperages on small-diameter wire produces high levels of arc force. The force is such that the arc cannot be deflected from a straight line, as it can in shielded metal-arc welding. Because the arc must contact all areas to be fused, the joint design must provide intersection with the arc-force line.

Design Considerations

As for joint designs in any material, 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 joint designs different from those used for other common materials. The most significant characteristic is the sluggish nature of the molten weld metal. Unlike steel weld metal, nickel-alloy weld metal does not spread. The operator must place the weld metal at the proper location in the joint. The joint must, therefore, be sufficiently open to provide space for manipulation of the torch or filler metal.

A second characteristic is the lower weld penetration inherent with nickel alloys. The lower penetration makes necessary the use of smaller lands in the root of the joint. Increases in amperage will not significantly increase the penetration of the arc, and welding at amperages beyond the recommended range can overheat the electrode. Overheating of coated electrodes can cause the flux to flake off as the coating binder breaks down from the heat. Overheating also causes puddling of the molten weld metal and resultant loss of deoxidizers, leading to unsound welds.

Many different joint designs might be capable of carrying a given calculated load. The designer should estimate the cost for edge preparation and welding as well as the influence of joint design on expected service life. The most economical joint is usually that which requires the minimum of preparation, welding material, and welding time for the desired result.

Groove Joints

Beveling is usually not required for groove joints in material 0.093 in (2.36 mm) or less in thickness.

Material thicker than 0.093 in (2.36 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 raisers.

For the best underbead contour on joints that cannot be welded from both sides, the gas tungsten-arc process should be used for the root pass.

For material over 3/8 in (9.5 mm) thick, a double-U or double-V joint design is preferred. The added cost of preparation is justified by the decreased welding material and lower welding time needed to complete the joint, and less residual stress will be developed than 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 (4.8-8.0 mm) bottom radius. Single bevels 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.

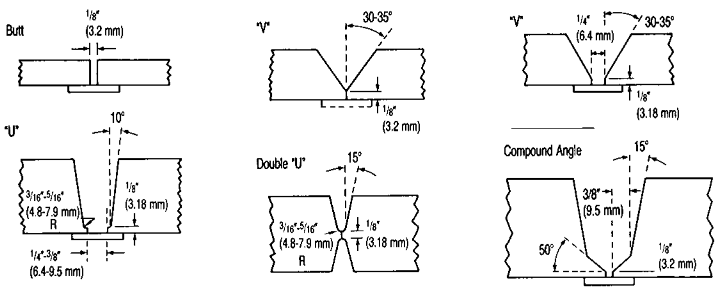


Figure 5. Joint designs for submerged-arc welding.

Table 2 — Metal Required for Submerged-Arc Butt Welds in Plate

Compound Angle Joint

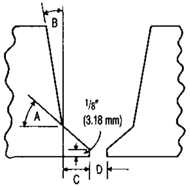


Plate Thickness						
A, °	40	40	50	50	50	40
B, °	10	10	10	15	10	10
C, in. (mm)	3/8 (9.53)	1/2 (12.7)	3/8 (9.53)	3/8 (9.53)	3/8 (9.53)	3/8 (9.53)
D, in. (mm)	0 0	0 0	0 0	0 0	1/4 (6.35)	1/4 (6.35)
Plate Thickness, in.	**Approximate Amount of Metal Deposited, lb/linear ft**					
1	2.19	2.74	1.95	2.03	2.87	3.11
1-1/4	3.10	3.56	2.83	2.95	3.98	4.25
1-1/2	4.10	4.84	3.79	4.08	5.17	5.48
1-3/4	5.17	6.16	4.82	5.29	6.43	6.78
2	6.33	7.61	5.93	6.62	7.77	8.17
2-1/4	7.56	8.96	7.13	8.10	9.20	9.63
2-1/2	8.90	10.45	8.40	9.68	10.70	11.20
2-3/4	10.28	12.05	9.68	11.40	12.21	12.81
3	11.77	13.73	11.18	13.20	13.94	14.53
3-1/4	13.30	15.48	12.72	15.15	15.71	16.29
3-1/2	14.95	17.32	14.00	17.30	17.22	18.17
3-3/4	16.70	19.25	16.00	19.50	19.45	20.15
4	18.50	21.00	17.70	21.78	21.38	22.18
Plate Thickness, mm	**Approximate Amount of Metal Deposited, kg/linear m**					
25	3.26	4.08	2.90	3.02	4.27	4.63
32	4.61	5.30	4.21	4.39	5.92	6.32
38	6.10	7.20	5.64	6.07	7.69	8.16
44	7.69	9.17	7.17	7.87	9.57	10.09
51	9.42	11.33	8.82	9.85	11.56	12.16
57	11.25	13.33	10.61	12.05	13.69	14.33
64	13.24	15.55	12.50	14.41	15.92	16.67
70	15.30	17.93	14.41	16.97	18.17	19.06
76	17.52	20.43	16.64	19.64	20.75	21.62
83	19.79	23.04	18.93	22.55	23.38	24.24
89	22.25	25.78	20.83	25.75	25.63	27.04
95	24.85	28.65	23.81	29.02	28.95	29.99
102	27.53	31.25	26.34	32.41	31.82	33.01

Single U Joint

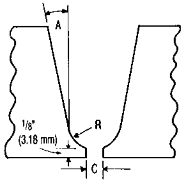


Plate Thickness								
A, °	10	10	10	15	15	15	10	10
R, in. (mm)	3/16 (4.76)	1/4 (6.35)	5/16 (7.94)	3/16 (4.76)	1/4 (6.35)	5/16 (7.94)	3/16 (4.76)	1/4 (6.35)
C, in. (mm)	0 0	0 0	0 0	0 0	0 0	0 0	1/4 (6.35)	1/4 (6.35)
Plate Thickness, in.	**Approximate Amount of Metal Deposited, lb/linear ft**							
1	1.46	1.77	2.03	1.60	1.90	2.17	2.38	2.69
1-1/4	2.07	2.47	2.86	2.36	2.73	3.08	3.22	3.62
1-1/2	2.76	3.25	3.68	3.23	3.68	4.14	4.14	4.63
1-3/4	3.53	4.12	4.71	4.22	4.76	5.30	5.14	5.73
2	4.37	5.06	5.76	5.34	5.96	6.60	6.21	6.90
2-1/4	5.32	6.10	6.87	6.58	7.28	7.97	7.39	8.17
2-1/2	6.33	7.20	8.10	7.94	8.74	9.55	8.63	9.50
2-3/4	7.40	7.38	9.37	9.41	10.30	11.17	9.93	10.91
3	8.60	9.67	10.70	11.00	12.00	12.90	11.36	12.43
3-1/4	9.85	11.00	12.20	12.78	13.80	14.80	12.84	13.99
3-1/2	11.20	12.45	13.70	14.60	15.78	16.90	14.42	15.67
3-3/4	12.61	13.95	15.30	16.47	17.80	19.00	16.06	17.40
4	14.10	15.60	17.00	18.68	20.00	21.40	17.78	19.28
Plate Thickness, mm	**Approximate Amount of Metal Deposited, kg/linear m**							
25	2.17	2.63	3.02	2.38	2.83	3.23	3.54	4.00
32	3.08	3.68	4.26	3.51	4.06	4.58	4.79	5.39
38	4.11	4.84	5.48	4.81	5.48	6.16	6.16	6.89
44	5.25	6.13	7.01	6.28	7.08	7.89	7.65	8.53
51	6.50	7.53	8.57	7.95	8.87	9.82	9.24	10.27
57	7.92	9.08	10.22	9.79	10.83	11.86	11.00	12.16
64	9.42	10.71	12.05	11.82	13.01	14.21	12.84	14.14
70	11.01	10.98	13.94	14.00	15.33	16.62	14.78	16.24
76	12.80	14.39	15.92	16.37	17.86	19.20	16.91	18.50
83	14.66	16.37	18.16	19.02	20.54	22.03	19.11	20.82
89	16.67	18.53	20.39	21.73	23.48	25.15	21.46	23.32
95	18.77	20.76	22.77	24.51	26.49	28.28	23.90	25.89
102	20.98	23.22	25.30	27.80	29.76	31.85	26.46	28.69

V Joint

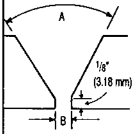


Plate Thickness			
A, °	60	70	60
B, in. (mm)	0 0	0 0	1/4 (6.35)
Plate Thickness, in.	**Approximate Amount of Metal Deposited, lb/linear ft**		
1	1.63	1.96	2.55
1-1/4	—	—	—
1-1/2	—	—	—
1-3/4	—	—	—
2	—	—	—
2-1/4	—	—	—
2-1/2	—	—	—
2-3/4	—	—	—
3	—	—	—
3-1/4	—	—	—
3-1/2	—	—	—
3-3/4	—	—	—
4	—	—	—
Plate Thickness, mm	**Approximate Amount of Metal Deposited, kg/linear m**		
25	2.43	2.92	3.79
32	—	—	—
38	—	—	—
44	—	—	—
51	—	—	—
57	—	—	—
64	—	—	—
70	—	—	—
76	—	—	—
83	—	—	—
89	—	—	—
95	—	—	—
102	—	—	—

Butt joints, where stresses act axially, are preferred to corner or lap joints, where 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

In the fabrication of thin 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 metal.

Steel or cast iron may be used for all parts of gas-welding fixtures, but for arc welding, any portion of the fixture apt to be contacted by 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 the groove and the spacing of hold-down bars should be adjusted to obtain a proper balance between 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 (0.381-0.813 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 6. For oxyacetylene welding, backup bars should be grooved to 1/16 in (1.6 mm) maximum depth and to an approximate width of 5/16 in (8.0 mm).

Nickel alloys 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 only 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

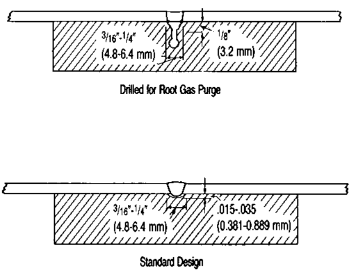


Figure 6. Groove designs for backup bars.

Table 3 — Approximate Current Settings for Downhand Welding[a]

MONEL Nickel-Copper Alloys				
Base Material Thickness		**Electrode Diameter**		**Current, A**
in	**mm**	**in**	**mm**	
0.037	0.940	3/32	2.4	b
0.043	1.09	3/32	2.4	b
0.050	1.27	3/32	2.4	b
0.062	1.57	3/32	2.4	50
0.078	1.98	3/32	2.4	55
0.093	2.36	3/32	2.4	60
0.109	2.77	3/32	2.4	60
0.109	2.77	1/8	3.2	65
0.125	3.18	1/8	3.2	75
0.140	3.56	1/8	3.2	85
0.156	3.96	1/8	3.2	95
0.125	3.18	5/32	4.0	100
0.140	3.56	5/32	4.0	110
0.156	3.96	5/32	4.0	115
0.250 and up	6.35 and up	5/32	4.0	150
0.375	9.53	3/16	4.8	170
0.500 and up	12.7 and up	3/16	4.8	190

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

In most cases, the composition of the electrode resembles that of the base metal with which it is used. It has been adjusted to satisfy weldability requirements.

Prior to use, electrodes should be left in their sealed, moistureproof 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.

Electrodes that have absorbed excessive moisture can be reclaimed by rebaking. Electrodes should be rebaked at 600°F (316°C) for 1 hr or 500°F (260°C) for 2 hr. Rebaking should be done in a vented oven, and the electrodes must be removed from the containers.

Electrode quantities required for various joint designs are shown in Table 1. The choice of electrode diameter should always be based on quality requirements rather than speed of production.

Current

Each electrode diameter has an optimum amperage range in which it has good arcing characteristics and outside of which the arc becomes unstable or the electrode overheats. 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. Some approximate current settings for downhand welding with various material thicknesses and electrode diameters are listed in Table 3. Slight reductions (5 to 15 A) in current from the values in Table 3 are necessary for overhead welding. Vertical welding requires 10 to 20% less current than downhand welding. Actual current should be developed on scrap material of the same thickness.

Table 3 — Continued

Nickel Alloys				
Base Material Thickness,		Electrode Diameter,		Current, A
in	mm	in	mm	
0.037	0.940	3/32	2.4	b
0.043	1.09	3/32	2.4	b
0.050	1.27	3/32	2.4	b
0.062	1.57	3/32	2.4	75
0.078	1.98	3/32	2.4	80
0.093	2.36	3/32	2.4	85
0.109	2.77	1/8	3.2	105
0.125	3.18	1/8	3.2	105
0.125	3.18	5/32	4.0	110
0.140	3.56	5/32	4.0	130
0.156	3.96	5/32	4.0	135
0.187 and up	4.75 and up	5/32	4.0	150
0.250	6.35	3/16	4.8	180
0.375 and up	9.53 and up	3/16	4.8	200

INCONEL and INCOLOY Alloys				
Base Material Thickness,		Electrode Diameter,		Current, A
in	mm	in	mm	
0.037	0.940	3/32	2.4	b
0.043	1.09	3/32	2.4	b
0.050	1.27	3/32	2.4	b
0.062	1.57	3/32	2.4	60
0.109	2.77	1/8	3.2	75
0.125	3.18	1/8	3.2	75
0.156	3.96	1/8	3.2	80
0.187	4.75	5/32	4.0	105
0.375	9.53	3/16	4.8	140

a Selection of electrode diameter should be based on joint design. For example, smaller diameters than those listed for material 0.125 in. (3.18 mm) and over in thickness may be necessary for the first passes in the bottom of a groove joint.
b Amperage should be the minimum at which arc control can be maintained.

Welding Procedure

Typical welding conditions for several different joints are shown in Table 4. Whenever possible, the work should be positioned to gain the advantages of speed and economy provided by downhand welding. As indicated in Table 4, the recommended electrode position for downhand welding is at an incline of 20 degrees from the vertical, ahead of the puddle. That position facilitates control of the molten flux and elimination of slag entrapment. It is essential that a short arc be maintained.

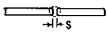
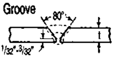
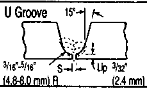
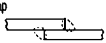
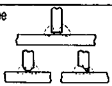
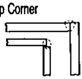
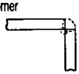
Overhead and vertical welding usually require a shorter arc and lower current than downhand welding. For vertical welding, the electrode should be held at approximately a right angle to the base material.

Because nickel-alloy weld metal does not spread, it must be placed where required. Thus, it is necessary to weave the electrode slightly. The amount of weave will depend on such factors as joint design, welding position, and type of electrode. A straight drag (stringer) bead laid down 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. A weave, however, is generally desirable. When a weave is used, it should not be wider than three times the electrode core diameter.

There should be no pronounced spatter. When excessive spatter occurs, it is usually 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 blow.

When the arc is broken for any reason, 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 oxida-

Table 4 — Conditions for Shielded Metal-Arc Welding

Joint Type[a]	Position	Base Material Thickness, in, Min.	Base Material Thickness, in, Max.	Base Material Thickness, mm, Min.	Base Material Thickness, mm, Max.	Root Spacing (S), in, For Min. Thick.	Root Spacing (S), in, For Max. Thick.	Root Spacing (S), mm, For Min. Thick.	Root Spacing (S), mm, For Max. Thick.
Square Butt[b]  S	Flat	0.037	0.125	0.940	3.18	0.156	1/16	3.96	1.6
	Vertical	0.062	0.125	1.57	3.18	0.156	1/16	3.96	1.6
	Overhead	0.050	0.125	1.27	3.18	0.156	3/32	3.96	2.4
V Groove  80°; t; 1/32"-3/32" (0.8-2.4 mm)	Flat	0.156	0.500	3.96	12.7	1/16	1/8	1.6	3.2
	Vertical	0.187	0.437	4.75	11.1	1/16	1/8	1.6	3.2
U Groove  15°; 3/16"-5/16" (4.8-8.0 mm) R; S; Lip 3/32" (2.4 mm)	Flat	0.500	—	12.7	—	1/16	3/32	1.6	3.2
	Vertical	0.500	—	12.7	—	1/16	3/32	1.6	3.2
Lap 	Flat	0.037	—	0.940	—	None		None	
	Vertical	0.062	—	1.57	—				
	Overhead	0.062	—	1.57	—				
Tee 	Flat	0.062	—	1.57	—	None		None	
	Vertical	0.062	—	1.57	—				
	Overhead	0.062	—	1.57	—				
Lap Corner 	Flat	0.050	0.125	1.27	3.18	None		None	
	Vertical	0.062	0.125	1.57	3.18				
	Overhead	0.062	0.125	1.57	3.18				
Corner 	Flat	0.093	—	2.36	—	None		None	
	Vertical	0.093	—	2.36	—				
	Overhead	0.093	—	2.36	—				

a 100% penetration is assumed.

b Joint backing (preferably copper) is necessary for thicknesses 0.050 in. (1.27 mm) and less. If design permits, backing should be provided for thicknesses of 0.062 to 0.093 in. (1.57 to 2.36 mm) Thicknesses over 0.093 in. (2.36 mm) will require welding from both sides.

tion, eliminates the rolled leading edge of the crater, and prepares the way for the restrike.

The manner in which the restrike is made will have a significant influence on 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 three advantages: (1) the correct arc length can be established away from the unwelded joint, (2) some preheat is applied to the cold crater, and (3) the first drops of quenched or rapidly cooled weld metal are placed where they can be remelted to minimize porosity.

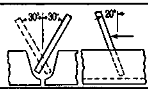
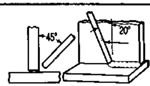
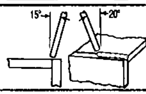
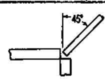
Another commonly used restrike technique involves placing the metal apt to be porous where it can be readily removed. The restrike is made 1/2 to 1 in (13 to 25 mm) behind the crater on top of the previous pass, and the restrike area is later ground level with the rest of the bead. This technique is used when welds must meet rigid radiographic inspection standards. The method produces high-quality welds with less operator skill than the "T" restrike.

Cleaning

The slag on shielded metal-arc welds can be removed with hand tools or a powered wire brush. In multipass welding, it is essential that all slag be removed before each bead is deposited.

Slag removal from all completed welds is recommended. Removal is mandatory for high-temperature service.

Table 4 — Continued

Tack Welds				Electrode Diameter				
				in		mm		
Length, in	Spacing, in	Length, mm	Spacing, mm	For Min. Thick.	For Max. Thick.	For Min. Thick.	For Max. Thick.	Electrode Positions for Downhand Welding[c]
1/8	3 or 4	1.6	76 or 100	3/32	1/8	2.4	3.2	
1/4 to 1/2	6	6.4 to 13	150	1/8	3/16	3.2	4.8	
1	8	51	200	1/8	5/32 or 3/16	3.2	4.0 or 4.8	
1/4	6	6.4	150	3/32	5/32 or 3/16	2.4	4.0 or 4.8	
1/4 to 1/2	6	6.4 to 13	150	3/32	5/32 or 3/16	2.4	4.0 or 4.8	
1/4	4	6.4	100	3/32	1/8	2.4	3.2	
1/4	4 to 8	6.4	100 to 200	1/8	5/32 or 3/16	3.2	4.0 to 4.8	

c Number of passes required to complete the joint is 1 or more, depending on plate thickness.

Gas Tungsten-Arc Welding

Gas tungsten-arc welding is widely used for nickel alloys, especially for thin sections and when flux residues would be undesirable. The process is also the principal joining method for precipitation-hardenable alloys.

Gas

The recommended shielding gas is 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.[5] Small quantities (about 5%) of hydrogen can be added to argon for single-pass welding. The hydrogen addition produces a hotter arc and more uniform bead surfaces.

For welding thin material without the addition of filler metal, helium has shown the advantages over argon of reduced porosity and increased welding speed. With direct current and straight polarity, 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, and, 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 A. When low currents are required for joining small parts of thin material, welding should be done with argon or a high-frequency current should be added.

The correct gas-flow rate must be used. Rates that are too low will not protect the weld; high rates can cause turbulence and aspirate air into the gas shield. For argon, 10 to 20 ft^3/h (0.28 to 0.57 m^3/h) is average for manual welding. Machine welding may require considerably higher rates. Flow rates for helium should be 1½ to 3 times the rates for argon to compensate for the lighter weight of helium. The largest gas cup possible for the job should be used, and the cup should be maintained at the minimum practical distance from the work.

Both argon and helium are produced with a high degree of purity, and care must be taken to maintain the purity during use. Even a small amount of air will contaminate the protective gas shield and cause porosity in the weld. The protective atmosphere can be disrupted by drafts, fans, or generators. Air movement from such sources should be avoided, and 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 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. The O-rings in water-cooled equipment should be checked periodically. An extremely small leak can provide sufficient contamination to cause porosity. The gas hose should also be inspected for pin-point holes which can allow air to leak into the hose.

Electrodes

Either pure tungsten electrodes or those alloyed with thorium may be used. A 2% thorium electrode will give good results for most welding. Although the initial cost of alloyed electrodes is greater, their longer life, resulting from lower vaporization and cooler operation, and their greater current-carrying capacity make them more economical. Regardless of the electrode used, it is important to avoid overheating through use of excessive amperage.

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 A.[6] 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 more penetration.

The electrode can be contaminated by contact with the weld metal. If contamination occurs, the electrode should be cleaned and reshaped.

Current

Direct current, straight polarity (electrode negative) is recommended for both manual and machine welding. A high-frequency circuit for starting the arc and a current-decay unit should be incorporated in the power-supply equipment.

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.

Filler Metals

Welding products for the gas tungsten-arc process are, in general, similar to the base materials with which they are used. Because of high arc currents and high puddle temperatures, the filler metals are alloyed to resist porosity and hot fissuring of the weld.

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. An acute angle can cause aspiration of air into the shielding gas.

The electrode extension beyond the gas cup should be short, but it should also be appropriate for the 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 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). If filler metal is added, the arc may be longer, but it should be the minimum consistent with filler-metal diameter. As shown in Figure 7, an excessive arc length can cause porosity.

When filler metal is used, it must be the appropriate size for the thickness of 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 those elements, the completed weld should consist of at least 50% and preferably about 75% filler metal.

Welding speed has a significant effect on the soundness of the finished 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, either too fast or too slow, result in increased porosity.

Shielding of the weld root is usually required with gas tungsten-arc welding. If a completely penetrated weld is made in the open, the weld metal exposed on the underside of the bead will be oxidized or porous. Shielding can be provided by grooved backup bars, inert-gas backing, or a backing flux. If flux is used, it should be of a relatively thick consistency. The flux should be applied in a heavy layer on the root side of the joint and must be allowed to dry thoroughly before the joint is welded. As shown in Figure 8, moisture can cause porosity. All slag must be removed from welds intended for high-temperature or corrosive service.

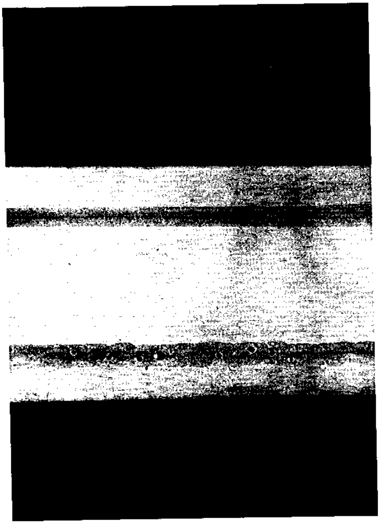


Figure 7. Effect of arc length on soundness of welds in MONEL alloy 400. Top weld made with correct 0.050 in. (1.27 mm), arc length. Bottom weld made with excessive, 0.150 in. (3.81 mm), arc length.

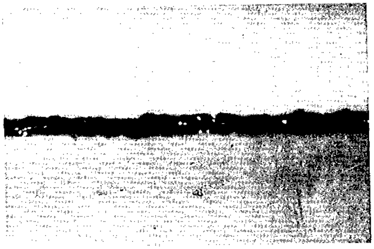


Figure 8. Porosity in gas metal-arc weld caused by wet backing flux.

Gas Metal-Arc Welding

Gas metal-arc welding is performed on nickel alloys using either the spray, short-circuiting, or pulsing-arc method of metal transfer. Globular transfer can also be used, but the erratic penetration and uneven bead contour are conducive to defect formation.

The methods of metal transfer have the same areas of usefulness with nickel alloys as with other materials. Short-circuiting transfer is normally used for material up to about 1/8-in (3.2-mm) thick, and spray or pulsing-arc transfer for thicker material. 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. It is also useful for out-of-position welding. Spray transfer is accompanied by high heat input, but it gives a stable arc and high deposition rates. Spray transfer is generally limited to flat-position welding. With pulsing-arc transfer, the current has its peak in the spray transfer range and its minimum in the globular range. Pulsing-arc transfer provides the benefits of spray at a lower average heat input, which allows the method to be used in all positions.

Gas

The protective atmosphere for gas metal-arc welding is usually argon or argon mixed with helium. The optimum shielding gas will vary with the type of metal transfer used.

Spray and Globular Transfer

With spray and globular transfer, good results have been obtained with pure argon. The addition of helium, however, has been found to be beneficial. Increasing helium content results in progressively wider and flatter beads and less penetration.

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 Nickel 200 and MONEL alloys. Helium alone has been used, but it creates 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.

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 lead to cold lapping (lack of fusion). The wetting action provided by helium results in flatter beads, and the possibility of cold lapping is reduced.

Gas flow rates 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 to 160-180 A without oxidation of the weld bead.

Pulsing-Arc 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 (0.71 m^3/h) and 45 ft^3/min (1.3 m^3/h) maximum. Excessive rates can interfere with the arc.

Filler Metals

Filler metals for gas metal-arc welding are the same as those for gas tungsten-arc welding.

The proper wire diameter depends on the type of metal transfer and the thickness of the base material. In general, 0.062-in-(1.6-mm) diameter wire is used with spray transfer, 0.035-in (0.9-mm) diameter with short-circuiting transfer, and 0.045-in (1.1-mm) diameter with pulsing-arc transfer.

Current

Reverse-polarity direct current 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. Pulsing-arc transfer requires two power sources, one for each of the two ranges. Switching back and forth between the two sources produces a pulsed output.

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, but 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 the method of metal transfer. Some typical conditions are shown in Tables 5, 6, and 7.

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 multipass welding, highly convex beads can increase the tendency toward cold lapping.

With pulsing-arc transfer, manipulation is similar to that used for shielded metal-arc welding. A slight pause at the limit of the weave 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. The tube must be blown out periodically, and the spool of wire must be covered when not in use or cleaned after every extended idle period.

Table 5 — Conditions for Pulsing-Arc-Transfer Gas-Metal-Arc Welding[a]

Filler Metal	Typical Wire Feed		Peak Voltage, V		Average Voltage, V		Current, A	
	in/min	m/min	Range	Typical	Range	Typical	Range	Typical
Nickel Filler Metal 61	160	4.1	45-46	46	21-22	21	90-150	130
MONEL Filler Metal 60	140	3.6	39-40	40	21-22	21	90-150	125
INCONEL Filler Metal 82	140	3.6	43-44	44	20-22	21	90-150	110

[a]Vertical welding with 0.045-in (1.1 mm) wire and argon shielding gas at a flow rate of 30 ft^3 (0.8 m^3)/h.

Table 6 — Parameters for Short-Circuiting-Transfer Gas Metal-Arc Welding[a]

Filler Metal	Open-Circuit Voltage, V		Welding Voltage, V		Welding Current, A		Wire Feed in/min		Wire Feed m/min		Secondary Inductance[b]		Slope[b]	
	Range	Typical	Range	Typical	Range	Typical	Range	Typical	Range	Typical	Range	Typical	Range	Typical
Nickel Filler Metal 61	28-34	30	20-24	22	90-150	110	200-450	235	5.1-11.4	6.0	5-12	10	6½-8½	7½
MONEL Filler Metal 60	27-33	30	19-24	22	90-150	110	200-450	275	5.1-11.4	7.0	7-12	10	6½-8½	8
MONEL Filler Metal 67	27-36	28	19-25	20	100-175	130	225-450	275	5.7-11.4	7.0	5-14	7½	6-7½	6½
INCONEL Filler Metal 82	29-36	33	21-26	23	90-150	115	175-375	275	4.4-9.5	7.0	10-17	15	7-9½	9½
INCONEL Filler Metal 625	29-36	33	21-26	23	90-150	110	175-375	275	4.4-9.5	7.0	10-17	15	7-9½	9½

[a]Parameters were developed for vertical welding of 0.125 in (3.18 mm)-thick base metal using 0.035-in (0.9 mm)-dia. filler metal and 65% argon/35% helium shielding gas at 35 cfh (0.99 m^3/h).
[b]Relative values only. Higher numbers denote greater secondary inductance or slope.

Table 7 — Conditions for Spray-Transfer Gas-Metal-Arc Welding[a]

Filler Metal	Wire Diameter in	Wire Diameter mm	Wire Feed in/min	Wire Feed m/min	Voltage, V	Current, A
Nickel Filler Metal 61	0.035	0.9	425-520	10.8-13.2	26-32	200-300
	0.045	1.1	275-320	7.0-8.1	26-32	250-325
	0.062	1.6	175-220	4.4-5.6	27-33	275-350
MONEL Filler Metal 60	0.035	0.9	475-520	12.1-13.2	26-32	175-230
	0.045	1.1	250-300	6.4-7.6	26-32	225-300
	0.062	1.6	150-200	3.8-5.1	27-33	250-300
MONEL Filler Metal 67	0.035	0.9	475-575	12.1-14.6	26-32	200-300
	0.045	1.1	250-320	6.4-8.1	26-32	225-325
	0.062	1.6	175-230	4.4-5.8	27-33	275-350
INCONEL Filler Metal 62	0.035	0.9	425-520	10.8-13.2	26-32	175-240
	0.045	1.1	250-310	6.4-7.9	26-32	225-300
	0.062	1.6	175-220	4.4-5.6	27-33	250-330
INCONEL Filter Metal 82, INCOLOY Filter Metal 65, and INCO Filler Metal G-3	0.035	0.9	450-520	11.4-13.2	26-32	175-240
	0.045	1.1	250-310	6.4-7.9	26-32	225-300
	0.062	1.6	125-200	3.2-5.1	27-33	250-330
INCONEL Filler Metal 92	0.035	0.9	450-520	11.4-13.2	26-32	175-240
	0.045	1.1	250-320	6.4-8.1	26-32	225-300
	0.062	1.6	125-200	3.2-5.1	27-33	250-330
INCONEL Filler Metal 617, INCONEL Filler Metal 625, and INCO Filler Metal C-276	0.035	0.9	450-600	11.4-15.2	26-32	180-245
	0.045	1.1	250-350	6.4-8.9	26-32	225-300
	0.062	1.6	125-225	3.2-5.7	27-33	250-330

[a]Flat welding with argon shielding gas at a flow rate of 60 ft^3 (1.7 m^3)/h.

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.

Flux

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

The flux burden should be only sufficient to prevent arc breakthrough. Excessive amounts of flux can cause deformed bead surfaces.

Fused flux is easily removed from most joints and is self-lifting on exposed weld beads. The slag should be discarded, but 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 unused flux.

Submerged-arc fluxes are chemical mixtures and are subject to moisture pickup. The fluxes should be stored in a dry area, and open containers of flux should be resealed for protection against moisture. Flux that has absorbed moisture can be reclaimed by baking at 600° to 900°F (315° to 480°C) for 2 hr.

Table 8 — Filler-Metal Deposition Rates

Filler Metal and Flux[a]	Wire Dia., in	Wire Dia., mm	Polarity	Deposition Rate,[b] lb/h	Deposition Rate,[b] kg/h
INCONEL Filler Metal 82 with INCOFLUX 4	1/16	1.6	Straight	16-18	7.3-8.2
	1/16	1.6	Reverse	14-17	6.4-7.7
	3/32	2.4	Straight	20-21	9.1-9.5
	3/32	2.4	Reverse	16-17	7.3-7.7
MONEL Filler metal 60 with INCOFLUX 5	1/16	1.6	Straight	16-17	7.3-7.7
	1/16	1.6	Reverse	14-16	6.4-7.3
	3/32	2.4	Straight	20-21	9.1-9.5
	3/32	2.4	Reverse	16-17	7.3-7.7

[a]Weight of flux consumed is approximately equal to weight of filler metal.
[b]100% arc time.

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 3/32 in (1.1 to 2.4 mm) are used. The 1/16-in (1.6-mm) diameter is generally preferred. Small-diameter wire is useful for welding thin material, and the 3/32-in (2.4-mm) diameter wire is used for heavy sections. Table 8 gives representative deposition rates for some filler metals.

Current

Direct current with either straight or reverse polarity 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

Table 9 — Typical Conditions for Submerged-Arc Butt Welding

	Nickel Filler Metal 61 with INCOFLUX 6	MONEL Filler Metal 60 with INCOFLUX 5	INCONEL Filler Metal 82 with INCOFLUX 4
Base Material	Nickel 200	MONEL alloy 400	INCONEL alloy 600[a]
Filler Metal Dia., in. (mm)	1/16 (1.6)	1/16 (1.6)	1/16 or 3/32 (1.6 or 2.4)
Electrode Extension, in. (mm)	7/8-1 (22-25)	7/8-1 (22-25)	7/8-1 (22-25)
Power Source	DC, Constant Voltage	DC, Constant Voltage	DC, Constant Voltage
Polarity	Reverse	Reverse	Reverse
Current, A	250	260-280	250 with 1/16-in (1.6-mm) wire 250-300 with 3/32-in (2.4-mm) wire
Voltage, V	28-30	30-33	30-33
Travel Speed, in./min. (mm/min)	10-12 (250-300)	8-11 (200-280)	8-11 (200-280)
Joint Restraint	Full	Full	Full

[a]The conditions also apply to INCOLOY alloy 800.

Table 10 — Chemical Composition, %, of All-Weld-Metal Samples from Butt Welds

Filler Metal and Flux	Base Material	Ni	C	Mn	Fe	S	Si	Cu	Cr	Ti	Others
MONEL Filler Metal 60 with INCOFLUX 5	MONEL alloy 400	Bal.	0.06	5.0	3.5	0.013	0.90	26.0	-	0.48	
INCONEL Filler Metal 82 with INCOFLUX 4	INCONEL alloy 600	Bal.	0.07	3.21	1.75	0.006	0.40	-	19.25	0.17	Cb + Ta = 3.38

polarity is preferred for overlaying because it gives a slightly higher deposition rate and less penetration. Straight polarity, however, requires a deeper flux burden, with resulting increased flux consumption. The shallow penetration with straight polarity increases the possibility of slag entrapment, especially in butt welding.

Welding Procedure

Typical conditions for submerged-arc welding with some different flux/filler-metal combinations are given in Table 9. Typical chemical compositions of weld metal from submerged-arc butt welds are shown in Table 10.

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 placement of the beads. In a multipass layer, beads should be placed so as to provide an open or reasonably wide root area for the next bead. Figure 9 illustrates bead placement in a 3-in (76-mm)-thick butt weld in INCONEL alloy 600.

Bead contour is important. Slightly convex beads are preferred to flat or concave beads. Bead contour is most effectively controlled by voltage and travel speed. Higher voltages and travel speeds result in flatter beads.

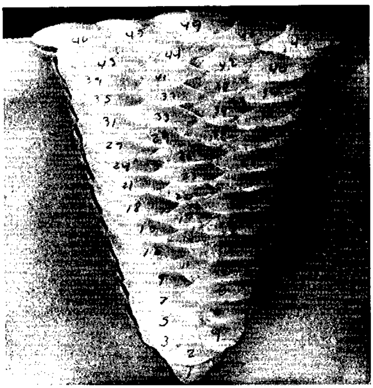


Figure 9. INCONEL alloy 600 joint 3-in (76-mm) thick completed with 0.062-in. (1.6-mm) diameter INCONEL Filler Metal 82 and INCOFLUX 4 Submerged Arc Flux (numerals indicate sequence of bead placement).

The submerged-arc process, with standard procedures, gives good results in thick-section welding. INCONEL alloy 600 plates 6-in (150-mm) thick 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.

Chemical composition remains virtually constant through such joints, with no accumulation of flux components. Table 11 lists compositions of samples removed at approximately 1/2-in (13-mm) intervals, beginning at the top surface, of a 3-in (76-mm)-thick weld.

Circumferential welding of joints in pipe is performed with the same procedures used for butt joints in plate. The degree of difficulty increases as the pipe diameter decreases, and welding parameters must be adjusted accordingly. The major difficulty in pipe welding is prevention of 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. Pipe diameter and joint design influence the operable electrode positions. Figure 10 shows the optimum position. Better control of fusion and penetration can be achieved by use of the gas tungsten-arc process for the root pass.

Table 11 — 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.

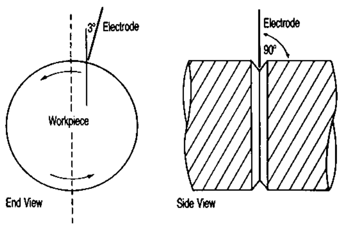


Figure 10. Optimum electrode position for submerged-arc circumferential welding.

Overlaying

Nickel-alloy weld metals are readily applied as overlays on carbon steels, low-alloy steels, and other materials. All oxide 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 will sometimes occur in the first layer of nickel-base overlays applied to some steels that contain high levels of sulfur even though the base material has been adequately cleaned. When this type of cracking occurs, all of the cracked overlay must be removed and one heavy or two light layers of carbon-steel weld metal applied to the base material. The nickel-alloy overlay can then be reapplied.

Nickel-alloy overlays can be applied to cast iron, but a trial overlay on material of the same composition should be made to determine whether standard procedures can be used. The casting skin, or as-cast surface, must be removed by a mechanical means such as grinding. Overlays on cast irons with high contents of sulfur or phosphorus may crack because of embrittlement by those elements. Cracking can often be eliminated by the application of a barrier layer of NI-ROD 55 Welding Electrode or NI-ROD FC 55 Cored Wire. Those products were especially developed for welding cast iron, and the deposit is more resistant to cracking caused by phosphorus, sulfur, and carbon dilution. When overlays are applied directly to cast iron without a barrier layer, amperage should be the minimum that provides proper arc characteristics to hold dilution at the lowest level.

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, 35-50% 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

Table 12 — Conditions for Submerged-Arc Overlaying on Steel

Flux and Filler Metal	Filler Metal Dia.		Current,[a] A		Voltage, V		Travel Speed				Oscillation Frequency cycles/min.	
							in/min.		mm/min.			
	in	mm	Range	Typical	Range	Typical	Range	Typical	Range	Typical	Range	Typical
INCOFLUX 4 and												
INCONEL Filler Metal 82	0.062	1.6	240-260	250	32-34	33	3½-5	4½	89-130	114	45-70	55
	0.093	2.4	300-400	350	34-37	36	3-5	4	76-130	102	35-50	40
INCOFLUX 5 and												
MONEL Filler Metal 60	0.062	1.4	260-280	260	32-35	33	3½-6	4½	89-150	114	50-70	60
	0.093	2.4	300-400	350	34-37	36	3-5	4	89-130	102	35-50	40
	0.062[b]	1.6[b]	260-280[b]	260[b]	32-35	34	7-9	8	180-230	203	-	-
	0.093[b]	2.4[b]	300-350[b]	325[b]	35-37	36	8-10	9	200-250	229	-	-
INCOFLUX 6 and												
Nickel Filler Metal 61	0.062	1.6	250-280	250	30-32	31	3½-5	4½	89-130	114	50-70	60
INCONEL Filler Metal 82	0.062	1.6	240-260	250	32-34	33	3-5	4½	76-130	114	45-70	55
	0.093	2.4	300-400	350	34-37	36	3-5	4½	76-130	114	35-50	40
INCONEL Filler Metal 625	0.062	1.6	240-260	250	32-34	33	3½-5	4½	89-130	114	50-60	55

[a]Straight-polarity direct current, except as noted.
[b]Non-oscillating technique, with reverse polarity.

Table 13 — Chemical Composition, %, of Submerged-Arc Overlays on Steel[a]

Flux and Filler Metal	Layer	Ni	Fe	Cr	Cu	C	Mn	S	Si	Ti	Nb + Ta	Mo
INCOFLUX 4 and												
INCONEL Filler Metal 82	1	63.5	12.5	17.00	-	0.07	2.95	0.008	0.40	0.15	3.4	-
	2	70.0	5.3	17.50	-	0.07	3.00	0.008	0.40	0.15	3.5	-
	3	71.5	2.6	18.75	-	0.07	3.05	0.008	0.40	0.15	3.5	-
INCOFLUX 5 and												
MONEL Filler Metal 60	1	60.6	12.0	-	21.0	0.06	5.00	0.014	0.90	0.45	-	-
	2	64.6	4.5	-	24.0	0.04	5.50	0.015	0.90	0.45	-	-
INCOFLUX 6 and												
Nickel Filler Metal 61	2	88.8	8.4	-	-	0.07	0.40	0.004	0.64	1.70	-	-
INCONEL Filler Metal 82	2	68.6	7.2	18.50	-	0.04	3.00	0.007	0.37	-	2.2	-
INCOFLUX 7 and												
INCONEL alloy 625	1	60.2	3.6	21.59	-	0.02	0.74	0.001	0.29	0.13	3.29	8.6

[a]Overlays on ASTM SA 212 Grade B steel applied by oscillating technique with 0.062-in-(1.6-mm)-dia. filler metal.

equivalent to three layers applied by the gas metal-arc method.

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-penetrant-inspected with no special surface preparation other than wire brushing.
5. Direct applications of nickel-copper alloy on steel without a nickel barrier layer.

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 12. Chemical compositions of overlay deposits are shown in Table 13.

The recommended power supply for all overlays applied by oscillating techniques is constant-voltage direct current with straight polarity. 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.

Table 12 — Continued

Oscillation Width				Electrode Extension			
in		mm		in		mm	
Range	Typical	Range	Typical	Range	Typical	Range	Typical
7/8-1 1/2	1 1/8	22-38	29	7/8-1	1	22-25	25
1-2	1 1/2	25-51	38	1 1/8-2	1 1/4	29-51	32
7/8-1 1/2	1 1/8	22-38	29	7/8-1	1	22-25	25
1-2	1 1/2	25-51	38	1 1/8-2	1 1/4	29-51	32
-	-	-	-	7/8 1	1	22-25	25
-	-	-	-	1 1/4-1 1/2	1 1/4	32-38	32
7/8-1 1/2	1 1/8	22-38	29	7/8-1	1	22-25	25
7/8-1 1/2	1 1/8	22-38	29	7/8-1	1	22-25	25
1-2	1 1/4	25-51	32	1 1/8-2	1 1/4	29-51	32
7/8-1 1/2	1 1/8	25-38	29	7/8-1	1	22-25	25

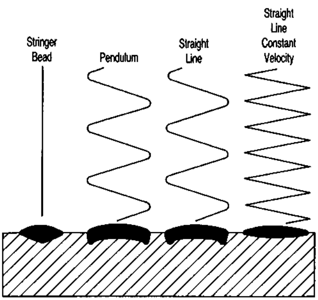


Figure 11. Basic submerged-arc oscillation techniques and bead configurations.

The most efficient use of the submerged-arc process for overlaying requires equipment with a means for oscillating the electrode. Figure 11 shows the three basic types of oscillation. All three types provide much wider and flatter beads with less iron dilution than is possible with stringer beads.

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.

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. Only enough overlap to produce a smooth top surface is required.

Non-oscillating techniques are sometimes best for overlaying narrow areas. 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. Figure 12 shows the proper electrode position.

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.

For overlays of INCONEL Filler Metal 82 on steel, INCOFLUX 6 Submerged Arc Flux can be used for up to three layers. For more than three layers, INCOFLUX 4 Submerged Arc Flux should be used.

For overlays of MONEL copper-nickel Filler Metal 67 on steel, a buffer layer of MONEL Filler Metal 60 must first be applied to the steel. Without the buffer layer, the high level of iron dilution can result in hot cracking of the overlay.

Stress relieving of the overlay is not necessary. When required by specification, stress relieving of steel overlaid with nickel-alloy weld metal can be performed at 1150°F (620°C) for 1 hr or more for each inch (25 mm) of base-metal thickness.

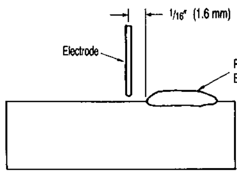


Figure 12. Proper electrode position for overlaying by non-oscillating technique.

Gas Metal-Arc Overlays

Gas metal-arc welding with spray transfer is successfully used to apply nickel-alloy overlays to steel. The overlays are usually produced with mechanized equipment and with oscillation of the electrode. As shown in Figure 13, overlaps should be sufficient to produce a level surface.

Argon alone is often used as shielding gas. The addition of 15 to 25% helium, however, has been found to be beneficial for overlays of nickel and nickel-chromium-iron. Wider and flatter beads and reduced penetration result as the helium content is increased to about 25%. Gas-flow rates are influenced by welding technique and will vary from 35 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 require larger gas cups for protection. When oscillation is used, a trailing shield may be necessary for adequate protection. In any case, the cup should be large enough to deliver an adequate quantity of gas under low velocity to the overlay area.

Representative chemical compositions of automatic gas metal-arc overlays are shown in Table 14. The overlays were produced with the following welding 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 DC
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, a barrier layer of Nickel Filler Metal 61 must be applied first. Nickel weld metal will tolerate greater iron dilution without fissuring.

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 at a reduced travel speed to dissipate much of the digging force of the arc in a heavy pool of weld metal and reduce the iron content of the bead. The iron content of subsequent beads, as well as the surface contour of the overlay, can be controlled by elimination of weaving and maintaining the arc at the fusion line of the preceding bead. Such a procedure will result in a 50% overlap of beads, and the weld metal will wash out onto the steel 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 does not impinge on the steel.

Shielded Metal-Arc Overlays

Shielded metal-arc overlays on cast and wrought steels are widely used for such applications as facing on vessel outlets and trim on valves. Typical properties are shown in Table 15. The electrodes shown are well suited to welding operations in which the weld metal will be diluted by ferrous base material.

The procedures outlined for shielded metal-arc joining should be followed, except that special care must be taken to control dilution of the overlay. Excessive dilution can result in weld metal that is crack-sensitive or that has reduced corrosion resistance.

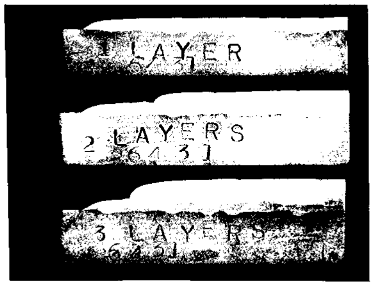


Figure 13. Automatic gas-metal-arc overlays with sufficient overlap for level surface.

Table 14 — Chemical Composition of Gas Metal Arc Overlays on Steel[a]

Filler Metal	Current, A	Voltage, V	Layer	Ni	Fe	Cr	Cu	C	Mn	S	Si	Mg	Ti	Al	Nb+Ta
			Chemical Composition, %, of Deposited Weld Metal												
Nickel Filler Metal 61	280-290	27-28	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	0.015	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

[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.

The amperage used should be in the lower half of the recommended range for the electrode. The major 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 applied, more layers will be required and the possibility of excessive dilution will be greater.

The underbead contour of the overlay should be as smooth as possible. As shown in Figure 14, a scalloped contour can result in excessive iron dilution and cracking of the overlay.

Table 15 — Properties of Shielded Metal-Arc Overlays on Steel

Overlay Metal	Electrode	Electrode Diameter, in	Electrode Diameter, mm	Direct Current, A	Typical Overlay Properties: Elongation in 1 in (25.4 mm), %	Hardness: Layer	Hardness: Rockwell B
Nickel	Nickel Welding Electrode 141	3/32	2.4	70-105	45	1	88
		1/8	3.2	100-135		2	87
		5/32	4.0	120-175		3	86
		3/16	4.8	170-225			
Nickel-Copper	MONEL Welding Electrode 190	3/32	2.4	55-75	43	1	84
		1/8	3.2	75-110		2	86
		5/32	4.0	110-150		3	83
		3/16	4.8	150-190			
Nickel-Chromium-Iron	INCONEL Welding Electrode 182	3/32	2.4	40-65	39	1	91
		1/8	3.2	65-95		2	93
		5/32	4.0	95-125		3	92
		3/16	4.8	125-165			

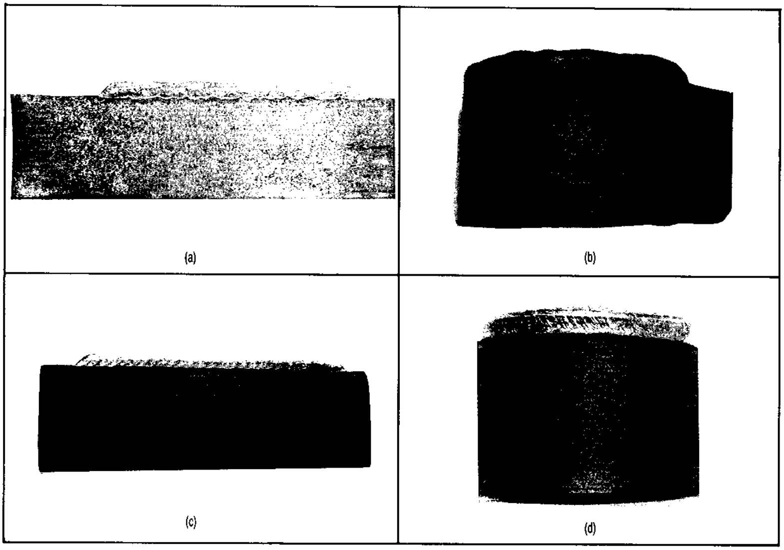


Figure 14. Manual shielded-metal-arc overlays. (a) Overlay with scalloped underbead contour. (b) Bend-test specimen with cracks caused by improper underbead contour. (c) Overlay with smooth underbead contour. (d) Bend-test specimen from overlay shown in (c).

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. For optimum uniformity, however, a dilution rate in the 5 to 10% range is recommended.

High deposition rates result from the use of two filler-metal wires which are resistance-heated by a separate AC power source. The filler metal is in a nearly molten state before it enters the weld puddle. Deposition rates for nickel-alloy weld metal are 35-40 lb/h (16-18 kg/h), approximately double those obtained with submerged-arc overlaying.

Figure 15 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.

Welding parameters for hot-wire plasma-arc overlaying with INCONEL Filler Metal 82 and MONEL Filler Metal 60 are given in Table 16. Chemical compositions of two-layer overlays made with those filler metals are listed in Table 17.

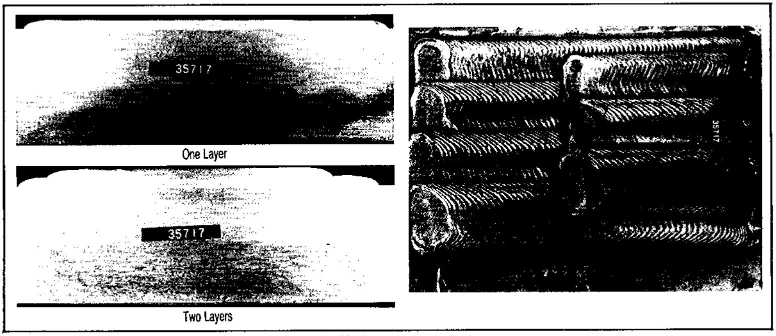


Figure 15. Cross sections and surface of hot-wire plasma-arc overlays of INCONEL Filler Metal 82 on steel.

Table 16 — 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 DC	Straight-Polarity DC
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/h^3)
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 17 — 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	63.7	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]Overlays on ASTM A 387 Grade B steel made with 0.062-in-(1.6-mm)-dia. filler metal.

Welding of Clad Steel

Steels clad with a nickel alloy are frequently joined by welding. Since the cladding is normally used for its corrosion resistance, the cladding alloy must be continuous over the entire surface of the structure, including the welded joints. This requirement influences joint design and welding technique.

Butt joints should be used when possible. Figure 16 shows recommended designs for two thickness ranges. Both designs include a small edge of unbeveled steel above the cladding to protect the cladding during welding of the steel. The steel side should be welded first with a low-hydrogen welding product. It is important to avoid penetration into the cladding during the first welding pass. Dilution of the steel weld with the nickel-alloy cladding can cause cracking of the deposit. The clad side of the joint should be prepared by grinding or chipping and welded with the welding product recommended for solid sections of the alloy used for cladding. The weld metal will be diluted with steel. To maintain corrosion resistance, at least two and preferably three or more layers should be applied.

The strip-back method is sometimes used instead of the procedure described above. The cladding is removed from the vicinity of the joint as shown in Figure 17. The remaining steel is then welded using a standard joint design and technique for steel, and the nickel-alloy cladding is reapplied by weld overlaying. The 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.

Some joints, such as those in closed vessels or tubular products, are accessible only from the steel side. In such cases a standard joint design for steel is used, and the cladding at the bottom of the joint is welded first with nickel-alloy weld metal. After the cladding is welded, the joint can either be completed with nickel-alloy weld metal, or a barrier layer of carbon-free iron can be applied and the joint completed with steel weld metal. If the thickness of steel is 5/16 in (8.0 mm) or less, it is generally more economical to complete the joint with nickel-alloy weld metal.

Welding Metallurgy and Design

Joining procedures must reflect any special metallurgical aspects of the operation. For instance, the presence of a coarse grain structure (ASTM Number 5 or coarser) in the base material can restrict the use of processes having high energy input, including spray-transfer gas-metal-arc welding and electron-beam welding. Table 18 illustrates the effect of grain size on selection of welding processes for several alloys.

Metallurgical factors can have a controlling influence on 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 optimum life in fabricated equipment.

Dissimilar Welding

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 from the two base metals. Many different dissimilar-metal combinations are possible, and the amount of dilution varies with the welding process, the operator technique, and the joint design. All of

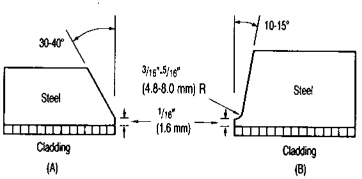


Figure 16. Joint designs for clad steel. (A) Material 3/16 to 5/8 in (4.8 to 16 mm) thick. (B) Material 5/8 to 1 in (16 to 25 mm) thick.

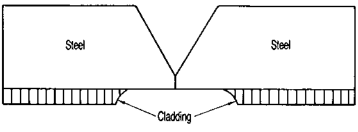


Figure 17. Strip-back method of joint preparation.

Table 18 — 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	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 is ASTM Number 5 or larger.
[c]Spray transfer.

these factors influence the selection of a joining method and welding material that will produce a welded joint having the properties required by the application.

Several Inco Alloys International welding products are commonly used for dissimilar joints. Welding-product recommendations for many frequently encountered dissimilar joints are given in Table 19. The nickel-chromium electrodes and filler metals (INCO-WELD A and C Electrodes, INCONEL Welding Electrodes 112 and 182, INCONEL Filler Metals 82, 92, and 625) 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 will then be based on the strength required, service environment to be withstood, or on economics (cost of the welding product). For example, either INCONEL Welding Electrode 112 or INCO-WELD A Electrode would be suitable for a joint between MONEL alloy K-500 and INCONEL alloy 718. If maximum strength is required in the joint, INCONEL Welding Electrode 112 would be the better choice. If maximum strength is not required, the joint could be welded more economically with INCO-WELD A Electrode.

When a suitable welding product for a dissimilar joint is not known, potential electrodes and filler metals must be evaluated on the basis of their ability to accept dilution from the two base metals without forming a composition that is crack-sensitive or that has other undesirable characteristics. For a joint between a nickel-base alloy and another material, the best results will usually be obtained with a nickel-alloy welding product.

The information presented here can be used as a general guide in the selection of a welding product for a dissimilar joint. The effects of interalloying dissimilar materials are too complex to permit prediction of results with certainty in all cases. With an accurate estimate of dilution rate, however, the procedures outlined will eliminate needless trials by showing which electrodes and filler metals have a high probability for success and which do not.

Dilution Rates

The dilution rate produced by 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 18, the rate is calculated from measurements of the final weld-metal area and the area of original base metal included in it.

For flat-position shielded metal-arc welding, a dilution rate of 30% is normally used to calculate weld-deposit compositions. That is, 70% of the completed weld bead is supplied by the electrode, and 30% is supplied by the base metals (15% from each). Operator technique has less effect on dilution rate with shielded metal-arc welding than with other welding processes. Technique variations can cause the rate to range from about 20% to 40%.

The dilution rate for shielded metal-arc welding is relatively well-established. For other processes, dilution depends more on the specific technique used and can vary widely. Dilution rates with the gas metal-arc process usually range from about 10% to 50%, depending on torch manipulation and type of metal transfer. The highest rates are obtained with spray transfer and the lowest with short-circuiting transfer. The greatest variation in dilution rate is with the gas tungsten-arc process. Depending on welding technique, dilution rates can range from about 20% to over 80%. The dilution rate would be 100% for a joint made without filler

Table 19 — Welding Products[a] for Dissimilar Joints Between Nickel Alloys and Other Materials

Nickel Alloy	Type of Welding Product	Dissimilar Material					
		Stainless Steel	Low-Alloy and Carbon Steels	5-9% Nickel Steels	Cast Iron	Copper	Copper-Nickel
Nickel 200, 201	Electrode	INCO-WELD A	INCO-WELD A	INCO-WELD A	NI-ROD 55	MONEL 190	MONEL 190
	Filler Metal	INCONEL 82	INCONEL 82	INCONEL 82	-	MONEL 60	MONEL 60
MONEL alloys 400, K-500, 502	Electrode	INCO-WELD A	MONEL 190	MONEL 190	NI-ROD 55	MONEL 190	MONEL 190
	Filler Metal	INCONEL 82	Nickel 61	Nickel 61	-	MONEL 60	MONEL 60
INCONEL alloys 600, 601	Electrode	INCO-WELD A	INCO-WELD A	INCO-WELD A	NI-ROD 55	Nickel 141	Nickel 141
	Filler Metal	INCONEL 82	INCONEL 82	INCONEL 82	-	Nickel 61	Nickel 61
INCONEL alloys 625, 706, 718, X-750	Electrode	INCO-WELD A	INCO-WELD A	INCONEL 113	NI-ROD 55	Nickel 141	Nickel 141
	Filler Metal	INCONEL 82	INCONEL 82	INCONEL 625	-	Nickel 61	Nickel 61
INCOLOY alloy 800	Electrode	INCO-WELD A	INCO-WELD A	INCO-WELD A	NI-ROD 55	Nickel 141	Nickel 141
	Filler Metal	INCONEL 82	INCONEL 82	INCONEL 82	-	Nickel 61	Nickel 61
INCOLOY alloy 825	Electrode	INCONEL 112	INCONEL 112	INCONEL 113	NI-ROD 55	Nickel 141	Nickel 141
	Filler Metal	INCONEL 625	INCONEL 625	INCONEL 625	-	Nickel 61	Nickel 61

[a]The electrodes and filler metals shown represent logical selections for normal conditions. In many cases, the materials can be effectively joined with welding products other than those listed. The welding-product descriptions in the Appendix contain additional dissimilar-joining applications for Inco welding products.

metal since all of the weld metal is supplied by the base materials.

With a known dilution rate, the approximate composition of the final weld metal can be determined. For example, assuming 30% dilution, the weld metal 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 19 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% × 70% Ni = 49% Nickel
- 70% × 15% Cr = 10.5% Chromium
- 70% × 8% Fe = 5.6% Iron

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

Dilution by Type 304 stainless steel:
- 15% × 8% Ni = 1.2% Nickel Dilution
- 15% × 18% Cr = 2.7% Chromium Dilution
- 15% × 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 but varies with bead location. The root bead is diluted equally by the two base metals. As shown in Figure 20, subsequent beads may be diluted partially by a base metal and partially by a previous bead or entirely by previous beads.

Dilution Limits

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 the welding materials that have solid-solution compositions. Precipitation-hardenable weld metals are not usually recommended for dissimilar joining. Also, the values should be considered as guidelines. Borderline cases may require that a trial joint be evaluated. When a weld metal will be diluted by more than one potentially detrimental element, allowance should be made for possible additive effects.

MONEL 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. If a gas-shielded process is used, the deposit can 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 MONEL Welding Electrode 190, Nickel Filler Metal 61 or Nickel Welding Electrode 141 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%.

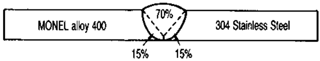


Figure 19. Weld metal contributed by each source in a dissimilar weld.

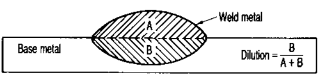


Figure 18. Calculation of dilution rate from cross-sectional area of weld bead.

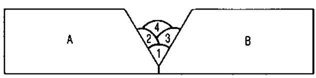


Figure 20. Multiple-pass dissimilar weld. Bead 1 is 15% A, 15% B, 70% filler metal. Bead 2 is 15% A, 15% Bead 1, 70% filler metal. Bead 4 is 15% Bead 2, 15% Bead 3, 70% filler metal.

Nickel Welding Products. Nickel Welding Electrode 141 and Nickel Filler Metal 61 have high solubilities 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 specially formulated for the welding of cast irons.

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.

INCONEL 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%.

A maximum total chromium content in the completed weld of up to 30% is acceptable. Since the welding products contain 15-20% chromium, dilution by chromium must be kept below about 15%.

Shielded metal-arc deposits of nickel-chromium coated electrodes can accept up to about 40% 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%.

Other Considerations

In addition to weld-metal dilution, factors such as differences in thermal expansion and melting point often influence the selection of filler metal for dissimilar joints, especially if the joints will be exposed to high service temperatures.

Unequal expansion of joint members places stress on the joint area and can cause a 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.

A joint between 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 the stainless base metal, and INCONEL welding products have expansion rates near that of mild steel. If the joint is welded with the stainless electrode, both the weld metal and the stainless base metal will expand more than the mild steel, placing the line of differential expansion 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.

Differences in melting point between the 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 places stress on the lower melting point material, which 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. 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 joint.

Carbon migration is sometimes an important consideration in the selection of a filler metal for a dissimilar joint involving carbon steel. Nickel-alloy weld metals are effective barriers to carbon migration. For example, in joining carbon steels to stainless steels, high-nickel weld metals are sometimes used to prevent undesirable carbon migration.

Welding of Precipitation-Hardenable Alloys

Precipitation-hardenable (age-hardenable) alloys are usually welded by the gas tungsten-arc process, but several other methods are applicable.

There are two systems of Inco Alloys International precipitation-hardenable alloys. 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-aluminum-titanium system, which includes INCONEL alloys 706 and 718.

The alloys of both systems have good weldability. The significant difference between the two systems is the rate at which precipitation occurs. The aluminum-titanium-hardened alloys respond quickly to precipitation-hardening temperatures. The niobium-aluminum-titanium-hardened alloys respond more slowly. The delayed precipitation reaction enables the alloys to be welded and directly aged with less possibility of cracking.

The type of cracking that can occur when high residual welding stresses are present during the aging treatment is shown in Figure 21. Cracking occurs in the base-metal near the heat-affected zone, the area of highest stress. Little stress relief occurs at aging temperatures, and high residual welding stresses may exceed the rupture strength of the base metal at aging temperatures. The residual stresses are augmented by stresses introduced by precipitation.

General Welding Procedures

Heat input during welding should be held to a moderately low level to obtain the highest joint efficiency. For multiple-bead or multiple-layer welds, several small beads should be used instead of a few large, heavy beads.

In gas-shielded welding of multiple-pass joints, some interbead or interlayer cleaning must be done to remove oxide films as they accumulate. The oxide films should be removed when they become heavy enough to be visually apparent on the weld surface. The oxide films must be removed by abrasive blasting or grinding. Power wire brushing will only polish the oxide surface.

If oxide films are not removed, they can inhibit proper fusion and result in laminar oxide stringers such as those shown in Figure 22). Oxide inclusions of this type act as mechanical stress raisers and can significantly reduce joint efficiency and service life.

Rigid or complex structures must be assembled and welded with care to avoid excessively high stress levels. Units or subassemblies should be given sufficient annealing treatments to ensure a low level of residual stress when they are precipitation-hardened. Any part that has been subjected to severe bending, drawing, or other forming operations should be annealed before it is welded. Heating should be done in controlled-atmosphere furnaces to limit oxidation and 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.

Figure 21. 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 1300°F (705°C) for 20 h after welding.

Aluminum-Titanium System

The strong susceptibility to base-metal cracking of the aluminum-titanium-hardened alloys when they are welded and directly aged makes special handling of welded structures necessary. The alloys must be given the appropriate thermal treatment after they are welded and before they are precipitation-hardened. 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 part mass is large in relation to furnace area, it may be necessary to preheat the furnace to 200-500°F (95-260°C) above the normal temperature and then reset the furnace controls when the parts reach the proper temperature. The stress created by repair or alteration welding must be relieved in a similar fashion by rapid heating to the proper annealing temperature prior to re-aging.

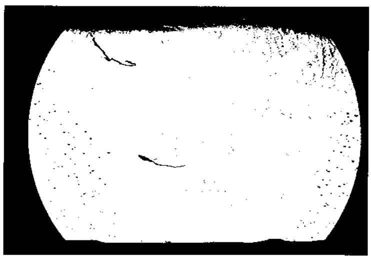


Figure 22. Oxide stringers in INCONEL alloy X-750 weld resulting from inadequate interpass cleaning.

Sometimes a satisfactory postweld stress relief is not feasible, particularly with complicated structures. Preweld heat treatments may be helpful in such cases. Two procedures that have been used successfully for INCONEL alloy X-750 are:

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

All of the aluminum-titanium-hardened alloys can be welded in the aged condition. Because of the problem of base-metal cracking, however, the weld and heat-affected zone must not be subsequently exposed to age-hardening temperatures. If service temperatures are to be in the age-hardening range, the weldment must be annealed and re-aged before being put in service.

Niobium-Aluminum-Titanium System

INCONEL alloys 706 and 718 have good resistance to postweld cracking. Pierce-Miller weld-patch tests have shown that alloy 718 annealed sheet can be welded and directly aged without cracking. However, repair welding or welding of sheet in the aged condition and re-aging after welding (highly restrained 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. The rapid-heating procedure described for aluminum-titanium-hardened alloys should be used.

Generally, INCONEL alloys 706 and 718 are 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.

Effect of Cold Work and Heat Treatment

As-deposited weld metal has a dendritic microstructure, and the ductility of the weld metal is lower than that of the base metal. The heat of welding produces slight grain enlargement and softening in narrow bands at the edges of the weld. The width of this heat-affected zone will vary with the heat input. Cold work and subsequent annealing will result in more uniform microstructure and mechanical properties across the joint area. Figure 23 illustrates the effects of cold work and recrystallization (annealing) on the microstructures of welds in three alloys.

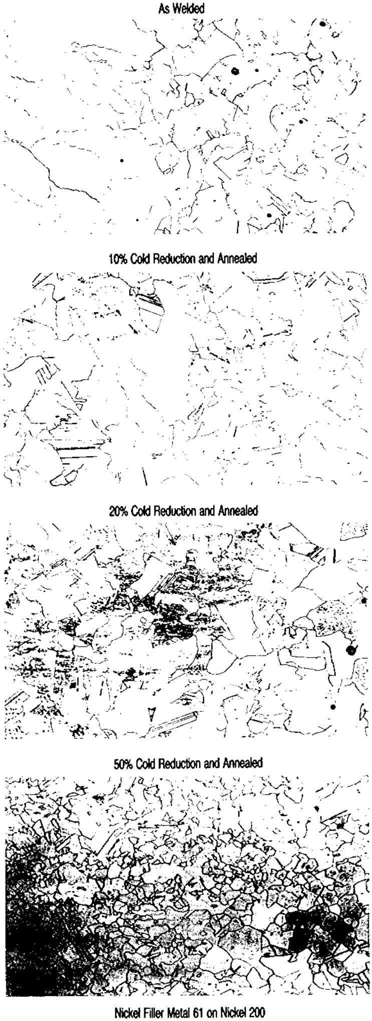


Figure 23. Microstructures of weld metal (left two-thirds of photos) and base material and heat affected zone (right third of photos). Heat treatments: Nickel 200, 1600°F (870°C)/1 h; MONEL alloy 400, 1600°F (870°C)/2 h; INCONEL alloy 600, 1900°F (1040°C)/2 h.

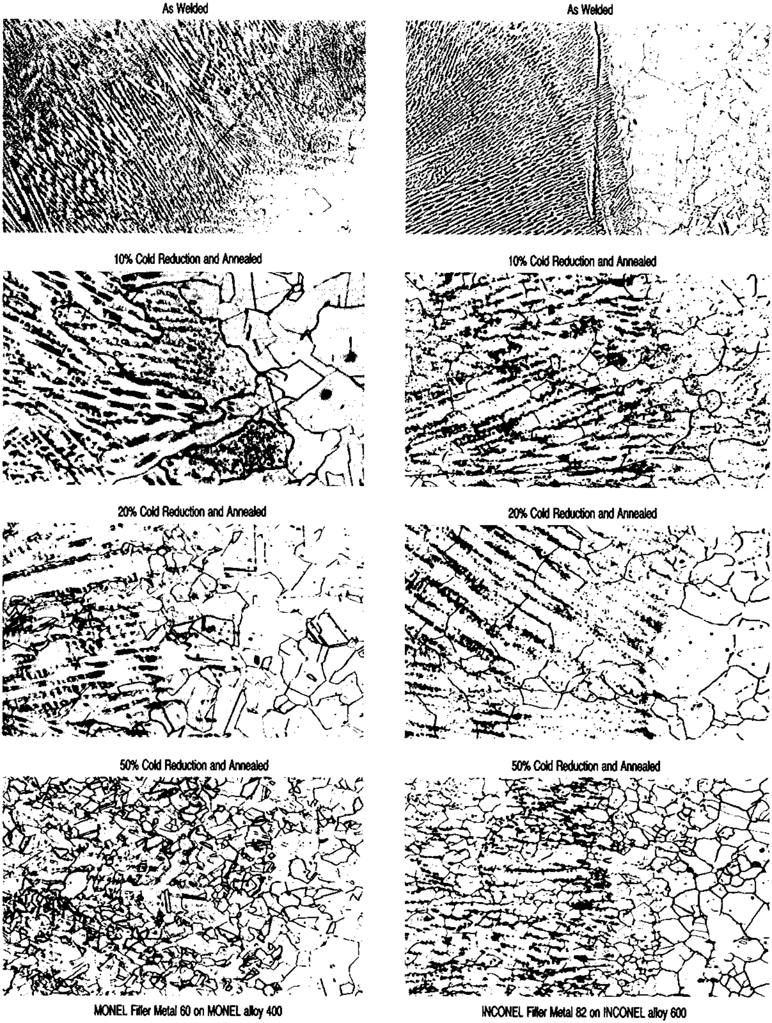


Figure 23—continued

Fabrication For High-Temperature Service

Equipment for high-temperature service is often fabricated of nickel alloys. The severe demands imposed by high temperatures must be considered in the design and welding of the equipment.

Design Factors

Weld metals usually have lower stress-rupture ductility and lower thermal-fatigue strength than wrought materials. Proper design of welded structures can minimize the effects of these lower properties.

Equipment should be designed so that welds are placed in locations where the effects of low stress-rupture ductility will not be detrimental. Generally, this involves placing the welds in areas where minimum deformation at high temperature occurs. For example, a horizontally positioned pipe having a longitudinal weld should be turned to locate the weld at the top rather than at the bottom. That location results in greatly reduced weld-metal elongation when the pipe sags during high-temperature service.

To minimize the effects of thermal or mechanical fatigue, welds should be located in areas of low-stress. Corners and areas where shape or dimensional changes occur are points of stress concentration and should not contain welded joints. Butt joints are preferred because the stresses act axially rather than eccentrically as in corner and lap joints. Figure 24 shows some examples of design modifications that locate welds in areas of low stress. If relocation of the joint is not possible, the weld must completely penetrate the joint, and a backing weld should be applied if the root side of the joint is accessible.

Welding Procedures

The weld should completely penetrate or close the joint. No unfused areas should be left in any joint if the design permits. Thermal-fatigue failures can often be traced to incomplete welds that create stress concentrations. Figure 25 shows an example.

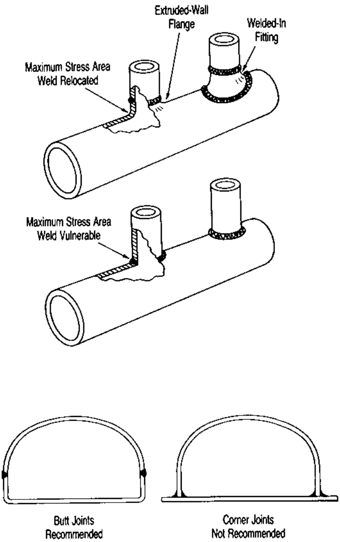


Figure 24. Designs for high-temperature service.

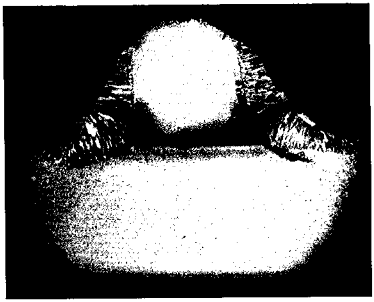


Figure 25. Thermal-fatigue cracking emanating from incomplete welds.

Some joint designs that facilitate complete penetration are shown in Figure 26.

If welds must be placed in areas where changes in sectional size or direction occur, 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 27 shows two joint types that can be completely sealed with weld metal.

Welds in heat-treating fixtures fabricated of round or flat stock should be smoothly flared into the base metal without undercut. When fixtures are to be subjected to heating and quenching cycles, wrap-around or loosely riveted joints are sometimes desirable because they provide some freedom of movement.

All welding slag must be removed from completed joints. As shown in Figure 28, slag that becomes molten during high-temperature service can cause severe corrosion.[7] In oxidizing environments, the slag will become increasingly fluid and agressively attack the metal. In reducing atmospheres, the slag can act as an accumulator of sulfur and cause failure by sulfidation in atmospheres that are otherwise adequately low in sulfur. In one case, with only 0.01% sulfur in the atmosphere, the sulfur content of slag was found to increase from 0.05% to as much as 1.6% in 1 month. Sulfur pickup can also depress the melting temperature of the slag, causing the slag to become corrosive at lower temperatures.

If all slag cannot be removed from areas such as the tight root of a lap or crossover joint in round stock, subsequent welding passes must completely enclose the joint to prevent contact of the slag with the atmosphere.

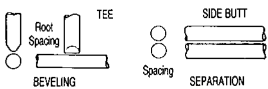


Figure 26. Designs for achievement of completely penetrated weld (high-temperature service).

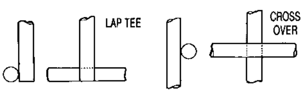


Figure 27. Designs for sealed joints by weld-all-around techniques (high-temperature service).

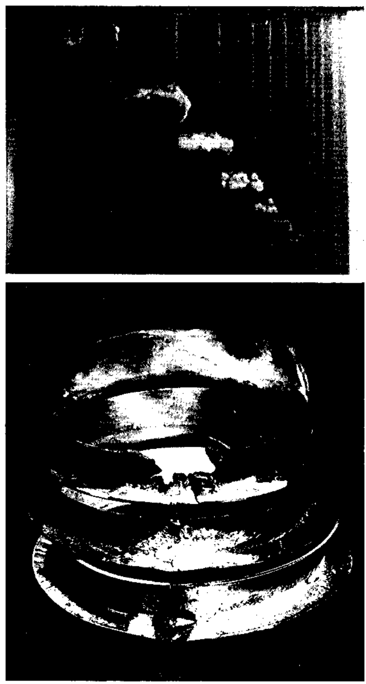


Figure 28. Attack by molten welding flux.

Testing and Inspection

Welds in nickel alloys are tested and inspected by the same standard procedures used for welds in steel. Some of these methods are visual inspection, radiography, various mechanical tests, and sectioning and etching for micro- and macroexamination. Magnetic-particle inspection is not very useful since only alloys such as Nickel 200 are sufficiently magnetic to produce a recording. Fluorescent and nonfluorescent dye-penetrant inspections are appropriate for detection of small surface defects.

Bend Testing

The strength and ductility of welded joints are frequently evaluated by free-bend or guided-bend tests. Specimens for bend testing may have the weld in either the transverse or longitudinal orientation.

Transverse specimens are commonly used for qualification purposes, but they may give misleading weld-metal ductility values and cause rejection of weldments having acceptable soundness and ductility. An indication of low weld-metal ductility can result from variation in strength and hardness across the joint. The bending area includes five separate zones: weld metal, two heat-affected zones, and two areas of unaffected base metal. During bending of the specimen, greater elongation occurs in the unaffected base metal and heat-affected zones if those areas are softer than the weld metal. The low elongation of the weld metal could be erroneously interpreted as an indication of low ductility.

The effect is more pronounced in dissimilar joints in which one member is of lower strength than the other. Figure 29 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. With a gauge length spanning the entire joint, average elongation may be 20%. Elongation of the Nickel 200 side of the joint, however, may be 40% or more.

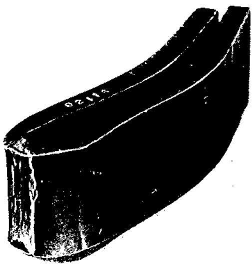


Figure 29. Transverse face-bend specimen.

A longitudinal test specimen in which the weld is in the center and parallel to the long edge is preferred. As shown in Figure 30, all areas of the joint are forced to elongate at the same rate regardless of strength. When weld quality is to be evaluated, results from such a test are more realistic, and welded joints will meet most requirements without difficulty.

Misleading ductility values can also be obtained from transverse tensile tests. Longitudinal tests are preferred for determining weld quality.

Figure 31 shows another bend-test specimen that can be misinterpreted. On first inspection, the spec-

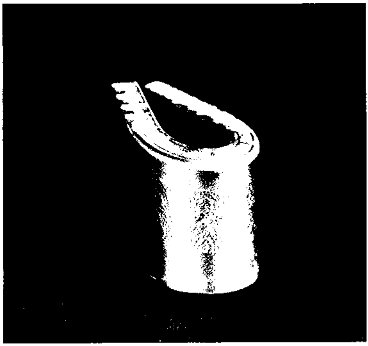


Figure 30. Longitudinal bend-test specimen in which weld runs central and parallel to the long edge.

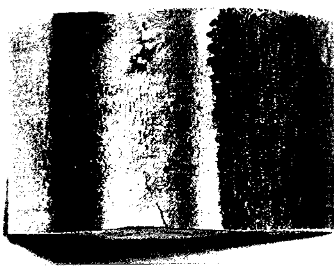


Figure 31. Base-metal cracks in guided-bend specimen of MONEL alloy 400.

imen may appear to be embrittled. Microscopic examination (Figure 32), however, will show that improperly ground shaper or milling tools have caused a drag or flow of metal that opens the specimen surface during bending.

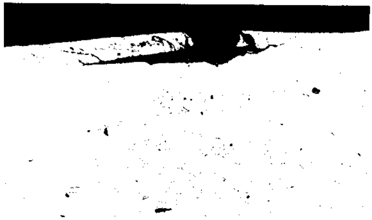


Figure 32. Photomicrograph of MONEL alloy 400 bend specimen showing crack that originated in heavily cold-worked area.

Macroetching

The surface of a sample to be macroetched should be prepared by grinding. Rough grinding on an abrasive wheel or emery-cloth belt is usually adequate. Some etching solutions that give good results on weld metals are described in Table 20.

Table 20 — 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 together 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 200°F (95°C) before etching.

Appendix

References

1. *Welding Products*, Inco Alloys International, Huntington, West Virginia 25720, U.S.A., and Hereford HR4 9S4, England.
2. "Safety in Welding and Cutting," American National Standard Z49.1, American Welding Society, 2501 N.W. 7th Street, Miami, Florida 33125.
3. Occupational Safety and Health Standards, 29 CFR 1910, United States Department of Labor, Washington, D.C. 20210.
4. "Safety and Health in Welding and Cutting," NIOSH Publication 78-138, National Institute for Safety and Health, 4676 Columbia Parkway, Cincinnati, Ohio, 45226.
5. G. R. Pease, R. E. Brien, and P. E. Legrand. "The Control of Porosity in High-Nickel-Alloy Welds," *Welding Journal,* Vol. 37, No. 8 (August, 1958), pp. 354s-360s.
6. W. F. Savage, S. S. Strunck, and Y. Ishikawa. "The Effect of Electrode Geometry in Gas Tungsten-Arc Welding," *Welding Journal,* Vol. 44, No. 11 (November, 1965), pp. 489s-496s.
7. G. R. Pease. "Corrosion of Nickel-Chromium-Iron Alloys by Welding Slags," *Welding Journal,* Vol. 35, No. 9 (September, 1956), pp. 469s-472s.

Nominal Chemical Composition, %, of Alloys

Alloy	Ni	Cr	Fe	Cu	Co	Mo	Ti	Al	Nb	Others
Nickel 200	99.6	—	—	—	—	—	—	—	—	C 0.08
Nickel 201	99.6	—	—	—	—	—	—	—	—	C 0.01
Nickel 205	99.6	—	—	—	—	—	—	—	—	C 0.04; Mg 0.04
Nickel 212	97.0	—	—	—	—	—	—	—	—	Mn 2.0
Nickel 222	99.5	—	—	—	—	—	—	—	—	Mg 0.075
Nickel 270	99.98	—	—	—	—	—	—	—	—	C 0.01
MONEL alloy 400	66.5	—	1.2	31.5	—	—	—	—	—	Mn 1.1
MONEL alloy 401	42.5	—	0.3	55.5	—	—	—	—	—	Mn 1.6
MONEL alloy R-405	66.5	—	1.2	31.5	—	—	—	—	—	Mn 1.1; S 0.04
MONEL alloy 450	30.0	—	0.7	68.0	—	—	—	—	—	Mn 0.7
MONEL alloy K-500	66.5	—	1.0	29.5	—	—	0.6	2.7	—	—
FERRY alloy	45.0	—	—	55.0	—	—	—	—	—	—
INCONEL alloy 600	76.0	15.5	8.0	—	—	—	—	—	—	—
INCONEL alloy 601	60.5	23.0	14.4	—	—	—	—	1.4	—	—
INCONEL alloy 617	52.0	22.0	1.5	—	12.5	9.0	—	1.2	—	—
INCONEL alloy 625	61.0	21.5	2.5	—	—	9.0	—	—	3.6	—
INCONEL alloy 718	54.0	18.0	18.5	—	—	3.0	0.9	0.5	5.1	—
INCONEL alloy X-750	73.0	15.5	7.0	—	—	—	2.5	0.7	1.0	—
INCONEL alloy 751	73.0	15.0	7.0	—	—	—	2.5	1.1	1.0	—
INCONEL alloy MA 754	77.5	20.0	1.0	—	—	—	0.5	0.3	—	Y_2O_3 0.6
INCOLOY alloy 800	32.5	21.0	46.0	—	—	—	0.4	0.4	—	C 0.05
INCOLOY alloy 800HT	32.5	21.0	46.0	—	—	—	0.4[a]	0.4[a]	—	C 0.08; Al+Ti 1.0
INCOLOY alloy 825	42.0	21.5	30.0	2.2	—	3.0	1.0	—	—	—
INCOLOY alloy 903	38.0	—	42.0	—	15.0	—	1.4	0.9	3.0	—
INCOLOY alloy 907	38.0	—	42.0	—	13.0	—	1.5	0.03	4.7	Si 0.15
INCOLOY alloy 909	38.0	—	42.0	—	13.0	—	1.5	0.03	4.7	Si 0.4
INCOLOY alloy 925	44.0	21.0	28.0	1.8	—	3.0	2.1	0.3	—	—
INCOLOY alloy DS	37.0	18.0	41.0	—	—	—	—	—	—	Mn 1.0; Si 2.3
INCOLOY alloy MA 956	—	20.0	74.0	—	—	—	0.5	4.5	—	Y_2O_3 0.5
INCO alloy A-286	25.5	15.0	56.5	—	—	1.25	2.1	—	—	—
INCO alloy C-276	57.0	15.5	5.5	—	1.2	16.0	—	—	—	W 3.8
INCO alloy G-3	44.0	22.2	19.5	2.0	2.5	7.0	—	—	—	—
INCO alloy HX	47.5	21.8	18.5	—	1.5	9.0	—	—	—	W 0.6
INCO alloy 020	35.0	20.0	37.0	3.5	—	2.5	—	—	0.6	—
INCO alloy 330	35.5	18.5	44.0	—	—	—	—	—	—	Si 1.1
INCO alloy MS 250	19.0	—	76.0	—	—	3.0	1.4	—	—	—
NIMONIC alloy 75	80.0	19.5	—	—	—	—	—	—	—	—
NIMONIC alloy 80A	76.0	19.5	—	—	—	—	2.4	1.4	—	—
NIMONIC alloy 81	67.0	30.0	—	—	—	—	1.8	0.9	—	—
NIMONIC alloy 86	65.0	25.0	—	—	—	10.0	—	—	—	Ce 0.03
NIMONIC alloy 90	60.0	19.5	—	—	16.5	—	2.5	1.5	—	—
NIMONIC alloy 105	54.0	15.0	—	—	20.0	5.0	1.3	4.7	—	—
NIMONIC alloy 115	60.0	14.2	—	—	13.2	3.2	3.8	4.9	—	—
NIMONIC alloy 263	51.0	20.0	—	—	20.0	5.8	2.2	0.5	—	—
NIMONIC alloy 901	42.5	12.5	36.0	—	—	5.8	2.9	—	—	—
NIMONIC alloy AP1	55.5	15.0	—	—	17.0	5.0	3.5	4.0	—	—
NIMONIC alloy PE11	39.0	18.0	34.0	—	—	5.2	2.3	0.8	—	—
NIMONIC alloy PE16	43.5	16.5	34.0	—	—	3.3	1.2	1.2	—	—
NIMONIC alloy PK33	56.0	18.0	—	—	14.0	7.0	2.4	2.1	—	—
BRIGHTRAY alloy B[b]	60.0	16.0	23.0	—	—	—	—	—	—	Si 1.0
BRIGHTRAY alloy C[b]	78.0	20.0	—	—	—	—	—	—	—	Si 1.5
BRIGHTRAY alloy F	37.0	18.0	42.0	—	—	—	—	—	—	Si 2.3
BRIGHTRAY alloy S	79.0	20.0	—	—	—	—	—	—	—	Si 1.0
BRIGHTRAY alloy 35[b]	35.0	20.0	43.0	—	—	—	—	—	—	Si 2.0
NILO alloy 36	36.0	—	64.0	—	—	—	—	—	—	—
NILO alloy 42	42.0	—	58.0	—	—	—	—	—	—	—
NILO alloy 48	48.0	—	52.0	—	—	—	—	—	—	—
NILO alloy 475	47.0	4.8	48.0	—	—	—	—	—	—	—
NILO alloy K	29.5	—	53.0	—	17.0	—	—	—	—	—

[a] Ti + Al 0.85 – 1.20.

[b] Also contains rare-earth additions for increased oxidation resistance.

Welding Products

Coated Electrodes	Major Uses	AWS Class	MIL-E-22200 Type
Nickel Welding Electrode 141	Nickel 200 and Nickel 201; the clad side of nickel-clad steel; joining steels to nickel alloys.	ENi-1	4N11
MONEL Welding Electrode 190	MONEL alloy 400 to itself, to low-alloy and carbon steels, to copper and copper-nickel alloys; surfacing of steels.	ENiCu-7	9N10
MONEL Welding Electrode 187	MONEL alloy 450; weldable grades of cast and wrought 70/30, 80/20, and 90/10 copper-nickel alloys.	ECuNi	CuNi
INCONEL Welding Electrode 132	INCONEL alloy 600; INCO alloy 330.	ENiCrFe-1	
INCONEL Welding Electrode 182	INCONEL alloys 600 and 601, surfacing of steel; dissimilar combinations of steels and nickel alloys.	ENiCrFe-3	8N12
INCONEL Welding Electrode 112	INCONEL alloys 625 and 601; pit-resistant alloys; dissimilar combinations of steels and nickel alloys; surfacing of steels.	ENiCrMo-3	
INCONEL Welding Electrode 117	INCONEL alloy 617; INCOLOY alloy 800HT; Dissimilar combinations of high-temperature alloys.	ENiCrCoMo-1	—
INCOLOY Welding Electrode 135	INCOLOY alloy 825.	—	—
INCO Welding Electrode C-276	INCO alloy C-276; other pit-resistant alloys; surfacing of steels.	ENiCrMo-4	—
INCO Welding Electrode G-3	INCO alloys G and G-3; other pit-resistant alloys; dissimilar combinations of steels and nickel alloys; surfacing of steels.	ENiCrMo-9	—
INCO-WELD A Electrode	INCOLOY alloys 800 and 800HT; dissimilar combinations of steels and nickel alloys; 9% nickel steel; surfacing of steels.	ENiCrFe-2	—
INCO-WELD B Electrode	Cryogenic steels (e.g., 9% nickel steel) with alternating current.	ENiCrFe-4	—
INCO-WELD C Electrode	Stainless steels; carbon steels; spring steels; general maintenance welding.	—	—
NI-ROD Welding Electrode	Cast irons, especially for thin sections and machinability.	ENiCI	—
NI-ROD 55 Welding Electrode	Cast irons, especially thick sections and high-phosphorus irons.	ENiFeCI	—
NI-ROD 44 Welding Electrode	Cast irons, especially for high strength and ductility.	—	—
NI-ROD 55X Welding Electrode	Cast irons, especially for out-of-position welding and high-phosphorus irons.	—	—
NI-ROD 99X Welding Electrode	Cast irons, especially for out-of-position welding, thin sections, and machinability.	—	—

Filler Metals	Major Uses	AWS Class	MIL-E-21562 Type
Nickel Filler Metal 61	Nickel 200 and Nickel 201; dissimilar combinations of nickel alloys and steels; surfacing of steels.	ERNi-1	RN61 EN61
MONEL Filler Metal 60	MONEL alloys 400, R-405, and K-500; surfacing of steel.	ERNiCu-7	RN60 EN60
MONEL Filler Metal 67	MONEL alloy 450; weldable grades of 70/30, 80/20, and 90/10 copper-nickel alloys.	ERCuNi	RN67 EN67
INCONEL Filler Metal 62	INCONEL alloy 600.	ERNiCrFe-5	RN62 EN62
INCONEL Filler Metal 82	INCONEL alloys 600 and 601; INCOLOY alloys 800 and 800HT; INCO alloy 330; dissimilar combinations of steels and nickel alloys; surfacing of steels.	ERNiCr-3	RN82 EN82
INCONEL Filler Metal 92	Dissimilar combinations of steels and nickel alloys.	ERNiCrFe-6	RN6A EN6A
INCONEL Filler Metal 601	INCONEL alloy 601.	—	—
INCONEL Filler Metal 617	INCONEL alloy 617; INCOLOY alloy 800HT; dissimilar combinations of high-temperature alloys.	ERNiCrCoMo-1	—
INCONEL Filler Metal 625	INCONEL alloys 625 and 601; pit-resistant alloys; dissimilar combinations of steels and nickel alloys; surfacing of steels.	ERNiCrMo-3	RN625 EN625
INCONEL Filler Metal 718	INCONEL alloys 718 and X-750.	ERNiFeCr-2	—
INCOLOY Filler Metal 65	INCOLOY alloy 825.	ERNiFeCr-1	RN65
INCO Filler Metal C-276	INCO alloy C-276; other pit-resistant alloys; surfacing of steels.	ERNiCrMo-4	—
INCO Filler Metal HX	INCO alloy HX.	ERNiCrMo-2	—
NC 80/20 Filler Metal	BRIGHTRAY electrical-resistance alloys; INCOLOY alloy DS.	—	—
NI-ROD Filler Metal 44	Cast irons, especially robotic and automatic welding.	—	—
NI-ROD FC 55 Cored Wire	Automatic welding of cast irons by flux-cored arc welding.	—	—

Submerged Arc Fluxes	Major Uses
INCOFLUX 4	Butt welding and surfacing with INCONEL Filler Metal 82.
INCOFLUX 5	Butt welding and surfacing with MONEL Filler Metal 60.
INCOFLUX 6	Butt welding and surfacing with Nickel Filler Metal 61; surfacing to three layers with INCONEL Filler Metal 82.
INCOFLUX 7	Butt welding and surfacing with INCONEL Filler Metal 625.
INCOFLUX 8	Butt welding with MONEL Filler Metal 67.

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