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WELDING AND BRAZING OF NICKEL AND NICKEL-BASE ALLOYS

A REPORT

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WELDING AND BRAZING OF NICKEL AND NICKEL-BASE ALLOYS

A REPORT

By
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Foreword

The Technology Utilization Office of the National Aeronautics and Space Administration has sponsored a series of state-of-the-art reports in the general field of materials fabrication. This is part of NASA's program to make generally available technological information resulting from its research and development efforts, much of which may have commercial application in American industry. The Battelle Memorial Institute, Columbus Laboratories, originally prepared these reports in 1965 under contract DA-01-021-AMC-11651(Z) and has revised and updated them under contract NASw-1842 to include new technology available to the present.

This report is one of a series pertaining to the fabricating of nickel, nickel-base, and cobalt-base alloys. Another series surveying the technology of processing precipitation-hardening stainless steels is available in NASA Special Publications 5084 through 5090.

This report reviews practices for joining nickel and nickel-base alloys that contain at least 50-percent nickel. The discussions deal generally with joining preparations, joining processes, and joint quality. Techniques and special considerations that are normally followed when joining these alloys are described.

Director
Technology Utilization Office

Acknowledgments

The information in this report was obtained from equipment manufacturers, nickel producers, technical publications, reports from Government contractors, and interviews with engineers employed by major fabricators of nickel-base alloys. Data from reports and memoranda issued by the Defense Metals Information Center also were used. Assistance afforded by previous programs has also helped in the preparation of this report. The literature search for this program began with 1962, since DMIC Report 181 issued in 1962 covered the joining of nickel-base alloys up to that time.

The following sources within Battelle were searched for appropriate references covering the period January 1962, to the present:

Defense Metals Information Center
Main Library
Slavic Library
Welding Journal Indexes (1960 to present)

Information also was obtained from sources outside of Battelle, viz., the Redstone Scientific Information Center, the Defense Documentation Center, and the NASA Master Tapes.

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CHAPTER 1

Introduction

Nickel and nickel-base alloys can be joined by many of the conventional joining processes. Some new joining processes also have been used successfully. In general, conventional joining procedures are used with only slight modifications, depending on the particular alloy to be welded. However, some special precautions must be taken. Harmful materials must be removed from the joint or surrounding areas to avoid damage to the weld and the nearby heated parent metal. Some high-strength, age-hardenable alloys are prone to cracking in or near joint areas, unless the material is in the proper condition of heat treatment. Foreign material and flux residues left from joining operations can cause trouble in subsequent service.

Procedures for joining these alloys have been developed that eliminate or minimize the usual difficulties that have been experienced. When proper procedures are employed, joining of nickel and nickel-base alloys can be performed satisfactorily.

This report is a summary of available information on the joining of nickel and nickel-base alloys. Considerations that are applicable to all nickel alloys or to large groups of nickel alloys are described in chapter 2. The discussion includes information on product materials, joint design, preweld and postweld cleaning, welding fixtures and tooling, and other preweld considerations. Chapter 3 deals with individual joining processes, the joining of dissimilar metals, and special considerations to be taken when joining the various alloys. The fourth chapter includes discussions of inspection techniques, defects, and repair procedures.

The joining of four types of nickel-base materials is described in this report:

(1) High-nickel, nonheat-treatable alloys
(2) Solid-solution-hardening nickel-base alloys
(3) Precipitation-hardening nickel-base alloys
(4) Dispersion-hardening nickel-base alloys.

The high-nickel and solid-solution-hardening alloys are widely used in chemical containers and piping. These materials have excellent resistance to corrosion and oxidation, and retain useful strength at elevated temperatures. The precipitation-hardening alloys have good properties at elevated temperature. They are important in many aerospace applications. Dispersion-hardening nickel also is used for elevated-temperature service.

The many uses of nickel and nickel-base alloys arise from certain inherently desirable properties:

(1) Corrosion resistance at room and elevated temperature
(2) Oxidation resistance at elevated temperature
(3) Good mechanical properties at cryogenic, room, and elevated temperature
(4) Easy fabrication.

Joining operations are important in fabricating all of the nickel alloys into useful products that have these properties in combinations suitable for the particular service conditions.

In broad terms, the factors that most affect the successful joining of nickel-base alloys are: (1) the material to be joined, (2) the joining process to be used, and (3) inspections and repair procedures. These factors are described in detail in this report.

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CHAPTER 2

Joining Preparation

The selections of materials, equipment, component designs, and processes are all important steps to be taken before starting a joining operation. The joining specialist should be familiar with the basic properties of the materials he will be joining. The necessary equipment for all processing associated with joining must be available. Joint designs, cleaning procedures, and heat-treating operations must be considered. Also, some planning must be done to control distortion and to anticipate required post-joining operations. Finally, the appropriate joining process must be selected. The selection criteria important in the joining of nickel-base alloys are discussed in the following sections.

MATERIALS

When planning joining operations for nickel and nickel-base alloys, a good understanding of the materials and of their behavior during joining operations is needed. Three basic types of materials, as discussed below, may be involved:

(1) *Base metals.*—The material being joined usually is called the "base metal," "parent metal," or "base plate." Nickel and nickel-base-alloy base metals range in thickness from that of foil to plate several inches thick and in size from that of microminiature electronic components to railroad tank cars. Often parts of base-metal materials are used to assist the welding operation but are removed when they are no longer needed. Starting and runoff tabs are typical examples.

(2) *Filler metals.*—Filler metals are those added to complete a joint. Filler metals for fusion welding include coated welding electrodes, coiled wire on spools, and short lengths of wire or strips sheared or machined from the parent-metal sheet or plate. For brazing, filler metals may or may not contain nickel and include foil, wire, powder, and powder-flux pastes. For soldering, they include wire, paste, and molten-solder baths. Filler metals are seldom used with the following processes: resistance spot and seam welding, roll resistance spot welding, and flash welding.

Filler metals for joining nickel and nickel-base alloys must be compatible with service requirements and subsequent processing. Corrosion resistance and mechanical properties of the completed joint, for example, may differ considerably from the parent metal. Filler metals also should be compatible with subsequent heat-treating requirements. Normally, they are expected to provide properties that equal or exceed the base-metal properties in the finished weldment.

(3) *Shielding gases and fluxes.*—Shielding gases are used during welding operations to protect the weld joint and welding arc from atmospheric contamination. Oxygen, nitrogen, water vapor, and other constituents of air and shop atmospheres can be harmful to the weldment. Several gases are used for shielding nickel and nickel-base alloys during joining. Argon, helium, argon-helium mixtures, and hydrogen are the most common. Argon and 1-percent oxygen mixtures also have been used for welding a limited number of alloys (ref. 1). When gases are used for joining, special high-purity grades are recommended; these high-purity grades are available commercially. A recent report on gas tungsten-arc weldments in Inconel 600 emphasizes this point (ref. 2). It was concluded that relatively small amounts of impurity elements, particularly oxygen, in argon shielding gas have a strong effect on the melting efficiency of the arc. An increase in total impurity content from 690 to only 2440 ppm caused a decrease in weld penetration of approximately 50 percent. While these impurity levels are considerably higher than those

encountered in commercial gases, the results indicate the drastic effect an increase in the impurity level can have.

Fluxes help protect the weld metals from contamination. They function by providing gases and slag coverings, or by blanketing the heated areas with protective films. They are provided in the form of electrode coverings and loose powders for fusion welding, and as powders and pastes for soldering and brazing operations.

Types of Nickel and Nickel-Base Alloys

The more familiar nickel-base alloys and their uses are given in table 1 (refs. 3 through 6 and 10). Individual alloys within each major type may have somewhat differing characteristics as illustrated by the varying uses of the alloys.

Each of the major types has distinctive characteristics as described below:

High-nickel, nonheat-treatable alloys.—The high-nickel, nonheat-treatable alloys generally contain more than 95-percent nickel. Mechanical properties of these alloys are dependent upon the degree of hot or cold work. Cold working increases hardness and strength; if a reduction in these properties is desired, it can be accomplished by heat treatment of cold-worked material. In general, heat treatment does not increase the strength of these alloys.

Solid-solution-hardening alloys.—These alloys include the older, less heat-resistant, but highly corrosion-resistant nickel-base alloys. They are not usually considered hardenable by heat treatment. Heat treatment may be used to soften them after cold-working operations, however.

Precipitation-hardening nickel-base alloys.—These alloys are strengthened by heat treatment. They were developed to meet needs for alloys that can operate at high temperatures under high stress. Practically all of them contain aluminum and titanium, and strengthening occurs due to precipitation of a nickel-aluminum-titanium phase, $Ni_3(Al, Ti)$, known as gamma prime (γ'). The usual heat treatment is a two-step procedure—solution treating and aging.

Dispersion-hardening nickel-base alloys.—Thoria-dispersion-strengthened nickel (TD or DS nickel) contains about 2-volume-percent thoria (thorium oxide) and the balance nickel. Submicron-size thoria particles are uniformly dispersed within the nickel matrix. This type of dispersion significantly increases the tensile strength of nickel at elevated temperatures. A newer alloy is TD nickel-chromium, containing about 20-percent chromium and offering higher strength and better corrosion resistance than TD nickel.

Effects of Alloying Elements

It is beyond the scope of this report to cover all the effects of alloying elements in nickel and nickel-base alloys, but it is useful to consider the effects of major alloying elements on weldability. A knowledge of the effects of about 25 elements is necessary for an understanding of the joining characteristics of nickel-base alloys. A summary of the effects of these elements on joining is shown in table 2 and discussed in the following paragraphs (refs. 7 through 9).

Sulfur.—Sulfur causes hot shortness. It is probably the most harmful element encountered when joining nickel-base alloys. Sulfur has a very limited solubility in nickel and forms low-melting sulfide materials that embrittle the alloy by collecting at grain boundaries. Vacuum melting of the alloys or magnesium fixation are means of overcoming the bad effects of sulfur. High-quality, nickel-base materials may be ruined by poor removal of sulfur-containing machining compounds, crayon marks, or shop dirt before joining.

Magnesium.—Magnesium sulfides have melting points much higher than nickel sulfides. Thus, sulfur fixation is accomplished with magnesium. Unfortunately, the recovery of magnesium is poor, especially when fusion welding is done with covered electrodes.

Columbium.—Columbium is used to prevent the occurrence of hot cracking in nickel-iron-chromium alloys containing silicon. The amount of columbium required varies with the nickel/iron ratio. The higher the ratio, the more columbium is required.

Lead.—Lead causes hot shortness in nickel-alloy weld metal. It is seldom found in high-quality base or filler metals.

Phosphorus.—Phosphorus, like lead, is seldom found in harmful amounts in nickel-base alloys. Phosphorus in very low concentrations can cause hot cracking. Generally, its detrimental effects are similar to those of lead and sulfur.

Boron.—Although boron is added to nickel-base alloys to improve their high-temperature mechanical properties, it is very harmful to weldments. The presence of boron, even in very low concentrations,

TABLE 1.–*Nickel and Nickel-Base Alloys–Chemical Composition and Uses*

Trademark	Compositions, weight percent													
	Ni[a]	C	Cr	Mo	Fe	Co	Cu	Al	Ti	Cb[b]	Mn	Si	Others	Uses
Commercially pure and high-nickel non-heat-treatable alloys														
Nickel 200	99.5	0.06	--	--	0.15	--	0.05	--	--	--	0.25	0.05	--	Rocket motors, chemical shipping drums
Nickel 201	99.5	0.01	--	--	0.15	--	0.05	--	--	--	0.20	0.05	--	Caustic evaporators, combustion boats
Nickel 204	95.2	0.06	--	--	0.05	4.50	0.02	--	--	--	0.20	0.02	--	Sonar equipment, ultrasonic cleaning and welding equipment
Nickel 205	99.5	0.06	--	--	0.10	--	0.05	--	0.02	--	0.20	0.05	0.04 Mg	Electronic components, wires, rods, pins
Nickel 211	95.0	0.10	--	--	0.05	--	0.03	--	--	--	4.75	0.05	--	Sparkplug electrodes, electron-tube grid wires
Nickel 212	97.7	0.10	--	--	0.05	--	0.03	--	--	--	2.00	0.05	--	Lamp-support wires, furnace lead wires
Nickel 220	99.5	0.06	--	--	0.05	--	0.03	--	0.02	--	0.12	0.03	0.04 Mg	Electron-tube cathodes
Nickel 225	99.5	0.06	--	--	0.05	--	0.03	--	0.02	--	0.13	0.20	0.04 Mg	Electron-tube cathodes
Nickel 230	99.5	0.09	--	--	0.05	--	0.01	--	0.003	--	0.10	0.03	0.06 Mg	Electron-tube cathodes
Nickel 233	99.5	0.09	--	--	0.05	--	0.03	--	0.003	--	0.18	0.03	0.07 Mg	Electron-tube plates, cathodes, and structural components
Nickel 270	99.97	0.02	Trace	--	Trace	--	Trace	--	--	--	Trace	Trace	--	Heat exchangers, electron-tube components
Alloys hardened principally by solid solution														
Monel 400	66.0	0.12	--	--	1.35	--	31.5	--	--	--	0.90	0.15	--	Marine and chemical heat exchangers
Monel 401	44.5	0.03	--	--	0.20	0.50	53.0	--	--	--	1.70	0.01	--	Electronic components
Monel 402	58.0	0.12	--	--	1.20	--	40.0	--	--	--	0.90	0.10	--	Pickling tanks for steel and copper
Monel 403	57.5	0.12	--	--	0.50	--	40.0	--	--	--	1.80	0.25	--	Gasoline and fresh-water tanks, mine sweeper fittings
Monel 404	55.0	0.06	--	--	0.05	--	44.0	0.02	--	--	0.01	0.02	--	Wave guides, transistor capsules, metal-to-ceramic seals
Monel R-405	66.0	0.18	--	--	1.35	--	31.5	--	--	--	0.90	0.15	--	Free-machining screw-machine products

TABLE 1.–*Nickel and Nickel-Base Alloys–Chemical Composition and Uses*–Continued

Trademark	Compositions, weight percent												
	Ni[a]	C	Cr	Mo	Fe	Co	Cu	Al	Ti	Cb[b]	Mn	Si	Others	Uses
Monel 406	84.0	0.12	--	--	1.35	--	13.0	--	--	--	0.90	0.15	--	Hot-water tanks
Nimonic 75	71-78	0.08-0.15	18-21	--	5.0	--	0.5	--	0.2-0.6	--	1.0	1.0	--	Combustion cans
	76	0.12	20	--	2.4	--	--	0.06	0.4	--	0.4	0.6	--	
Illium R	68	0.05	21.0	5.0	1.0	--	3.0	--	--	--	1.25	0.70	--	--
Illium G	56	0.20	22.5	6.4	6.5	--	6.5	--	--	--	1.25	0.65	--	--
Hastelloy B	Bal	0.05-0.12	1.0	26-30	4.0-7.0	2.5	--	--	--	--	1.0	[c]1.0	0.2-0.6V	Corrosion-resistant alloy
	61	0.10	1.0	28	5.0	--	--	--	--	--	0.8	0.7	--	
Hastelloy C	Bal	0.08-0.15	14.5-17.5	15-18	4.0-7.0	2.5	--	--	--	--	1.0	[c]1.0	0.35V, 3.0-5.25W	Combustion chambers, collector rings
	57	0.10	16	17	5	--	--	--	--	--	0.8	0.7	4W	
Hastelloy D	Bal	0.12	1.0	--	2.0	1.50	2.0-4.0	--	--	--	0.5-1.25	8.5-10.0	--	Corrosion-resistant alloy
	82	0.10	--	--	1.0	1.50	3.0	--	--	--	1.0	9.0	--	--
Hastelloy F	44	0.05-0.12	21-23	5.5-7.5	Bal	2.5	--	--	--	1.75-2.50	1.0-2.0	[c]1.0	1.0W	--
Hastelloy X	Bal	0.05-0.15	20.5-23	8.0-10.0	17-20	0.5-2.5	--	--	--	--	1.0	[c]1.0	0.2-1.0W	Jet-engine parts
	45	0.10	22.0	9.0	20	1.5	--	--	--	--			0.6W	
Hastelloy N	67-72	0.04-0.08	6.0-8.0	15-18	5.0	--	--	--	--	--	0.8	[c]0.5	Al + Ti = 0.5	Resistance to hot fluoride salts
Inconel 600	76.0	0.04	15.8	--	7.20	--	0.10	--	--	--	0.20	0.20	--	Jet-engine, heat-exchanger, and nuclear-reactor components
Inconel 625	61.0	0.05	22.0	9.0	3.00	--	0.10	--	--	4.0	0.15	0.30	--	Alloy evaluated for service up to 1200 °F
							Alloys capable of precipitation hardening							
Monel K-500	65.0	0.15	--	--	1.00	--	29.5	2.80	0.50	--	0.60	0.15	--	Pumps, shafts, impellers
Monel 501	65.0	0.23	--	--	1.00	--	29.5	2.80	0.50	--	0.60	0.15	--	Gyroscope parts and small machined products
Inconel 700	46.0	0.12	15.0	3.75	0.70	28.5	0.05	3.00	2.20	--	0.10	0.30	--	Turbine blades and rotors
Inconel 702	79.5	0.04	15.6	--	0.35	--	0.10	3.40	0.70	--	0.05	0.20	--	Afterburner liners
Inconel 718	52.5	0.04	19.0	3.0	18.0	--	0.10	0.60	0.80	5.2	0.20	0.20	--	Hydrofoils, spacecraft, jet engines, rocket motors, supersonic aircraft, cryogenic applications
Inconel 721	71.0	0.04	16.0	--	7.20	--	0.10	--	3.00	--	2.25	0.12	--	Internal-combustion-engine valves

Inconel 722	75.0	0.04	15.0	--	6.50	--	0.05	0.60	2.40	--	0.55	0.20	--	Jet-engine components
Inconel X-750	73.0	0.04	15.0	--	6.75	--	0.05	0.80	2.50	0.85	0.70	0.30	--	Gas-turbine parts, springs, bolts, bellows, aircraft sheet, vacuum envelopes
Inconel 751	72.5	0.04	15.0	--	6.75	--	0.05	1.20	2.50	1.00	0.70	0.30	--	Jet-engine turbine blades, diesel exhaust valves
Permanickel 300	98.6	0.25	--	--	0.10	--	0.02	--	0.50	--	0.10	0.06	0.35 Mg	Springs, grid side rods, and lateral windings
Duranickel 301	94.0	0.15	--	--	0.15	--	0.05	4.50	0.50	--	0.25	0.55	--	Springs, glass molds, plastic extrusion press parts
Inconel 713C	66-77	0.20	11-14	3.5-5.5	5.0	--	--	5.5-6.5	0.25-1.25	1.0-3.0	1.0	1.0	0.02B, Zr	Jet-engine blades, parts
	72	0.12	13	4.5	1	--	--	6	0.6	2.25	0.15	0.4	--	
DCM	63-70	0.08	14-16	4.5-6.0	4.0-6.0	--	--	4.4-4.8	3.35-3.65	--	0.10	0.15	0.07-.09B	Gas-turbine blades, parts
	68	0.05	14.3	5.3	4.6	--	--	4.4	3.4	--			0.08B	
Hastelloy R-235	Bal	0.16	14-17	4.5-6.5	9.0-11.0	2.5	--	1.75-2.25	2.25-2.75	--	^{c}0.25	^{c}0.6	^{c}0.005B	Gas-turbine and jet-engine parts
	63	0.15	15.5	5.5	10.0	--	--	2	2	--			--	
Waspaloy	56	0.05	19.0	4.3	1.0	14.0	--	1.3	3.0	--	0.70	0.40	0.005B 0.06Zr	Jet-engine blades, parts
Nimonic 80	70-77	0.1	18-21	--	5.0	2.0	--	0.5-1.8	1.8-2.7	--	1.0	1.0	--	--
	76	0.05	20	--	0.5		--	1.0	2.3	--	0.7	0.5	--	
Nimonic 80A	70-77	0.1	18-21	--	5.0	2.0	--	0.5-1.8	1.8-2.7	--	1.0	1.0	--	--
	75	0.04	21	--	0.5		--	0.6	2.5	--	0.7	0.5	--	
Nimonic 90	50-62	0.1	18-21	--	5.0	15-21	--	0.8-2.0	1.8-3.0	--	1.0	^{c}1.5	--	--
	58	0.10	19.5	--		18.0	--	1.2	2.4	--			--	
Nimonic 95	50-62	0.15	18-21	--	5.0	15-21	0.5	1.4-2.5	2.3-3.5	--	1.0	^{c}1.0	--	--
	50		20.0	--		20.0	--	2.0	3.0	--				
Nimonic 100	50-62	0.30	10-12	4.5-5.5	2.0	18-22	--	4.0-6.0	1.0-2.0	--	--	^{c}0.5	--	--
			11.0	5.0		20.0	--	5.0	1.5	--	--		--	
Udimet 500	46-55	0.15	15-20	3.0-5.0	4.0	13-20	--	2.5-3.25	2.5-3.25	--	0.75	^{c}0.75	0.005B 0.06Zr	Gas-turbine parts, sheet, bolting
	52	0.12	19.0	4.0	2.0	19.0	--	3.0	3.0	--	0.7	--	0.005B 0.05Zr	
Udimet 700	46-55	0.15	13-17	4.5-5.75	1.0	17-20	--	3.75-4.75	3.0-4.0	--	--	--	^{c}0.10B	Jet-engine parts
	53	0.12	15.0	5.1	0.75	18.5	--	4.25	3.5	--	--	--	0.08B	
Udimet 600	50	0.10	18.0	4.0	4.00	17.1	--	4.0	3.0	--	--	--	--	
Unitemp 1753	51	0.25	16.5	1.5	9.5	7.5	--	2.0	3.1	--	--	--	0.008B 8.5W, 0.05Zr	Gas-turbine components, buckets, wheel fasteners, rings, spacers
	Bal	0.02-0.28	15.5-17.5	1.0-2.0	7-11	6.5-8.5	--	1.75-2.25	2.9-3.4	--	--	--	0.002-0.010B, 0.02-0.10Zr, 7.5-9.5W	
M-252	51-57	0.10-0.20	18-20	9.10-11.0	5.0	9.0-11.0	--	0.5-1.25	2.25-2.75	--	0.5-1.5	0.3-1.0	--	--
	55	0.15	19.0	10.0	2.0	10.0	--	1.0	2.5	--	1.0	0.7	0.005B 0.06Zr	

TABLE 1.–*Nickel and Nickel-Base Alloys–Chemical Composition and Uses*–Concluded

Trademark	Compositions, weight percent													Uses
	Ni[a]	C	Cr	Mo	Fe	Co	Cu	Al	Ti	Cb[b]	Mn	Si	Others	
René 41	52-58	0.06-0.12	18-20	9.0-10.5	5.0	10-12	--	1.5-1.8	3.0-3.3	--	0.5	[c]0.5	0.01B	Jet-engine components, sheet bolting, turbine disks
	55	0.10	19.0	10.0	1.0	10.0	--	1.5	3.0	--	0.05	0.1	0.005B	
René 62	48	--	15.0	9.0	22.50	--	--	1.25	2.5	2.25	--	--	--	
Nitrotung	61	0.10	12.0	--		10.0	--	4.0	4.0	--			0.05B, 8.0W 0.05Zr	High-strength parts
Astroloy	56	0.50	15.0	5.25	--	15.0		4.40	3.5	--	0.05	--	--	
Dispersion-hardening alloys														
TD nickel	Bal	--	--	--	--	--	--	--	--	--	--	--	2.0ThO$_2$	Turbine blades
TD nickel chromium	Bal	--	20.0	--	--	--	--	--	--	--	--	--	2.0ThO$_2$	Jet-engine components

Note: When two compositions are given, maximum compositions or ranges are in the first line; those in the second line are typical compositions.

[a] Includes small amount of cobalt unless otherwise specified.
[b] Includes tantalum.
[c] Indicates minimum amount.
[d] Indicates maximum amount.

TABLE 2.–*Effect of Elements on Joining Nickel and High-Nickel Alloys*

Beneficial	No real effect[a]	Variable	Harmful
Columbium	Manganese	Aluminum	Sulfur
Magnesium	Copper	Titanium	Phosphorus
	Chromium	Carbon	Lead
	Iron	Molybdenum	Zirconium
	Cobalt	Silicon	Boron
			Oxygen
			Nitrogen
			Hydrogen

[a] Within normal concentration ranges.

causes cracking of weld metal, heat-affected zones, and heated parent metals.

Zirconium.–Zirconium, like boron, can be added to improve the high-temperature mechanical properties, but such additions ruin weldability. A few tenths of 1 percent of zirconium will make nickel-base alloys very weld-crack sensitive. Zirconium-nickel alloys are not fusion-weldable.

Carbon.–Carbon in the nonchromium-bearing nickel alloys may cause trouble if the service temperature is in the range 600° to 1400°F because the thermal cycles involved in joining promote carbon precipitation as intergranular graphite, which has a weakening effect. The remedy is to limit the carbon content to below 0.02 percent. In the chromium-bearing nickel-base alloys, carbon in normal amounts causes no problems.

Molybdenum.–Molybdenum in the amount of 20 to 30 percent in two-phase alloys causes hot cracking. Single-phase alloys do not crack seriously. Thus, molybdenum should be a problem with only one or two of the important alloys.

Silicon.–Silicon causes hot cracking in nickel-base alloys. The severity of this effect is quite variable, depending both upon the alloy and the joining process used. It is especially bad in high-nickel chromium-bearing alloys. Columbium is often added to high-nickel alloys to counteract the effects of silicon.

Aluminum.–Aluminum is added to nickel alloys as a deoxidizer and to develop age-hardening properties. In general, aluminum has the same effect as silicon on joining. The usefulness of aluminum as an age hardener in high-temperature high-nickel alloys makes it a desirable addition to fusion-welding filler metals for these alloys. Usually, however, hot-cracking problems arise before the full benefit of the aluminum is obtained. Thus, other means must be found to match weld-metal properties with base-metal properties.

Titanium.–Titanium is added to high-nickel alloys for two reasons: (1) to develop age-hardening response and (2) to reduce gas porosity. The effect of titanium when welding these alloys is very much like that of aluminum. The weld metal becomes hot-short and crack-free welds become hard to obtain, especially in restrained joints.

Oxygen, nitrogen, and hydrogen.–Oxygen, nitrogen, and hydrogen are the primary sources of weld-metal porosity. However, these elements have not been shown to promote cracking in nickel and nickel-base alloys.

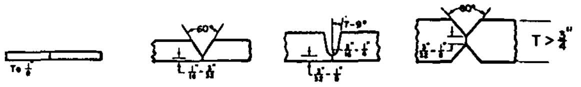
Some alloying elements have a considerable effect in joining operations other than fusion welding, such as brazing. Other alloying elements have only a small effect. The most important consideration in brazing, after the proper choice of filler metal, is what surface contaminants are produced by the alloying elements in the base material. Nickel-base alloys containing aluminum and/or titanium require special consideration for successful brazing. This will be discussed later in this report.

JOINT DESIGN

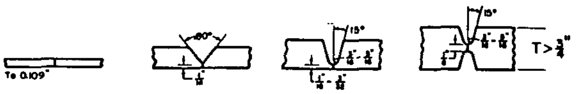
Joint design can limit the selection of a welding process, although some welding processes are more tolerant than others. Joints with square abutting edges are suitable for arc or electron-beam fusion welding for thin gages of nickel and nickel-base-alloy sheet. Thicker sheet requires a more complex joint design. Typically, such preparation involves machining bevels or contours on the abutting edges. Part tolerances also are an important consideration in establishing good joint designs. Close tolerances are always preferred, but they cannot always be produced in production parts.

Joints designed for either tungsten inert-gas (TIG), metal inert-gas (MIG), or electron-beam welding of nickel and nickel-base alloys normally are prepared by machining to provide a good joint fit. The joints are machined by milling, shaping, grinding, and other conventional machining methods.

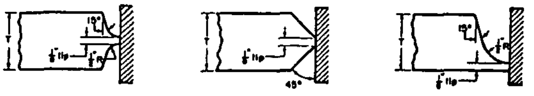
Suggested joint designs for arc welding of nickel-base alloys are shown in figure 1 (ref. 11). Joint preparations for similar thicknesses of steel are also shown for comparison. Nickel and high-nickel alloys



a. Steel



b. Nickel and Nickel Alloys



c. Dissimilar Thickness Nickel Alloy

FIGURE 1.–Joint preparations for arc-welding nickel and nickel-base alloys compared with those for steel.

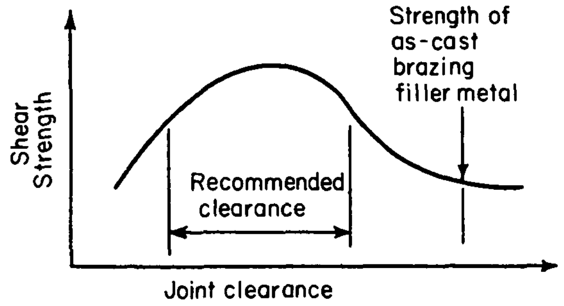


FIGURE 2.–Effect of joint clearance on the shear strength of brazed joints.

do not flow as readily as mild steel, and weld penetration normally is less. Consequently, greater operator skill is required to prepare satisfactory welds. Heat-input rates for welding should be normal; high rates can result in loss of residual deoxidizing agents.

For electron-beam welds, which are very narrow, square-butt joints are employed to ensure a good fit over the full thickness of the joint.

Resistance welding of the spot, seam, and projection types usually involves joints that consist of overlapping layers of material. Multiple layers may be included in a single joint. Many of the joint designs used for resistance welding are not intended to transmit transverse tensile loads. In resistance welding, such factors as edge distances, flatness, interspot spacings, initial sheet separation, and accessibility are important in the selection of a suitable joint design.

Joints designed for brazing also must have controlled fit. There are many variations of braze-joint designs but it is useful to consider that joint clearance must be controlled at brazing temperatures. The effect of joint clearance on the strength of brazed joints is illustrated in figure 2 (ref. 12). The shape of the joint-clearance-strength curve and the optimum strength of the joint is determined by the composition of the base and filler metals, the brazing parameters, and the method of testing.

CLEANING

Cleaning is very important to the successful welding of nickel and nickel-base alloys. The degree of cleanliness before, during, and often after welding can affect weld quality. Clean materials are particularly essential to the successful joining of electronic components (ref. 13). Two main types of surface contamination must be considered when cleaning: (1) Surface dirt such as paint, grease, and oil; and (2) Oxide films and scales. Proper surface preparation is necessary (1) to prevent the harmful effects of sulfur, lead, and other elements that are often present in paint, oil, and other surface dirt, and (2) to prevent the entrapment of oxide film or scale.

Surface Dirt, Grease, and Oil

Both the weld metal and adjacent base-metal areas can become contaminated by surface dirt. It is evident that any foreign material on the joint surfaces can be trapped easily in the weld and cause contamination. Foreign material on surfaces outside the joint also can contaminate the parts during joining. When the parts are heated, elements such as sulfur and lead can diffuse into the parent parts. This is often referred to as "burning in." Burning in of elements from crayon, pencil, or paint markings can cause severe cracking.

Processes for removing foreign matter from the surfaces of nickel and nickel-base alloys are the same as for cleaning other metal products (ref. 14). Grease and oil are removed with commercial solvents and by vapor degreasing. Soaps can be removed with hot water. The removal of soluble oils, tallow, fats, and fatty acid combinations is more complex. A typical cleaning procedure is

(1) Immerse in a hot solution of 10- to 20-percent sodium carbonate or sodium hydroxide, 10- to 20-percent trisodium phosphate, and water for 10 to 30 min

(2) Rinse thoroughly with water.

This alkaline treatment also is suggested to remove films that remain after solvent cleaning. Drying should be performed with clean dry air to avoid contaminating the surfaces again with oil or other foreign material from the air supply.

The work should be protected from contamination during the entire joining operation. Furnace refractories, work supports, and unclean tooling can cause contamination.

Tarnish and Scale

Three types of surface contaminants are formed on nickel and nickel-base alloys:

(1) Tarnish
(2) Reduced oxides
(3) Oxide film or scale.

The procedures used for removing these contaminants are determined by alloy composition and by thermal history.

Tarnish is formed on nickel when annealing is performed in a strongly reducing atmosphere, and cooling is performed either in the absence of oxygen or by quenching in a 2-percent-by-volume alcohol solution. When nickel alloys are hot-worked, oxide films form on the surface. When heat-treated in a reducing atmosphere and cooled in the absence of oxygen, the oxide is reduced to metallic nickel (and metallic copper when the alloy contains copper). Neither tarnish nor reduced oxide films interfere with joining. Both can be removed by acid pickling.

Alloys containing chromium and iron form oxide films even when heated and cooled in atmospheres that keep other alloys bright. When heated in air, all nickel alloys can oxidize. These oxide films have much higher melting temperatures than the parent metal and, if not removed, will cause difficulties in joining. In arc welding, the oxide remains as a crust cover on the underlying metal; this makes it difficult for the welding operator to maintain proper control of the weld pool. Also, the oxides can be trapped in the weld metal. In addition, the oxides can interfere with all types of resistance welding, brazing, soldering, and solid-state bonding operations.

Light oxides are removed from nickel and nickel-base alloys by acid pickling. When properly heat-treated, nickel alloys usually can be pickled in the following solution (ref. 14):

Nitric acid – 42 Bé	296 cc
Hydrofluoric acid – 30 Bé	50 cc
Water	1000 cc

Usual pickling conditions are

Temperature	125°F (max)
Time	5 to 60 min.

Pickling procedures used by one fabricator for several selected nickel-base alloys are shown in figure 3 (ref. 15).

Without proper care, some undesirable effects can be produced during pickling. These are

(1) Copper may deposit on the parts. Coppering is prevented by maintaining the copper ions in cupric rather than cuprous form.

(2) Nitric-hydrofluoric acid baths may cause intergranular attack. To prevent this, time in the bath should be kept at a minimum, and the temperature should never exceed 125°F.

When pickling procedures are planned, producers of the alloys and producers of proprietary pickling materials should be contacted for additional information.

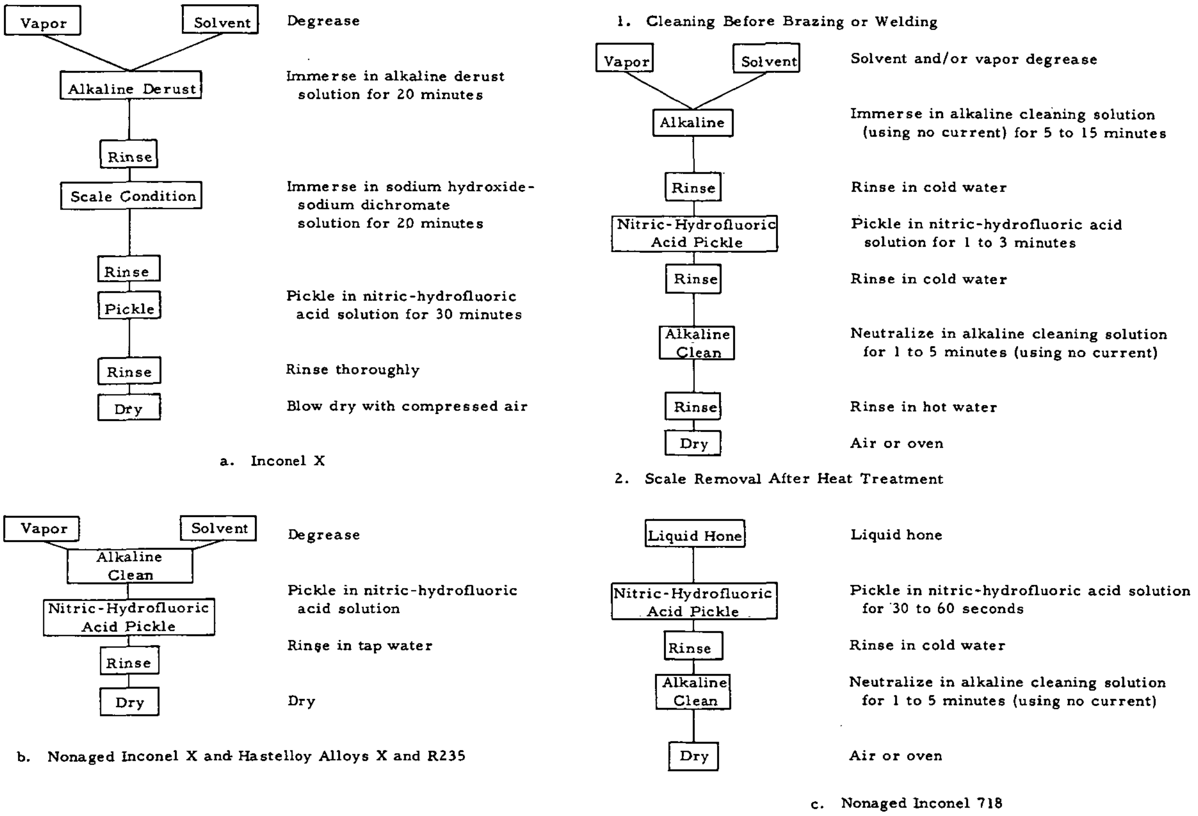
Heavy oxides can be removed by fused-salt pickling. Heavy scale also can be removed by abrasive blasting or grinding, followed by a flash pickle. Aluminum-oxide blasting followed by manual stainless-steel wire brushing has been used for cleaning between passes when welding Inconel X (ref. 16).

Evaluation of Cleaning

The effectiveness of cleaning is evaluated by various methods. The least satisfactory method is to find porosity, cracks, or other evidence of contamination in a completed weldment. A common method for evaluating the cleanliness of a part emerging from descaling and pickling operations is to inspect for water breaks during the water rinse. No water break indicates a clean surface, while the presence of a water break indicates some foreign material remaining on the surface. Contact-resistance measurements can be made to compare the effectiveness of cleaning methods prior to joining.

Slag Removal

The coatings of shielded metal-arc-welding electrodes help to control oxidation of the weld zone by forming a slag over the surface of the weld and by releasing large quantities of gas that exclude air from the weld area. When multipass welding procedures are



a. Inconel X

1. Cleaning Before Brazing or Welding

2. Scale Removal After Heat Treatment

b. Nonaged Inconel X and Hastelloy Alloys X and R235

c. Nonaged Inconel 718

FIGURE 3.–Cleaning procedures for several nickel-base alloys.

used, all slag should be removed before starting subsequent passes. After welding, all slag must be removed from the weldment. Slag removal is especially important when weldments must operate at elevated temperatures. If slag is left on the weldment and becomes molten during service, severe attack of the metal can occur. Fluxes used for submerged-arc welding (refs. 17 and 18), brazing, and soldering also should be removed carefully after joining is completed to prevent attack or corrosion of the weldment in later service.

Handling and Storage After Cleaning

Joining should be performed as soon as possible after cleaning. Oxides begin to form on alloys immediately after their exposure to open-air atmospheres. Although the oxides may be extremely thin and invisible, they can interfere with joint quality and consistency of quality in operations like resistance welding and solid-state diffusion welding. Care must be exercised to prevent paint or crayon markings, shop dirt, condensed moisture, and other harmful foreign matter from degrading joint quality.

After they are cleaned, the parts may become exposed to the open atmosphere where dust and fine dirt particles may settle on the joint surfaces and adjacent areas. The "fallout" dirt also can contaminate joints in nickel and nickel-base alloys. This kind of dirt may be removed by carefully wiping the joint area with lint-free cloths dampened with a solvent such as methyl ethyl ketone. So-called "white glove" handling operations are often used to prevent contamination after careful cleaning. Cleaned material should be joined within a few hours or protected with lint-free and oil-free wrapping until needed. Some recleaning of material that has been in storage may be required before certain joining operations.

Fabricated parts that are to be hot-formed or stress-relieved must be clean. In view of the problems involved in cleaning complex parts, it may be expedient to keep such parts from becoming dirty during joining operations. This will require careful handling and storage throughout all operations associated with the actual joining.

MATERIAL CONDITION

Pure nickel and the solid-solution-hardening alloys usually are joined in the annealed condition. Some precipitation-hardening alloys are joined only after they are heat-treated to the solution-treated condition. The remaining nickel and nickel-base alloy base metals can be joined in the annealed, the cold-worked, or the heat-treated condition.

TOOLING

The tooling used for joining nickel and nickel-base alloys generally is no different than that used for joining other materials. Welding equipment usually is purchased from commercial welding-equipment suppliers, but tooling, such as fixtures to hold the parts during welding, backup bars, and shielding devices, is often designed and fabricated for a particular application. Equipment for joining is described adequately in the welding literature and in manufacturers' literature and, therefore, is omitted from this discussion. Important considerations for tooling and inert-gas-shielding arrangements, however, are described in the following sections.

Fixtures and Fixture Materials

Proper tooling helps to provide consistently good-quality welds by minimizing distortion and maintaining alignment. Fixturing devices may range from simple clamps to hold parts in position to more elaborate holding devices designed for specific parts. Simple fixtures are adequate for joining when other means are used to insure adequate shielding, for example, when electron-beam or arc welding in an enclosed chamber. However, for fusion-welding operations conducted outside of chambers, fixtures can provide a much more effective safeguard against weld contamination than other shielding devices. Tooling often is used also to cool the weld area rapidly so that exposure in the temperature range of high chemical reactivity is minimized. Such tooling is referred to as "chill" type.

Improperly designed tooling can cause welding problems. For example, tooling may restrain the weld zones so greatly that cracking results, and weak tooling can be pulled out of shape during welding, allowing the weldment to distort.

Tooling in contact with nickel and nickel-base alloys on both the root and face sides of welds usually is made from copper, but other materials can and have been used (ref. 19). Often, these materials are used in the form of bar-type inserts or sheet- or plate-type facing plates for fixtures. Access-side hold-down bars and backup bars extend the full length of the weld and often contain inert-gas passages for weld face and root shielding. When grooved backup bars are used, the grooves should be shallow to minimize burnthrough and to control the root reinforcement contour. In addition, the grooves should be round to prevent entrapment of slag in corners. Considerable trouble with welding operations is inevitable unless weld joints are accurately machined, and are held properly in welding fixtures.

The tooling used in resistance welding of nickel alloys is generally similar to that used in resistance welding of other materials. Resistance-welding tooling consists of suitable fixtures or jigs to hold the parts in proper position for welding and to conduct welding current to the parts. Sometimes, tooling is designed to index the part through the welding equipment to insure that welds are made at the proper positions. The same general rules followed in designing any resistance-welding tooling should be followed for tooling designed for use with nickel and nickel-base alloys. Generally, this means that nonmetallic or nonmagnetic components should be used exclusively, and the tooling should not contaminate the nickel-base alloys.

Tooling for soldering and brazing also needs to be considered carefully. Tooling for use with these processes must hold the parts in position during joining, and it should not contaminate the filler metals or the base metals.

Tooling for Inert-Gas Shielding

Protection of nickel from contamination during joining operations can be accomplished in several ways:

(1) Perform the operation inside an inert-gas-filled chamber

(2) Perform the operation while flowing inert

gases through the welding torch, backups, fixtures, or auxiliary tooling

(3) Perform the operation in a good vacuum in a closed chamber

(4) Perform the operation while using suitable fluxes.

A wide variety of tooling has been designed to provide needed shielding during joining operations. Although shielding devices vary in detail, they all serve the same basic purpose, that of protecting the metal being joined from gases that can contaminate the hot metal.

Several types of shielding and controlled-atmosphere chambers are in use for welding and brazing. Such chambers are designed to contain either the entire component to be joined, or, in some cases, merely a weld joint area. The air in the chamber is replaced with inert gas by (1) evacuation and backfilling, (2) flow purging, or (3) collapsing the chamber and refilling it with inert gas. Welding chambers are particularly useful in the welding of complex components that would be difficult to fixture and to protect properly in the air. Use of a welding chamber, however, is not a cure-all. The inert gas in many welding chambers can be of much poorer quality than the inert gas contained in the conventional flowing shields. Leakage of air or water vapor into a chamber atmosphere must be avoided to prevent contamination. Devices for continuous monitoring that disclose contamination of a chamber atmosphere are available.

A tank-type, controlled-atmosphere welding chamber for manual and machine gas tungsten-arc and gas metal-arc welding is shown in figure 4 (ref. 20). Many small chambers are made from plastic domes and steel or stainless steel; stainless steel is preferred because it does not rust and is easy to clean. Several small-size chambers for welding small subassemblies are shown in figure 5 (refs. 21 and 22). The adaptation of a small-size chamber to the welding of an oversize part is shown in figure 6 (ref. 22); only the localized area that is heated needs to be shielded with inert gas. A flexible plastic chamber is illustrated in figure 7 (ref. 23).

Shield gas used in these chambers may or may not flow through the torch, depending on the fabricator. Also, the shielding gas can be recirculated through a purifying train to remove undesirable gases that are evolved either from the alloy being welded or from the chamber walls and tooling as they become heated.

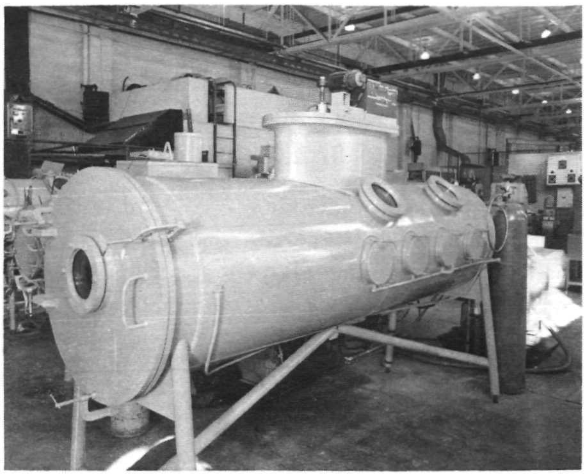


FIGURE 4.—Tank-type controlled-atmosphere welding chamber.

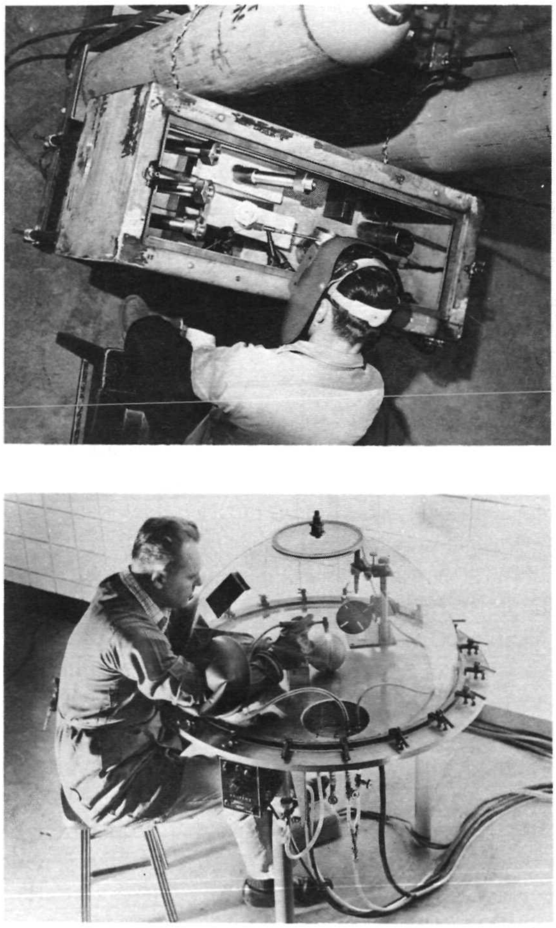


FIGURE 5.—Small-size welding chambers.

FIGURE 6.–Adaptation of a small chamber to provide localized shielding of a large part during welding.

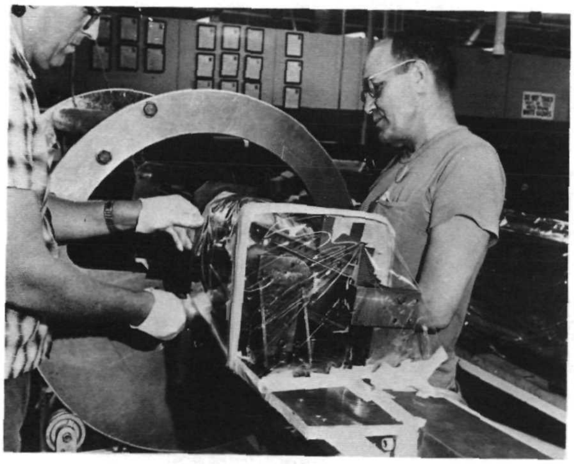


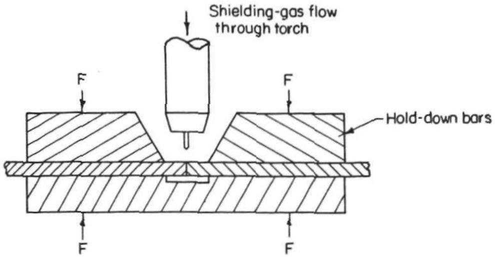
FIGURE 7.–Flexible inert-gas shielding chamber.

For in-air welding with the gas-tungsten-arc (GTA) and gas-metal-arc (GMA) processes, shielding is provided in several ways:

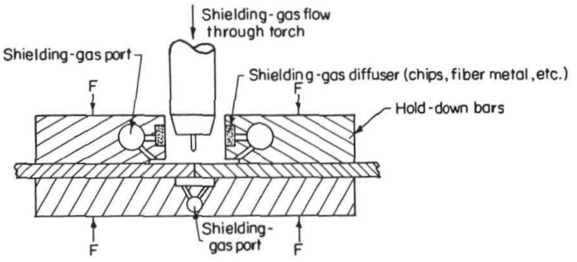
(1) Flowing the inert gas through the torch to shield the molten weld pool and adjacent surfaces

(2) Flowing the inert-gas shield through a trailing shield to protect the weldment as it cools

(3) Flowing the inert-gas shield through hold-down and backup bars. Shielding gases flowing through the hold-down bars provide additional shielding for the face side of the weld. The backup gas flow protects the root side of the weld during welding and during cooling of the weld metal.



a. Weld Tooling for Aluminum and Stainless Steels



b. Special Tooling for Titanium (F represents clamping force)

FIGURE 8.–Tooling for conventional and special gas shielding.

Various inert-gas shields have been developed for welding in open-air atmospheres. All are designed primarily for blanketing the hot metal from the surrounding air atmosphere. Figure 8 illustrates two different shielding methods that are used for such metals as nickel, aluminum, and stainless steels. The hold-down and backup shielding method shown in figure 8(a) is used in many joining operations. The shielding method shown in figure 8(b) is used when better shield is required. A torch-trailing shield for GTA and GMA welding is shown in figure 9 (refs. 24 and 25). The detachable-trailing-shield concept provides for interchangeable trailing-shield units for use with other joint designs or degrees of accessibility. Baffles also are used to help retain inert gases in desired areas and to prevent stray drafts from disturbing and deflecting the shield-gas-flow pattern (refs. 21 and 26). Similar concepts are used to protect the nonaccess (root) side of a weld joint (refs. 21 and 24 to 26). Figure 10 illustrates two shielding devices used to prevent root contamination in the welding of pipe (ref. 21).

Advantage also is taken of the fact that argon tends to settle and displace air. Conversely, helium is best suited for displacing air when a rising gas flow is desirable. For welding, in-air trailing shields designed for MIG welding are usually considerably longer than

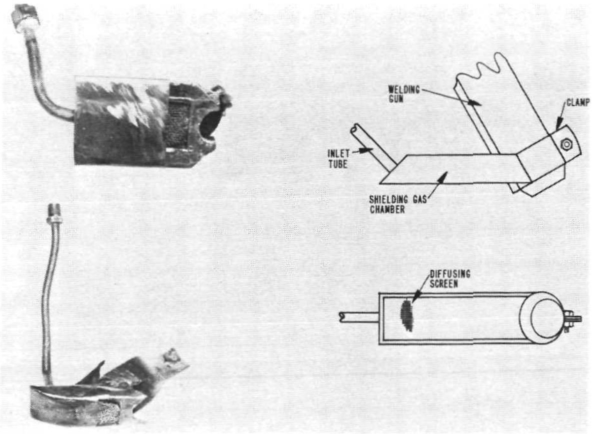


FIGURE 9.–Trailing shields. Top left shows a wide shield for wide joint openings and capping passes; bottom left shows a narrow shield for narrow joint openings and root passes. Sketches at the right show trailing-shield attachments to a welding torch.

those used in TIG welding. This is to insure good protection for the larger volumes of material that are heated during MIG welding, and which cool more slowly as a consequence.

Inert-gas-shielding considerations also are important in designing joints for welding. Some joint designs cannot be protected adequately by inert gases except at great expense.

RESIDUAL STRESS

Residual stresses are developed during all joining processes. Their effects should be considered before joining operations are started. Residual stresses are those that exist in a body without any external force acting. The residual stresses in a welded joint are caused by the contraction of the weld metal and the plastic deformation produced in the base metal near the weld during welding. Residual stresses in a welded joint are classified as follows: (1) residual welding stress, which occurs in a joint free from any external constraint and (2) reaction stress or locked-in stress, which is induced by an external constraint.

For most nickel-base alloys, a heat treatment of between 900° and 2175° F for a period of time ranging from 5 min. to several hours is recommended for stress relieving, depending on the particular alloy. This is discussed in greater detail later in this chapter. Possible interactions between a thermal stress-relieving treatment and other changes in a material that may affect its properties must be anticipated. For example, age hardening will occur in Inconel X over a certain temperature range. A similar effect is found with other nickel-base alloys. Inconel X should be heated to the normal stress-relieving temperature range as rapidly as possible. Other methods of relieving the residual stresses in the alloy may be suitable. For example, mechanical treatments, such as peening have been used to alter the residual-stress patterns and magnitude (ref. 27).

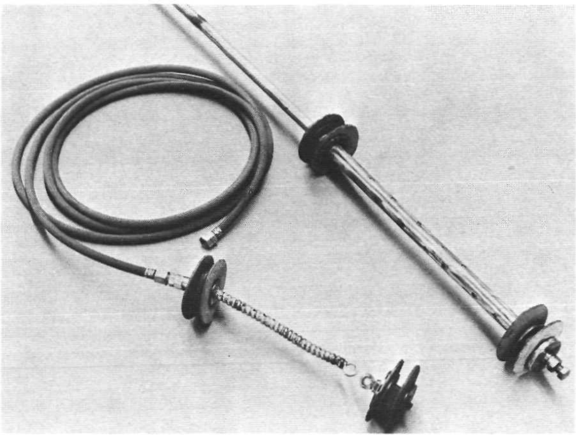


FIGURE 10.–Internal shielding devices for protecting the root sides of pipe welds.

Residual stresses in resistance welds can be altered and, to some extent, eliminated by either mechanical or thermal stress-relieving treatments. The application of mechanical stress-relieving methods to spot welds is difficult because of the complexity of the residual stress patterns and the limitations generally imposed by joint configurations. At best, mechanical techniques can probably result only in a redistribution of the residual-stress pattern and not the complete elimination of residual stress. On the other hand, thermal stress relieving can be used effectively to eliminate all residual stresses resulting from resistance welding. The most fruitful method of controlling residual stresses in resistance-welded joints may be by the selection of suitable processing parameters.

Residual stresses generally are not a serious problem in brazed or solid-state-welded joints because heating and cooling of the parts are uniform.

Shrinkage and Distortion

Joining processes are often characterized by thermal cycles that cause localized shrinkage. In turn, this shrinkage often causes distortion of the parts being joined. Figure 11 illustrates the changes in shape that occur when welding a simple butt joint. More complex weldments obviously involve much more complex shrinkage and distortion patterns. Weld shrinkage must be planned for, since there is no absolute way to avoid it. Expected shrinkage values for typical weld configurations often are obtained before making production welds. Also, a logical sequence for welding components involving several welds must be established with shrinkage in mind.

With the proper welding sequence, shrinkage can be used to minimize distortion. This is accomplished by properly balancing the various shrinkage forces developed. Shrinkage also can be controlled to some extent by the restraint imposed by tooling. The use of this technique is sometimes helpful in preventing serious part distortion. Shrinkage and distortion can also be minimized by using low- and/or uniform-heat inputs and by avoiding unnecessary weld reinforcement. Freedom from distortion, however, does not mean that a weldment is not highly stressed. Quite often the converse is true.

Thermal cycles employed in resistance welding also bring about highly localized shrinkage. This shrinkage may cause some distortion of the part being joined; generally, however, distortion is not as noticeable in resistance-welded components as it is in fusion-welded parts.

The effects of weld shrinkage and subsequent distortion are generally minimized in resistance welding by starting the welding near the center of a component and moving progressively toward the edges of the component. Sequences of this type are not easily used during seam welding or roll spot welding; consequently, distortion may be more of a problem when these processes are used. Selection of improper welding sequences can also introduce various problems with sheet separation prior to welding. For example, if three welds are being made in a row and the two outside rows are welded first, excessive sheet separation is likely to occur in the center row. In such a case, the center row should be welded first, followed by the outside rows.

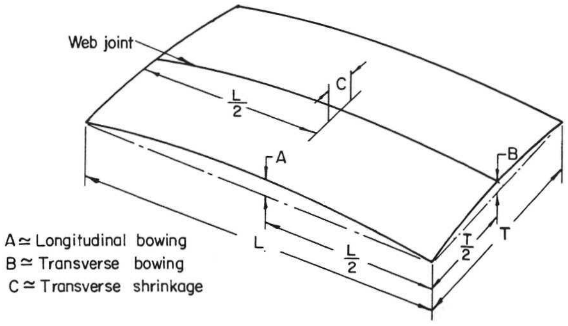


FIGURE 11.–Weldment distortion caused by fusion welding.

Shrinkage and distortion are much less troublesome in brazing and solid-state welding, because heating is usually uniform.

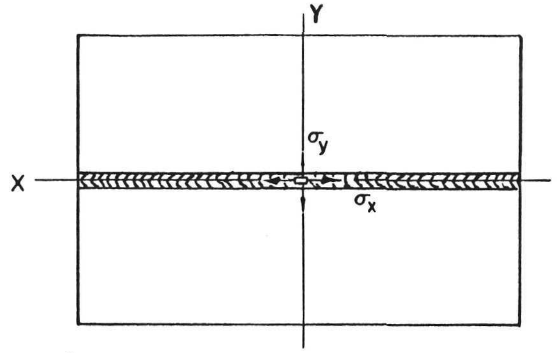
Stress Distribution

The distribution of residual stresses is determined largely by joint geometry. Similar stress distributions are found in joints of similar geometry, regardless of how the joint was made. For example, resistance seam welding and TIG welding will result in a similar stress distribution in a long straight joint.

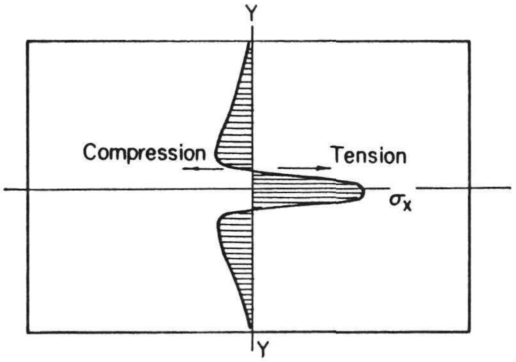
A typical distribution of residual stresses in a butt weld is shown in figure 12(a). The stress components concerned are those parallel to the weld direction, designated σ_x and those transverse to the weld, designated σ_y. The distribution of the σ_x residual stress along a line transverse to the weld, YY, is shown in figure 12(b). Tensile stresses of high magnitude are produced in the region of the weld; these taper off rapidly and become compressive at a distance of several times the width of the weld, then gradually approach zero as the distance from the weld increases.

The distortion of σ_y residual stress along the length of the weld, XX, is shown by curve 1 in figure 12(c); tensile stresses are produced in the middle part of the joint, and compressive stresses are observed at the ends of the joint. When the lateral contraction (contraction in YY direction) is restrained by an external constraint, the distribution of σ_y is that shown by curve 2. The difference between curves 2 and 1 is the reaction stress. Only limited information has been obtained on the effects of joint constraint and welding procedures on the magnitudes of lateral contraction and reaction stress in weldments in nickel and nickel-base alloys.

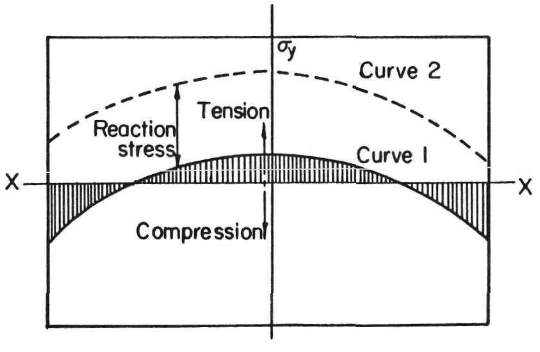
Residual stresses in the thickness direction (Z direction) become significant in butt joints made in heavy plate that is over about 1-in. thick. There has been no published information on three-dimensional



a. Butt Weld



b. Distribution of σ_x Along YY



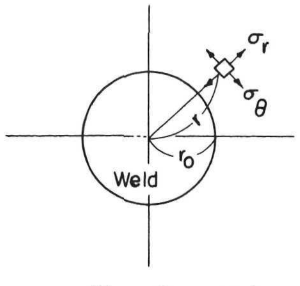
c. Distribution of σ_y Along XX

FIGURE 12.–Distribution of residual stresses in a butt weld.

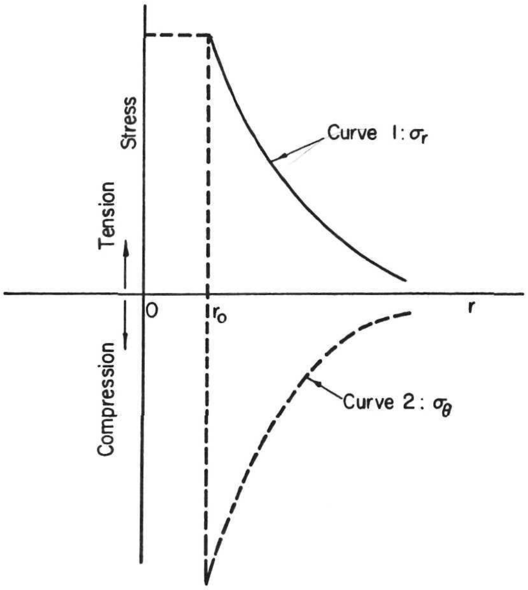
distributions of residual stresses in weldments in nickel and nickel-base alloys.

The maximum residual stress in the weld is determined by

(1) Expansion and contraction characteristics of the base metal and the weld metal during the welding thermal cycle



a. Stress Components



b. Relationships Between Radius From the Weld Center, r, and Stresses

FIGURE 13.–Distribution of residual stresses around a spot weld.

(2) Temperature versus yield-strength relationships of the base metal and the weld metal.

Much research in mild-steel weldments has shown that the maximum residual stress cannot exceed the magnitude of the yield stress of the weld metal. In one investigation (ref. 28), the maximum stresses in weldments made with heat-treated SAE 4340 steel were about 50 000 to 80 000 psi, considerably less than the yield strengths of the weld metal (about 150 000 psi) and the base metal (224 000 psi). The effects of base-metal and weld-metal properties and welding processes on the magnitude of residual stresses on nickel-alloy weldments have not been established.

Out-of-flat base plate also can contribute to restraint problems in welding (ref. 25). As-received materials that are wavy and out-of-flat lead to misalignment when they are placed in the welding fixture. Where this creates fabrication difficulties it is necessary to flatten the plates. This working, when added to the already high level of restraint, can increase susceptibility to cracking, or cracking can occur during the flattening operation.

The residual-stress distribution in spot-welded joints is very dependent on the joint pattern or weld pattern used. The simplest case to consider is the residual stress caused by a single spot weld. Figure 13 is a schematic showing the distribution of residual stresses in the area near a single spot weld. The important components of stress are those in the radial direction and the circumferential direction. The relation between the distance from the weld center and the radial-residual stress is shown by curve 1 in the figure. Tensile stresses as high as the yield strength of the material may exist in the weld zone. Outside the actual weld zone the residual tensile stress decreases as the distance from the weld area is increased. Curve 2 shows the distribution of the circumferential stress. Again, very high tensile stresses exist within the weld zone; however, outside the weld these stresses are compressive and again fall off as the distance from the weld is increased. From curve 2 it is apparent that there is an extremely sharp stress gradient around the circumference of any spot weld where the stresses undergo a complete reversal from very high tensile value to high compressive values.

The actual stress distributions in a spot weld in the area very close to the weld are not nearly as simple as shown in figure 13. Very concentrated stresses often exist in the heat-affected zone close to the original interface of the sheets.

When several spot welds are considered instead of just a single spot, the resulting residual-stress patterns are even more complex. An approximate distribution of the residual-stress pattern produced by a series of spot welds can be obtained by superposing the residual-stress distributions produced by each weld shown in the figure. The interaction between the residual stresses accompanying each individual weld becomes significant when the distance between the welds is short—probably at any distance less than four times the diameter of the weld.

The residual stresses in resistance spot welds can be altered by changes in the welding schedule. Changes in heat input, heat pattern, or forging action that may be applied through the electrodes are effective. Some information on the effect of such changes in welding parameters on residual stresses has been obtained, but there are many conflicting aspects of these data.

Residual Stress Effects

For many years there was a tendency among engineers to discount the effect of residual stress, since it had been proven that this effect is almost negligible when a welded structure fails in a ductile manner. During the last several years, much information has been obtained on the effect of residual stress on brittle fracture in steel weldments. It has been found that such stresses decrease the fracture strength of weldments only when certain conditions are satisfied, but that the loss of strength can be drastic when other conditions are satisfied. A weld failure blamed on residual stress is shown in figure 14 (ref. 29). No systematic investigation has been made on effects of residual stresses on fractures in nickel- and nickel-base-alloy weldments. The following discussions are based on information on steel weldments and the limited data on nickel-alloy weldments.

In general, the effect of residual stress is significant on fractures that take place at low applied stresses. Observations that have been made on various types of fracture follow:

Ductile fracture.—Ductile fracture occurs at high stresses after general yielding. The effect of residual stress on fracture strength is negligible.

Brittle fracture.—When a notch is located in areas where high residual tensile stresses exist, brittle fracture can initiate from the notch at a low applied stress and then propagate through the weldment.

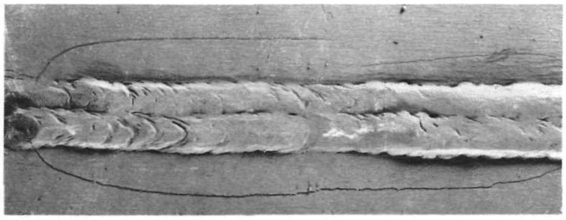


FIGURE 14.—Failure attributed to residual stress in 2-in.-thick Inconel X after aging at 1300° F for 20 hr. (The base metal was aged prior to welding.)

Extensive research has been conducted during the last several years on low-stress brittle fracture of steel weldments. No systematic investigations have been made on low-stress brittle fracture of nickel-alloy weldments. Some failures have been observed that indicate residual stresses may have caused premature failures in nickel-alloy weldments.

Stress-corrosion cracking and hydrogen-induced cracking.—Stress-corrosion cracking and hydrogen-induced cracking can occur under low applied stresses, and even under no applied stress. Residual welding tensile stresses promote the cracking, while residual compressive stresses suppress the cracking.

Fatigue cracking.—The effect of residual stress on fatigue fracture is a controversial subject. Many investigators have reported fatigue-test results that, they claim, were affected by residual stresses. However, others believe that the effect of residual stress on fatigue is not significant.

Buckling failure.—It is known that residual compressive stresses in the base-metal regions around welds may decrease the buckling strength of welded columns and plates.

Stress Relief

There are a number of reasons for reducing or relieving residual stresses associated with welded joints. It is probably necessary to relieve the residual stresses whenever a welded structure is: (1) manufactured to close dimensional tolerances; (2) complex and contains many stress risers; (3) subjected to dynamic loading; (4) subjected to low-temperature service; and (5) subjected to service conditions that might promote stress corrosion. The decision of whether or not to relieve stress and what method to use generally is based on judgment and previous experience.

Residual stresses can be relieved in two ways: (1) thermal stress-relieving treatments or (2) mechanical stress-relieving treatments. Occasionally, both treatments are used. Stress relieving can be performed on a finished part or during various stages of its processing when dimensional control is a problem.

Thermal stress-relieving treatments are commonly employed for many materials. These treatments can be combined quite effectively with hot-sizing operations to control both the existing residual stresses and to produce parts to close-dimensional tolerances. Thermal stress-relieving treatments produce much more uniform changes in the residual-stress patterns than do mechanical stress-relieving treatments.

Two kinds of heat treatments are used for altering the condition of stresses that may be present in fabricated nickel and nickel-base alloys (ref. 30):

(1) A stress-relieving heat treatment used to remove or reduce stress in work-hardened, non-age-hardenable alloys without producing a recrystallized grain structure. (Temperatures for such treatment range from about 800° to 2200° F, depending on the alloy and its condition.)

(2) A stress-equalizing low-temperature heat treatment used to balance stresses in cold-worked material without causing an appreciable decrease in the mechanical strength produced by cold working.

Conditions for stress relieving and stress equalizing of several nickel alloys are given in table 3 (ref. 30).

With precipitation-hardening alloys, a postweld

TABLE 3.—*Stress Relieving and Stress Equalizing of Nickel and Some Nickel Alloys*

Material	Stress relieving			Stress equalizing		
	Temperature, °F	Time at temperature, hr	Cooling method	Temperature, °F	Time at temperature, hr	Cooling method
Nickel 200	900-1300	3-1/2	Air cool	500-900	2-1	Air cool
Nickel 201	900-1300	3-1/2	Air cool	500-900	2-1	Air cool
Nickel 211	900-1300	3-1/2	Air cool	500-900	2-1	Air cool
Monel 400	1000-1050	2-1	Air cool	450-600	3-1	Air cool
Hastelloy B	2000-2165	1/12	Air cool or water quench		Not applicable	
Hastelloy C	2200	1/12	Water quench		Not applicable	
Hastelloy R-235	1975	1/12	Water quench		Not applicable	

thermal treatment is mandatory both to relieve stresses and to achieve the desired strength levels. Table 4 presents some common postweld treatments for these alloys (ref. 10). The postweld treatment generally includes a full anneal, except in the case of small repairs in aged material.

Mechanical stress-relieving treatments include tensile stretching, roll planishing, and peening. With any mechanical stress-relieving treatment, control of the process is difficult. In addition, the complete removal of residual stresses by mechanical techniques is difficult to accomplish. Mechanical stress-relieving techniques are most effective in accomplishing a redistribution of residual stresses in a single direction. Effective stress relieving by operations such as roll planishing requires that the weld geometry be very consistent prior to the planishing operation.

PROCESS SELECTION

Nickel and nickel-base alloys have been joined by most common welding, brazing, and soldering processes. Widespread use has been made of the following processes:

(1) Shielded metal-arc welding
(2) Gas tungsten-arc welding
(3) Gas metal-arc welding
(4) Electron-beam welding
(5) Resistance spot, roll spot, and seam welding
(6) Brazing and soldering.

Limited use has been made of many other joining processes including

(1) Arc spot welding
(2) Plasma welding
(3) Diffusion welding
(4) Roll welding
(5) Pressure-gas welding
(6) Flash welding
(7) Magnetic-force welding
(8) Explosive welding
(9) Laser welding
(10) Inertial welding.

Other processes also have been used that will not be discussed here. Excluded from this report are oxyacetylene, oxy-fuel gas, and air-fuel gas-fusion welding. These processes are rarely, if ever, used for new applications such as those involved with aerospace products. Table 5 shows the joining processes used most commonly for selected nickel and nickel-base alloys.

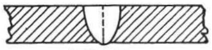
TABLE 4.–*Common Postweld Heat Treatments for Various Precipitation-Hardenable, Nickel-Base Alloys*

Alloy	Heat treatments
Monel K-500	Age at 1080° F after quench from 1400-1800° F
Inconel 700	2160° F for 2 hr, air cool then 1600° F for 4 hr and air cool
Inconel 702	2000° F for 1 hr, air cool then 1350° F for 4 hr and air cool
Inconel 718	1350° F for 4 hr and air cool for 1700° F for 1 hr, air cool then 1325° F for 8 hr and cool at 100° F/hr to 1150° F and hold for a total aging time of 20 hr
Inconel 721 (M)	1975° F for 4 hr and air cool
Inconel 722 (W)	1975° F for 4 hr and air cool then 1300° F for 20 hr
Inconel X-750	1950° F for 30 min, air cool then 1550° F for 24 hr plus 1300° F for 20 hr
Inconel 713C	As cast
Inconel 713LC	As cast
R-235	1975° F for ½ hr and air cool then 1400° F for 16 hr
Udimet 500	2100° F for 3 hr air cool then 1975° F for 4 hr and air cool then 1550° F for 24 hr and air cool then 1400° F for 16 hr and air cool
Udimet 700	2150° F for 4 hr and air cool + 1975° F for 4 hr and air cool + 1500° F for 24 hr and air cool + 1400° F for 16 hr and air cool
M252	1900° F for 1 hr and air cool then 1400° F for 16 hr and air cool
René 41	1975° F for ½ hr and air cool then 1400° F for 16 hr and air cool or 2050° F for 1 hr and air cool followed by 1650° F for 4 hr and air cool
René 62	2000°F for ½ hr and air cool then 1400° F for 16 hr and air cool followed by 1200° F for 24 hr and air cool
Astroloy	2150° F for 4 hr and air cool + 1975° F for 4 hr and air cool + 1500° F for 24 hr and air cool + 1400° F for 16 hr and air cool
Waspaloy	1975° F for 4 hr and air cool then 1550° F for 24 hr and air cool then 1400° F for 16 hr and air cool
B1900	As cast
Unitemp 1753	2150° F for 4 hr and air cool then 1650° F for 6 hr and air cool
GMR 235D	As cast
IN 100	As cast

TABLE 5.—*Joining Processes Applicable to Nickel and Some Typical Nickel-Base Alloys*[a]

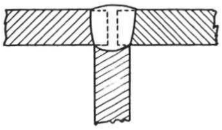
Alloy	Shielded metal arc	Gas tungsten arc	Gas metal arc	Arc spot	Sub-merged arc	Plasma arc	Electron beam	Resis-tance spot	Roll resistance spot	Resis-tance seam	Flash	Diffu-sion	Deforma-tion	Braz-ing	Solder-ing	Gas	Reference
High-nickel alloys																	
Nickel 200	X	X	X	--	X	--	X	X	X	X	X	--	X	X	X	X	9, 11, 31
Dispersion-strengthened nickel																	
TD nickel	--	X	--	--	--	--	X	X	--	--	X	X	--	X	--	--	5, 3, 2
Solid-solution-hardening alloys																	
Monel 400	X	X	X	--	X	--	--	X	X	X	X	--	X	X	X	X	11, 18
Inconel 600	X	X	X	--	X	--	X	X	X	X	X	--	X	X	X	X	11, 17, 31
Hastelloy B	X	X	X	--	--	--	--	--	--	--	--	--	--	--	--	--	9
Hastelloy X	X	X	X	--	--	--	--	X	X	X	--	--	--	--	--	--	9
Precipitation-hardening alloys																	
Monel K-500	X	X	X	--	--	--	--	X	X	X	X	--	X	X	X	X	11
Inconel X-750	X	X	X	--	--	--	--	X	X	X	X	--	X	X	X	--	3, 11
Nimonic 80A	--	X	X	--	X	--	--	X	--	X	--	--	--	--	--	--	1, 3
Udimet 500	--	X	--	--	--	--	--	--	--	--	--	--	--	--	--	--	3
Waspaloy	X	X	--	--	--	--	--	X	--	X	--	--	--	--	--	--	3
René 41	--	X	--	X	--	--	X	X	--	X	X	--	--	X	--	--	3, 31, 33

[a] X indicates that the process has been used for joining but is not necessarily the best joining method; - - indicates that the process is seldom, if ever, used for joining the alloy. Contact the producer for latest information.



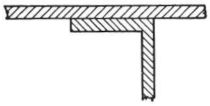
a. Butt Joint

Select: TIG, MIG, electron beam, flash, pressure gas
Exclude: resistance spot and seam
Consider: plasma, high frequency



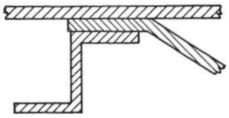
b. Fabricated Tee

Select: TIG, MIG, electron beam
Exclude: flash, resistance spot and seam
Consider: plasma, high frequency, solid state



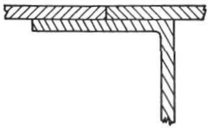
c. Sheet-Stringer Lap

Select: resistance spot or seam arc spot, solid state
Exclude: flash, pressure
Consider: electron beam, plasma



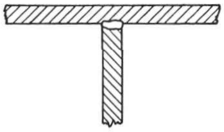
d. Multilayer Lap

Select: resistance or arc spot or seam, solid state
Exclude: flash, pressure gas
Consider: electron beam, plasma



e. Sheet Splice With Doubler

Select: resistance or arc spot or seam, solid state
Exclude: flash, pressure gas
Consider: electron beam, plasma



f. Cap or Tee

Select: electron beam, TIG, MIG, high frequency
Exclude: flash, arc and resistance spot
Consider: solid state, resistance seam

FIGURE 15.–Typical weld joints in nickel and nickel-base alloys.

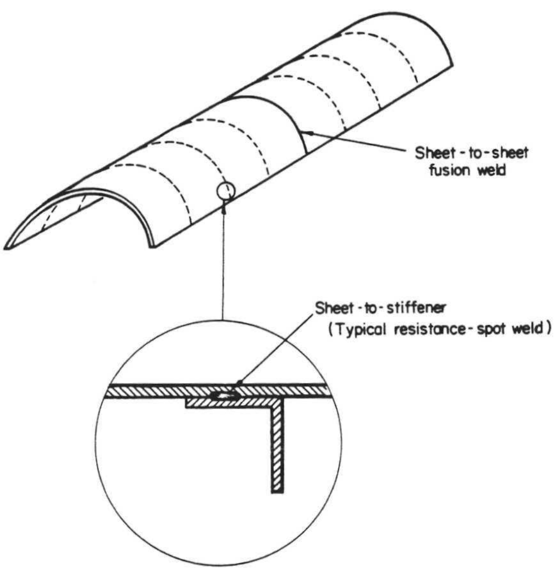
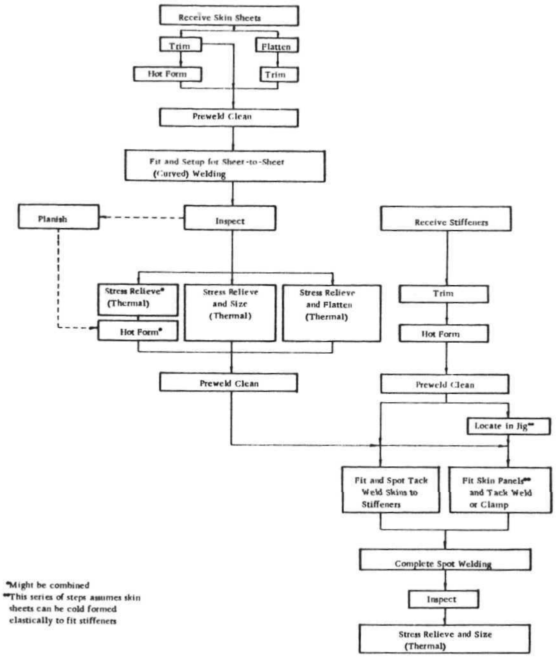


FIGURE 16.–Stiffened-skin component.



*Might be combined
**This series of steps assumes skin sheets can be cold formed elastically to fit stiffeners

FIGURE 17.–Flow chart showing possible relation of welding to other operations.

The selection of a joining process for nickel and nickel-base alloys often is influenced by the physical characteristics of the parts to be joined. Fortunately, the varied characteristics of joining processes lead to a very broad range of possible applications. Most joints in nickel and nickel-base alloys can be made by several different joining processes. However, welding is normally used in subassembly fabrication and for many large structural components. Cost, available equipment, maintenance, reliability, accessibility, thickness, and overall component size are important factors to be considered in assessing the proper usage of welding and alternative joining methods.

As noted earlier, joint design also can influence the selection of the joining process. Figure 15 illustrates several joint designs and lists the processes that normally would or would not be used for joining; it is apparent that several processes can be selected for making each joint. Other factors reviewed earlier may reduce the number of potentially useful processes, however.

The relationship of joining to other fabricating operations is an important aspect in process selection. A simplified subassembly-process flow chart illustrates some of the possibilities. The part used as an example is a contoured stiffened skin too large to make from a single sheet. The materials involved are skin sheets and formed stiffeners as sketched in figure 16. The flow chart, figure 17, shows that many possible approaches might be used to fabricate this single part. It is important to remember that the fabricating operations immediately before and after joining are closely related to successful part fabrication. Good joint fitups are needed and all parts must be properly cleaned before joining. Stress relieving of weldments immediately after welding is sometimes essential.

CHAPTER 3

Joining Processes

Many joining processes can be used successfully for joining nickel and nickel-base alloys. Discussions of joining processes in this report are presented in three major sections:

(1) Fusion welding
(2) Solid-state welding
(3) Brazing and soldering.

Discussions of fusion welding deal with those joining processes in which substantial amounts of molten metal are normally produced during the joining operation. Discussions of solid-state bonding are limited to those processes in which molten metal is not produced. Some processes, such as resistance spot welding, flash welding, and explosive welding, can rightfully be included within each of these discussions. Such processes are described in accordance with their conventional use. Brazing and soldering are conventional processes and are discussed separately. Processes not included are gas welding, adhesive bonding, mechanical fastening, and various other specific welding processes. Adhesive bonding and mechanical fastening of nickel and nickel-base alloys are covered in other reports in this series (refs. 34 and 35).

FUSION WELDING

The joining processes discussed in this section are those in which substantial amounts of molten metal are produced during the joining operation. The arc-welding processes typically involve the melting of filler metal, base metal, or both. Other processes, such as flash welding and high-frequency resistance welding, produce molten metal during the joining cycle but, often, little or no evidence of molten metal remains in the completed joint. Normally, molten metal is produced with resistance spot- and seam- and roll resistance spot-welding processes. Spot welding also has been used to make solid-state welds.

Shielded Metal-Arc Welding

Shielded metal-arc welding (SMA) is used extensively for joining nickel and some nickel-base alloys. It is applicable to a wide range of base-metal thicknesses, but as thickness decreases, other processes offer important advantages. SMA welding is adaptable to manual, semiautomatic, or fully automatic operations.

In SMA welding, the heat required to melt the filler metal and joint edges is provided by an arc between a covered metal electrode and the work. Electrode coverings can:

(1) Produce a gas that shields the arc from the atmosphere
(2) Promote electrical conduction across the arc
(3) Add slag-forming materials to the weld pool for refining the molten metal and, in some cases, for adding alloying elements
(4) Provide materials for controlling the bead shape.

Figure 18 is a schematic representation of the process (ref. 36). Metal is transferred from the electrode to the work in the form of large drops or a spray of small drops. Generally, both modes occur.

SMA-welding techniques for some nickel and nickel-base alloys are similar to those used for steel, and can be used in all positions. These alloys, however, are not as fluid as mild steel and low-alloy steel. The weld joints should be wide enough to facilitate the deposition of stringer passes. Excessive agitation or puddling of the weld pool can result in serious loss of alloying or refining elements. In addition, penetration with high-nickel alloys is shallower than that with steel; however, high-heat input rates to increase penetration also can cause the loss of some alloying elements.

The techniques for joining some nickel-base alloys differ from those used for steel. Welding operators

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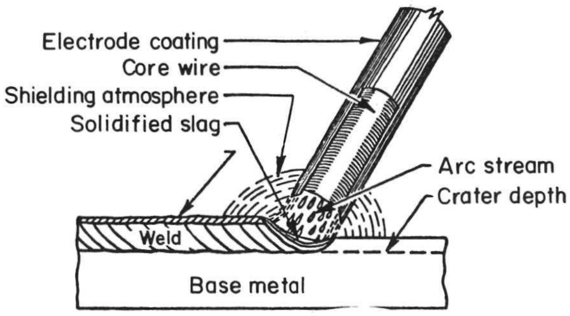


FIGURE 18.–The shielded-metal-arc-welding process.

familiar with techniques for joining steel need additional training to produce nuclear-quality welds; for example, with Inconel (ref. 37).

Equipment.–Conventional equipment is used for shielded metal-arc welding of nickel and nickel-base alloys. There are no preferred specific types of welding equipment with which improved welding characteristics or weld properties can be achieved. However, direct-current power sources with reversed polarity are recommended.

The welding current that may be used satisfactorily with covered electrodes depends on the electrode type and size and on the sheet thickness. Other variables, such as the type of backing groove, backing material, clamping, and joint design, also can affect current requirements and, in turn, determine the electrode size.

Materials.–High-nickel, solid-solution-hardening, and precipitation-hardening alloys are all welded with this process. The latter types are more difficult to weld, however, because of the inability to transfer hardener elements such as aluminum and titanium through the arc (ref. 10). With some exceptions, covered electrodes are available commercially for most of these nickel and nickel-base alloys. These electrodes are classified according to the chemical composition of the deposited weld metal as shown in table 6 (ref. 38). They are usually selected to match the composition of the base metal.

It should be noted that many electrode coatings contain hygroscopic materials. Electrode containers should remain sealed until needed. Once the containers are opened, the electrodes should be stored in a moisture-free area.

Welding conditions and weld properties.–SMA welding conditions depend on several factors including alloy composition, electrode type, material thickness, and tooling. Recommended welding conditions are readily available from equipment and material suppliers. It is difficult to establish strict rules regarding them, and this is often not necessary because various combinations of current, voltage, and welding speed will provide satisfactory welds for a specific material thickness and joint design.

The heat effects produced by metal-arc welding of nickel, Monel, and Inconel are not considered harmful. Grain growth and softening occur in the heat-affected zones, but there is no noticeable alteration in ductility or strength. Some properties of shielded metal-arc welds in nickel and nickel-base alloys are given in table 7.

When welding for high-temperature service, it is important to remove flux or slag from all weld passes and from the completed weldment. The slag may not be corrosive at low temperatures, but severe corrosion may occur at elevated operating temperatures.

Applications.–SMA welding is used for fabricating nickel and many nickel-base alloys. Some typical applications are described in the following discussion.

SMA welding has been used for joining nuclear-reactor components (refs. 37 and 39). Welds for nuclear-reactor applications must be of extremely high quality and essentially free from defects. Unusually heavy sections often must be welded. SMA welding was used for finishing joints in a 2-in.-thick Inconel reactor pressure vessel because of the high deposition rates available with this process (ref. 37). Porosity and slag inclusions were minimized by baking the covered electrodes and by interpass cleaning. Root passes were made by GTA process. Also, to meet the need for defect-free welds, a new covered welding electrode, MIL-4N85, was developed (ref. 39). The operating characteristics of this electrode are excellent, and the slag is easily removed from welds deposited in all positions. The electrode has produced crack-free and porosity-free welds in all positions and under high restraint in Inconel.

SMA welding of a large Monel-400 press roll is shown in figure 19 (ref. 11). The roll was fabricated from three 2-3/4-in.-thick plates, 38 in. wide by 240 in. long, that were welded by using Monel Welding Electrode 130 covered electrodes. High deposition rates were needed to deposit 700 lb of filler metal.

Metal-arc welding is one of the most common processes used for welding Hastelloy alloys. It is used in welding all grades except Hastelloy D (ref. 41). Direct current with reversed polarity is generally

TABLE 6.–*Chemical-Composition Requirements for Weld Metal Deposited From Nickel and Nickel-Base-Alloy-Covered Welding Electrodes*

AWS-ASTM classification	Carbon	Manganese	Iron	Phosphorus	Sulfur	Silicon	Copper	Nickel	Cobalt	Aluminum	Titanium	Chromium	Columbium plus tantalum	Molybdenum	Vanadium	Tungsten	Other elements, total
ENi-1	0.10	0.75	0.75	- -	0.020	1.25	0.25	[a]92.0 min	- -	1.0	1.0-4.0	- -	- -	- -	- -	- -	0.50
ENiCu-1	0.15	4.0	2.5	- -	0.025	1.25	Bal	[a]62.0-70.0	- -	1.0	1.5	- -	3.0	- -	- -	- -	0.50
ENiCu-2	0.15	6.0	2.5	- -	0.025	1.5	Bal	[a]60.0-68.0	- -	1.0	1.0	- -	2.5	- -	- -	- -	0.50
ENiCu-3	0.45	4.0	2.5	- -	0.025	1.25	Bal	[a]60.0-68.0	- -	1.0-4.0	1.0	- -	- -	- -	- -	- -	0.50
ENiCu-4	0.40	4.0	2.5	- -	0.025	1.0	Bal	[a]62.0-70.0	- -	1.5	1.0	- -	- -	- -	- -	- -	0.50
ENiCr-1	0.15	1.5	4.0	- -	0.015	0.75	0.50	[a]70.0 min	- -	- -	- -	17.5 min	1.5-4.0	- -	- -	- -	0.50
ENiCrFe-1	0.08	1.5	11.0	- -	0.015	0.75	0.50	[a]68.0 min	- -	- -	- -	13.0-17.0	1.5-4.0	- -	- -	- -	0.50
ENiCrFe-2	0.10	1.0-3.5	6.0-12.0	- -	0.020	0.75	0.50	Bal	- -	- -	- -	13.0-17.0	0.5-3.0	0.50-2.50	- -	- -	0.50
ENiCrFe-3	0.10	5.0-9.5	6.0-10.0	- -	0.015	1.0	0.50	Bal	(b)	- -	1.0	13.0-17.0	[c]1.0-2.5	- -	- -	- -	0.50
ENiMo-1	0.12	1.0	4.0-7.0	0.040	0.030	1.0	- -	Bal	2.5	- -	- -	1.0	- -	26.0-30.0	0.60	- -	0.50
ENiMo-2	0.12	1.0	4.0-7.0	0.040	0.030	1.0	- -	Bal	2.5	- -	- -	14.5-16.5	- -	15.0-18.0	0.35	3.0-4.5	0.50
ENiMo-3	0.12	1.0	4.0-7.0	0.040	0.030	1.0	- -	Bal	2.5	- -	- -	2.5-5.5	- -	23.0-27.0	0.60	- -	0.50

[a] Includes incidental cobalt.
[b] Cobalt – 0.12 max when specified.
[c] Tantalum – 0.25 max when specified.

TABLE 7.—*Mechanical Properties of Shielded Metal-Arc Welds in Nickel and Nickel-Base Alloys*[a]

Alloy	Thickness, in.	Groove type	Electrode diameter, in.	Average tensile strength,[b] psi	Minimum elongation (free bend), percent	Condition	Reference
Nickel 200	1/8	Square	3/32	69,900	25	- -	9
	11/16	Single vee	5/32	77,400	25	- -	9
Monel 400	1/8	Square	3/32	78,600	30	- -	9
	3/4	Double vee	5/32	84,400	30	- -	9
Monel K-500[c d]	1/8	Square	5/32	[a]129,900	19	- -	9
	3/8	Single vee	5/32	[a]121,400	4	- -	9
Inconel 625	1-1/4	Single vee	5/32	116,600	34.1	As welded	40
Inconel X-750[c d]	3/8	Single U	5/32	99,500/ 106,000	27	As welded	9
				167,200/ 169,000	24	Age only	9
				161,000	25	Quench and age[e]	9
IN-102	5/8	Single vee	5/32	115,000	31.5	As welded	40
Hastelloy B	1/8	Square	3/32	117,500	- -	- -	9
	3/8	Double vee	5/32	112,600	- -	- -	9
Hastelloy C	1/8	Square	3/32	114,000	- -	- -	9
	3/8	Double vee	5/32	112,600	- -	- -	9
Hastelloy F	5/64	Square	3/32	104,900	- -	- -	9
Hastelloy N	1/16	Square	- -	116,100	- -	- -	9
Hastelloy X	3/32	Square	- -	110,300	- -	- -	9
	3/8	Double vee	- -	108,700	- -	- -	9

[a] Flat position.
[b] Reduced section short gage length.
[c] Actual values.
[d] Aging treatments: Monel K-500, 1100° F, 16 hr, air-cool; Inconel X-750, 1300° F, 6 hr, air-cool.
[e] 2000° F, 6 hr, water-quench.

employed. When joint design permits, rapid travel with as little "weaving" as possible is preferred, to minimize heat. The Hastelloy alloys tend to "boil", which causes porosity in the welds. Overheating may occur in the starting and stopping of the bead. To avoid this, minimum currents that are consistent with the thickness and size of the parts should be used. It is occasionally desirable to strike the arc on a tab adjacent to the weld joint when starting the weld, and to run the electrode off to the side of the joint when stopping. Because of the fluidity of these alloys, position welding is somewhat difficult. Therefore, whenever possible, welding should be done in the downhand position. The inlet cooling sleeve shown in figure 20 is a typical application for the metal-arc welding of these alloys (ref. 41).

Gas Tungsten-Arc Welding

The gas tungsten-arc (GTA) process is used extensively for joining nickel and nickel-base alloys. It is particularly suited for joining very thin materials and is adaptable to a manual, semiautomatic, or fully automatic operation. It can be used on almost any thickness; but, as the thickness increases above 0.1 in., other fusion-welding processes offer important advantages. "TIG welding" and "tungsten inert-gas welding" are familiar synonyms for the process.

In GTA welding, the heat required to melt the joint edges is supplied by an arc between a tungsten electrode in the welding torch and the workpiece. The arc, electrode, and hot metal are protected from air by a flow of inert gas (such as argon, helium, or argon-helium mixtures) around the tungsten electrode. In many instances, supplementary shielding to protect the hot metals from contamination is provided by trailing shields, underbead shields, side shields, or by welding within a gas-filled chamber.

GTA welds can be made with or without the addition of filler metal. Whether filler metal is added depends on such factors as joint design, joint thickness, availability of suitable filler metals, and desired

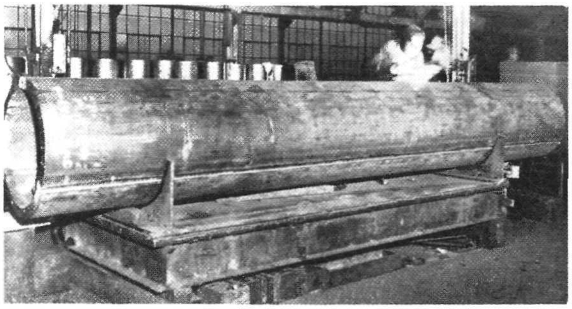


FIGURE 19.–Shielded metal-arc welding of a Monel press roll.

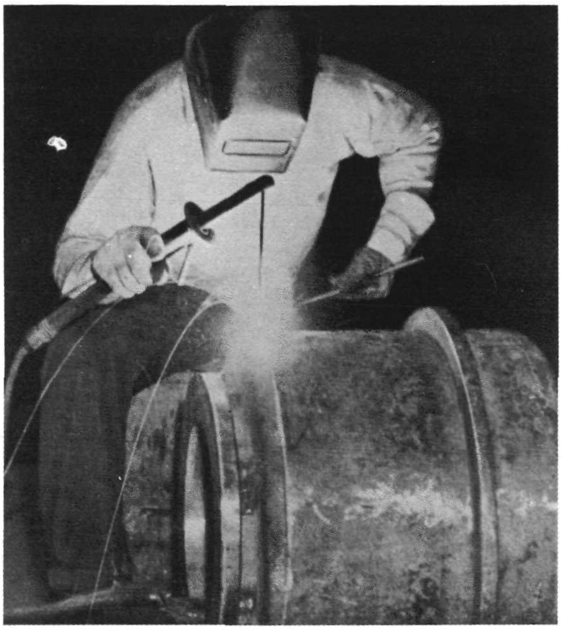


FIGURE 20.–Shielded metal-arc welding of a Hastelloy inlet cooling sleeve.

weld characteristics. GTA welds are often made by melting only the edges of the parts to be joined. Filler metal is always added when the joint contains a groove or similar preparation and, in some instances, when joints are not grooved. The addition of filler metal to square-butt joints, for example, increases the tolerance of GTA welding for slight variations in the joint fitup.

GTA welding of nickel and nickel-base alloys has been performed in all welding positions. When welding in other than the flat position, changes in the shielding afforded by the inert gases should be anticipated.

Equipment.–Conventional GTA power supplies, torches, and control systems are used for welding nickel and nickel-base alloys. The process is illustrated in figure 21 (ref. 42). No significant changes in welding characteristics or weld properties have been reported that can be attributed to the use of any specific type of welding equipment. However, welding techniques for some nickel-base alloys differ from techniques for other metals. Welding operators may require retraining to produce high-quality welds. High-frequency arc starting is used to avoid tungsten inclusions that are often found with touch-starting techniques.

Nickel and nickel-base alloys can be welded in open-air atmospheres with the right supplemental equipment. The inert-gas flowing from a conventional GTA welding torch may not provide complete protection from contamination during welding. Auxiliary trailing shields attached to the welding torch, or auxiliary underbead- or side-shielding devices built into the weld tooling are used when improved shielding is needed. The importance of tooling to assist in weld shielding was discussed earlier in the section on inert-gas shielding. Figure 22 illustrates a commonly used type of combined torch-trailing shield arrangement. Such shields are designed to supply a uniform nonturbulent flow of inert gas over the weld as it cools behind the torch. It is much easier to insure good shielding during mechanized GTA welding than in manual operations. Mechanized welding operations are recommended and used wherever possible in welding nickel and nickel-base alloys.

The shielding chambers used for GTA welding of nickel can be of several basic designs. This was

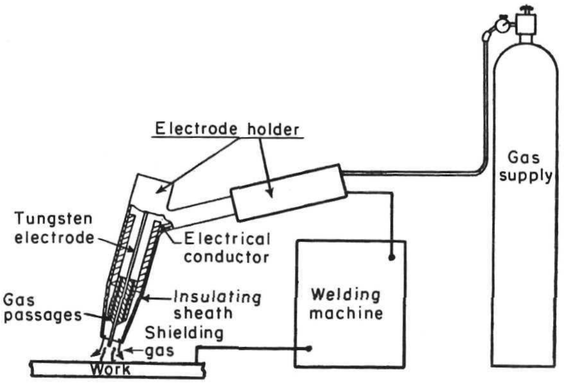


FIGURE 21.–Gas-tungsten-arc-welding process.

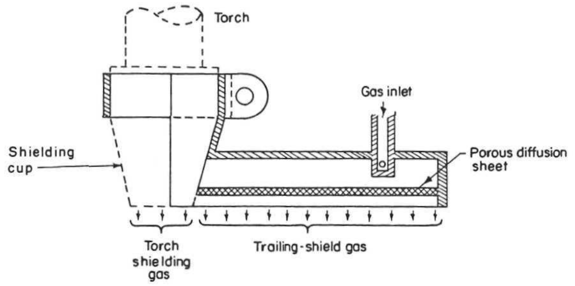


FIGURE 22.—A combination torch-trailing-shield arrangement.

TABLE 8.—*Chemical Compositions of Gas-Tungsten-Arc Welding Electrodes*

AWS-ASTM classification	Tungsten (min), percent	Thorium, percent	Zirconium, percent	Total other elements (max), percent
EWT	99.5	- -	- -	0.5
EWTh-1	98.5	0.8 to 1.2	- -	0.5
EWTh-2	97.5	1.7 to 2.2	- -	0.5
EWZr	99.1	- -	0.3 to 0.5	0.5

illustrated earlier in the section on tooling. Inert gases replace the air by evacuating and backfilling the chamber, by flow purging, or by collapsing the chamber and backfilling. Shielding chambers are used when welding nickel parts that cannot be protected satisfactorily in the open atmosphere. Precautions must be taken to prevent leakage of air, water vapor, or water into the chambers.

The gases used for shielding include helium, argon, and argon-helium mixtures. Helium, however, has definite advantages over argon for simple fusion welding of thin sheet material (ref. 11):

(1) Porosity is reduced in both Monel 400 and Nickel 200.

(2) Increased welding speeds can be obtained.

Electrodes for GTA welding nickel and nickel-base alloys consist of tungsten, tungsten-thoria, or tungsten-zirconium. These electrodes normally are operated on straight-polarity direct current, although alternating current may be used. The electrodes usually are ground to a sharp point (ref. 9).

Experience shows that weld-metal contamination by tungsten is less with the tungsten-thoria electrodes. Chemical compositions of conventional GTA-welding electrodes are given in table 8 (ref. 43). Extension of the electrode beyond the shielding cup should be as short as possible for more effective gas shielding.

The equipment used to drive the welding filler wire should provide uniform filler-metal feed rates. Feed rates should be as uniform as possible with both manual and machine wire feeding to prevent localized weld irregularities that may contribute to cracking. Even the best quality welding wire can be contaminated by foreign material, such as lubricating oils, that may become lodged in the wire-feed equipment. Periodic checks should be made to ensure that oil and other foreign material are not present in the drive system or guide components.

Materials.—All of the nickel-base alloys that are weldable have been joined with the GTA-welding process. Commercially pure nickel and many of its alloys can be welded readily. The filler-metal composition that is used for a particular alloy is determined by service requirements. The filler metal and base metal should be selected very carefully, particularly where corrosion is likely to be a major factor in service. Usually, the filler metal is selected to match the composition as closely as possible, although departures from this practice may be necessary. For welds of very short length, cut and straightened lengths of filler wire may be used instead of continuous coils. For manual GTA welding, sheared strips of a base-metal sheet are sometimes used as filler wire. Consumable filler-metal inserts also can be used to assist in welding root passes. On rare occasions, a similar procedure is used in mechanized welding when a preplaced strip of sheet or wire is inserted in the joint to serve as a filler metal. Care is recommended when using this procedure because of the difficult handling and potential contamination problems involved. Filler metals used for GTA welding of some nickel-base alloys are listed in table 9 (ref. 44). These filler metals are classified on the basis of as-manufactured chemical composition. They can be used for GMA and submerged-arc welding where applicable.

Joint designs for GTA welding of nickel and nickel-base alloys are similar to those used for SMA welding. Typical joint designs are as shown in figure 1.

Welding conditions.—Welding conditions are dependent on material thickness, joint design, the type of weld tooling, and whether manual or machine

TABLE 9.–*Chemical-Composition Requirements for Nickel and Nickel-Base-Alloy Bare Welding Rods and Electrodes*

AWS-ASTM classification	Carbon	Manganese	Iron	Sulfur	Silicon	Copper	Nickel plus cobalt[a]	Cobalt	Aluminum	Titanium	Chromium	Columbium plus tantalum	Molybdenum	Vanadium	Tungsten	Other elements, total
RNi-2	0.15	0.35	0.4	0.01	1.0	0.25	97.0 min	--	--	0.50	--	--	--	--	--	0.50
ERNi-3	0.15	1.0	1.0	0.01	0.75	0.25	93.0 min	--	1.5	2.0-3.5	--	--	--	--	--	0.50
RNiCu-5	0.30	2.0	2.5	0.02	0.50	Bal	63.0-70.0	--	--	--	--	--	--	--	--	0.50
RNiCu-6	0.30	1.0	1.0	0.02	0.50-1.50	Bal	55.0-60.0	--	--	--	--	--	--	--	--	0.50
ERNiCu-7	0.15	4.0	2.5	0.02	1.25	Bal	62.0-69.0	--	1.25	1.5-3.0	--	--	--	--	--	0.50
ERNiCu-8	0.25	1.5	2.0	0.01	1.0	Bal	63.0-70.0	--	2.0-4.0	0.25-1.00	--	--	--	--	--	0.50
ERNiCr-2	0.08-0.15	1.0	3.0	0.015	0.30	0.50	75.0 min	--	0.40	0.15-0.50	19.0-21.0	--	--	--	--	0.50
ERNiCr-3	0.10	2.5-3.5	3.0	0.015	0.50	0.50	67.0 min	(b)	--	0.75	18.0-22.0	[c]2.0-3.0	--	--	--	0.50
RNiCrFe-4	0.10	1.0	6.0-10.0	0.015	0.50	0.50	72.0 min	--	--	--	14.0-17.0	--	--	--	--	1.00
ERNiCrFe-5	0.08	1.0	6.0-10.0	0.015	0.35	0.50	70.0 min	--	--	--	14.0-17.0	1.5-3.0	--	--	--	1.00
ERNiCrFe-6	0.08	2.0-2.7	10.0	0.015	0.35	0.50	67.0 min	--	--	2.5-3.5	14.0-17.0	--	--	--	--	0.50
ERNiCrFe-7	0.08	1.0	5.0-9.0	0.01	0.50	0.50	70.0 min	--	0.40-1.00	2.00-2.75	14.0-17.0	0.70-1.20	--	--	--	0.50
ERNiMo-4	0.08	1.0	4.0-7.0	0.03	1.0	--	Bal	2.5	--	--	1.0	--	26.0-30.0	0.20-0.60	--	0.50
ERNiMo-5	0.08	1.0	4.0-7.0	0.03	1.0	--	Bal	2.5	--	--	14.5-16.5	--	15.0-17.0	0.35	3.0-4.5	0.50
ERNiMo-6	0.12	1.0	4.0-7.0	0.03	1.0	--	Bal	2.5	--	--	4.0-6.0	--	23.0-26.0	0.60	--	0.50

Note: Single values shown are maximum percentages except where noted otherwise.

[a] Cobalt, if determined, 1.00 percent maximum.

[b] Cobalt, 0.10 maximum when so specified.

[c] Tantalum, 0.30 maximum, when so specified.

welds are made. Also, for any given thickness and joint design, various combinations of amperage, voltage, welding speed, and filler-wire speed are satisfactory. Consequently, no hard and fast rules can be specified for welding conditions. Table 10 lists welding conditions for several nickel and nickel-base alloys.

Welding conditions generally do not have to be adjusted radically to accommodate the various nickel-base alloys, but they are often adjusted as a means of controlling weld porosity. With the precipitation-hardening alloys, care must be taken to avoid shallow, concave-shaped weld beads when joining highly restrained, relatively thick sections (ref. 10).

Tack welding is used to preposition detail parts or subassemblies for final welding operations. Elaborate fixtures often can be eliminated when tack welds are used to their full advantage. Various tack-welding procedures are used, but in all cases good cleaning practices and adequate shielding must be provided to prevent contamination of the welds. Contamination or cracks developed in tack welds can be transferred to the completed weld. One procedure is to tack-weld in a way that the finished weld never crosses over a previous tack weld. To accomplish this, sufficient filler metal is used to fill the joint completely at a particular location. The final weld beads are blended into each end of the tack welds.

Tack welds, while necessary to ensure proper alignment, can cause problems if they impose too rigid restraint. In a program to develop welding conditions for Hastelloy-X ring weldments for the Phoebus-2 rocket nozzle (ref. 47), minimal joint restraint appeared to permit a wider spread in welding conditions. On ring forging weldments, increases of current up to 40 amp above the nominal and interpass temperatures as much as 400° F above the specified 200° F were safely tolerated. These weldments represented a minimal restraint condition. On aft-nozzle joints, representing a complex constraint condition, weld cracking occurred. These were attributed to much less severe variations in the welding procedure than those discussed above.

Properties.—A large number of joint properties have been determined for GTA welds in nickel and nickel-base alloys. The properties measured by static tension, notch tension, bend- and crack-susceptibility tests compare very favorably with parent-metal properties. Properties of these welds can vary, depending on the condition of the base metal, postweld heat

TABLE 10.—*Conditions for Gas-Tungsten-Arc Welding Selected Nickel-Base Alloys*

Base metal and thickness, in.	Filler metal and wire diameter, in.	Electrode and size, in.	Groove type	Number of passes	Welding speed, ipm	Wire-feed speed, ipm	Arc voltage, volts	Current, amperes, and polarity	Shielding gas and CFH flow rate			Remarks	Reference
									Torch	Trailing	Backup		
Hastelloy B, 0.020	None	Th-W, 0.062	- -	- -	8	None	25	8 DCSP	He/50	- -	He/50	- -	- -
Inconel 718, 0.025	None	Th-W, 0.062	- -	- -	9	None	16	12 DCSP	He/50	- -	He/50	- -	- -
Inconel X, 0.025, 1.5	Inconel 69, 0.063	Th-W, 0.062	- -	- -	- -	- -	- -	- - DCSP	- -/20	- -	- -	Manual	45
	AWS ERN 69, 0.062	W, 0.094	Double U	- -	- -	- -	20	100-200 DCSP	He/20	- -	A/10	Manual	16
Hastelloy R-235, 0.020, 0.040	- -	Th-W, 0.040	- -	- -	15	- -	10	30 DCSP	A/16	- -	A/16	- -	46
	- -	Th-W, 0.062	- -	- -	30	- -	10	50 DCSP	17A-83He/50	- -	A/20	- -	46
René 41 (0.125)	René 41 (0.030)	Th-W, 0.094	45-deg Single V	1	5	23.5	10.4	65 - -	75He-25A/30	75He-25A/10		Automatic	10

treatments, and service conditions. Fatigue tests have been carried out on GTA-welded Nimonic 80A and Nimonic 90 at room temperature and at elevated temperatures (ref. 1). The strength for both conditions was higher at elevated temperatures than at room temperature. The increase in fatigue strength at elevated temperatures is attributed tentatively to strain-induced precipitation. Information also is available on the effects of postweld heat treatments on weld properties for a limited number of alloys. Some typical properties are given in table 11.

Applications to specific structures and materials.— GTA welding is used for joining all types of nickel-base alloys as shown in table 5. Some typical applications for GTA welding are discussed in the following paragraphs.

Gas-shielded arc-welding processes are preferred for many applications relating to nuclear reactors because of the increased joint cleanliness that can be obtained, particularly at the root of the weld, and because of the adaptability of the process to various materials (ref. 37). Some nickel-base alloys have excellent resistance to chloride-stress-corrosion cracking and to corrosion caused by fuels and coolants used in reactor and radiochemical piping. For these reasons, Inconel 600 has been used in the primary systems of certain nuclear-power plants, and TIG welding has been the primary joining process. The process is used often, with or without a consumable insert, for making root-pass welds in piping joints. The tungsten-arc process provides sound weld deposits, free from porosity and fissures. In one reactor in which flawless welded joints were required, TIG welding was selected in preference to shielded metal-arc welding (ref. 34). The welders who made these critical welds were skilled and capable of the highest

TABLE 11.—*Mechanical Properties of Gas-Tungsten-Arc Welds in Nickel and Nickel-Base Alloys*[a]

Alloy	Thickness, in.	Groove type	Electrode diameter, in.	Average tensile strength, 10^3 psi	Minimum elongation (free bend), percent	Joint efficiency, percent	Condition	Reference
Nickel 200	1/8	Square butt	- -	66.6	40	- -	- -	9
Monel 400	1/8	Square butt	- -	81.7	35	- -	- -	9
Inconel 600	1/8	Square butt	- -	94.7	31	- -	- -	9
Inconel 718	1/4	Square butt	1/16	188.0	[b]14	102	(c)	48
	1-1/8	U Groove	- -	189.7	165.6	- -	- -	49
Hastelloy B	1/8	Square butt	3/32	118.5	36	- -	- -	9
	3/8	Double vee	5/32	120.9	35	- -	- -	9
Hastelloy C	3/32	Square butt	3/32	113.8	19.8	- -	- -	9
	3/8	Double vee	5/32	115.0	24	- -	- -	9
Hastelloy R-235	- -	Double vee	- -	136.0	18.5	- -	- -	9
	0.016	- -	- -	117.6	- -	89	10 percent cold worked, welded	46
	0.040	- -	- -	128.3	- -	98	Solution heat treated,[d] welded	46
	0.020	- -	- -	137.9	- -	86	Solution heat treated,[e] aged, welded	46
	0.040	- -	- -	132.0	- -	94	Solution heat treated, welded, aged	46
Hastelloy X	1/8	Square butt	- -	110.1	26.2	- -	- -	9
	3/8	Double vee	- -	107.6	22.4	- -	- -	9
	1-1/2	Double U	- -	90.9	[b]19.5	- -	As welded	47
	1-1/2	Double U	- -	97.9	[b]30.7	- -	Anneal at 2150° F, water quench	47

[a] Flat position.

[b] in 2 in.

[c] 1950° F, 1 hr air cool, 1400° F, 10 hr furnace cool to 1200° F, hold to total of 20 hr.

[d] 1975° F, water quench.

[e] 1500° F, 2 hr, air cool.

possible quality welds. During this work, welding procedures that insured crack-free, porosity-free, full-penetration welds without the use of backing rings were developed. These procedures included the use of a root opening, argon shielding through the torch, helium shielding for the underbead side, and Inconel 600 filler wire.

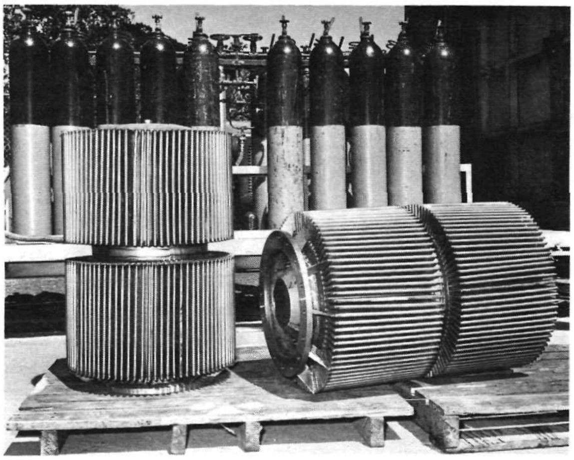
Filler metal MIL-EN87/RN87 was designed primarily for GTA and GMA welding of nickel-chromium-iron alloys such as Inconel 600 for nuclear-power-plant applications. This filler metal has produced crack-free and porosity-free welds under conditions of high restraint in plate and in simulated tube-to-tube sheet joints (ref. 39).

Inconel X has been used for pressure vessel applications in which operations are conducted at high-stress levels and at temperatures between 1000° and 1300° F (ref. 16). GTA welding was used for these vessels because weld-metal deposits could achieve an ultimate tensile strength of 92 to 93 percent of the base metal, and because of other advantages. Much useful information was generated during the welding-procedure development. Consistently sound root passes were made without the addition of filler metal. Inert-gas backing was needed to avoid oxide formation. Modified welding techniques, low welding current, and narrow stringer passes were required to avoid microcracks and fissures in filler passes, and to provide proper root penetration. Dendritic structures, in addition to oxides and microcracks, had a major effect on rupture life. Cracking problems were not encountered except those associated with weld defects present before heat treatment. The heat-treating sequence for weldments also differed from the heat treatment recommended for unwelded material as shown below

	For service below 1100° F	For service above 1100° F
Initial material condition	1900° F (mill anneal)	2100° F (solution anneal)
For nonwelded fabrication	1300° F, 20 hr	1550° F, 24 hr then 1300° F, 20 hr
Fabricated and welded	1625° F, 4 hr then 1300° F, 20 hr	1625° F, 4 hr then 1300° F, 20 hr

Some difficulties have been experienced with microcracking in thin-sheet Inconel-X weldments during postweld heat treatment. These cracks are believed to be caused by high residual stress and precipitation-hardening reactions. The effects of various heat treatments on cracking in welded, thin-sheet Inconel X have been studied using circular-patch-type weld-restraint specimens. Eighteen different heat-treating schedules failed to produce microcracks in the weld-fusion or heat-treated zones (ref. 45).

a. Subassembly



b. Finished Form

FIGURE 23.–Gas tungsten-arc welding for fabricating a corrugated-Monel heat exchanger.

GTA welding was used for fabrication of a corrugated Monel heat exchanger (fig. 23) for a shipboard seawater-distillation plant (ref. 50). All welding was performed in an air-conditioned room free from normal shop dirt. Initially, 0.050-inch-thick sheet Monel was welded without filler metal. Failures occurred in these welds because of stress corrosion in areas of microporosity because of the lack of deoxidizers in the Monel and lack of penetration. The use of filler metal and a weaving technique combined with underbead shielding eliminated these problems. Figure 23 illustrates the welding of corrugated fins to an end ring and a completed assembly, respectively. Figure 24 illustrates a manual GTA-welding technique being used for another type of heat exchanger (ref. 51). The unit shown is a tube-and-shell-type heat exchanger of Inconel 600. Tube-to-header joints like those shown in the figure are welded regularly by fabricators using either manual or automatic techniques.

Welded joints in chemical-processing equipment often must be free from crevices, particularly where corrosion conditions are severe. In addition, the underbead-reinforcement size and geometry must be closely controlled to provide smooth bores. GTA welding used in conjunction with consumable inserts, proper filler wire, and shielding gas can meet these requirements in nickel pipe (ref. 52). The consumable insert made from flattened wire and used for making such pipe joints is shown in figure 25. This insert provided in this case a satisfactory underbead contour for all normal chemical-processing applications. Unless the insert was flattened, the weld did not blend with the pipe bore, and a pronounced underbead reinforcement was formed. The consumable insert was made from a nickel-alloy filler wire containing titanium (Nickel Filler Metal 61) to eliminate porosity. When welding for nuclear-power-plant applications, an argon-10 percent hydrogen mixture for torch shielding, argon backside shielding, and a low-titanium nickel-alloy filler metal (Nickel Filler Metal 41) was used to provide flat, smooth weld beads to produce a smooth bore.

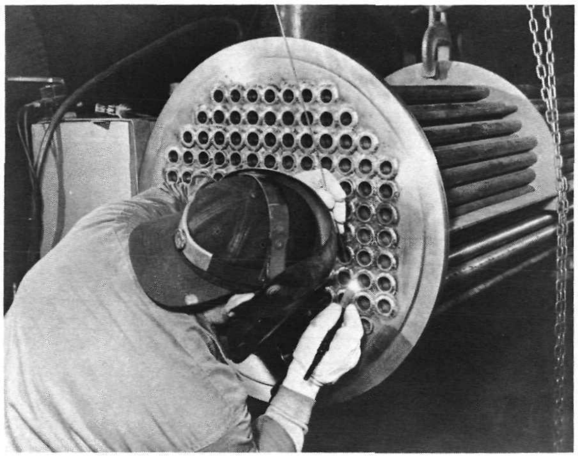


FIGURE 24.–Manual gas tungsten-arc welding of tube-to-heater joints in Inconel 600.

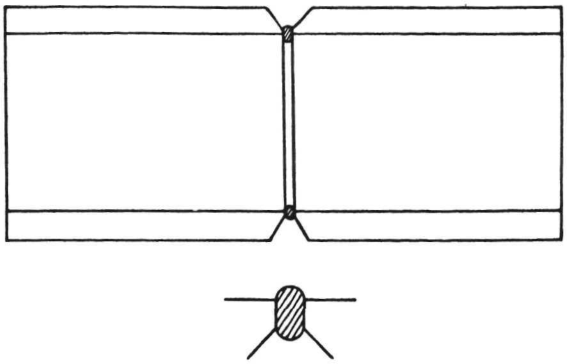


FIGURE 25.–Consumable insert for welding nickel pipe.

The welding of TD nickel has presented a special problem in the past. Because of agglomeration of thoria in the heat-affected zone, the alloy tends to become brittle after welding. A recently developed GTA technique (ref. 53), involving low-heat input, may overcome this problem. A J-joint configuration is used and welding variables are rigidly controlled so that filler wire can be cast in the joint. This minimizes agglomeration and thus improves mechanical properties. TD nickel specimens 1/4-in. thick, when welded with this technique, have exhibited tensile and yield strengths exceeding 90 percent of the parent-metal strength.

Gas Metal-Arc Welding

Gas metal-arc welding (GMA) is a process that can provide high deposition rates and long arc times as well as ease in welding in the the "out-of-flat position." The process has been used for joining nickel and nickel-base alloys, but to a somewhat lesser degree than GTA welding for actual production and prototype components. GMA welding can be manual, semiautomatic, or fully automatic. It is particularly well suited for the joining of thick sections (greater than about 1/8 in.) where high filler-metal deposition rates are desirable. The process is very economical for this type of work because high weld-finishing rates are obtainable. "MIG" welding and metal inert-gas welding are familiar synonyms for the process.

In GMA welding, the heat required to melt the joint edges is supplied by an arc between the filler wire and the work. The filler wire also is called electrode wire, consumable electrode, consumable electrode wire, and filler metal. The filler wire replaces the tungsten electrode. The GMA welding process is illustrated in figure 26 (ref. 42). For welding of nickel and nickel-base alloys the filler wire is usually a matching alloy wire. The arc and surrounding area is kept free of air by a flow of inert gas around the filler wire as is the case in GTA welding. Argon is generally recommended as the shielding gas for use with nickel and nickel-base alloys (ref. 54). This gas promotes good wetting and decreases weld metal fluidity. For material greater than 3/8-in. thick, argon-helium mixtures are recommended. All of the metal added to the weld joint is supplied by the filler wire. This metal is transferred from the filler wire to the workpiece as fine droplets, a metal spray, or by short-circuit transfer. The metal being transferred across the arc may be exposed to much higher temperatures than if it were just being melted. The combination of very high temperatures and fine-particle sizes represents a set of conditions suitable for contamination. Therefore, in GMA welding, it is extremely important that the arc area be completely protected from exposure to all harmful gases, i.e., oxygen, nitrogen, hydrogen, water vapor, etc.

GMA welding of nickel and nickel-base alloys can be performed in all positions. A check should always be made before GMA welding to insure that adequate gas shielding is obtained, regardless of the welding position. In general, there is more likelihood of there being poor shielding when welding is done in other than the flat position.

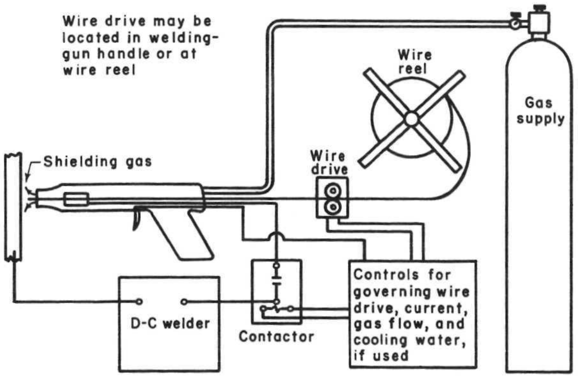


FIGURE 26.–Gas-metal-arc-welding process.

The mode of metal transfer is quite important to weld quality in GMA welding. As improvements have been made in metal transfer, the process has been increasingly used. Originally, GMA welding was used only in the higher-current ranges. The metal in this case is transferred in a continuous spray of fine droplets through the arc column. Because of the high-heat characteristics of the process, spray transfer is adaptable only to thicker sections welded in the downhand position. At lower currents, the mode of transfer changes to an erratic, globular type which is unsatisfactory.

Short-circuiting transfer was developed as a means to achieve satisfactory metal transfer at lower currents. In a short-circuiting arc, metal transfer takes place during repetitive short circuits through contact of the electrode with the weld pool, rather than by droplets through the arc column. The difference between spray and short-circuiting transfer is illustrated in figure 27.

The short-circuiting process has been used to weld nickel alloys, particularly those used for rocket-engine components (ref. 55). The low-heat input developed by this process is advantageous for age-hardenable alloys with "hot-short" cracking tendencies.

Equipment.–Conventional GMA-welding power supplies, torches, and control systems are used effectively in welding nickel and nickel-base alloys. However, when the short-circuiting technique is used with nickel alloys, the power source must be capable

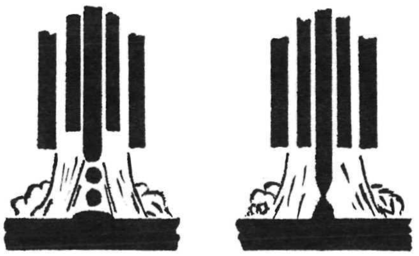


FIGURE 27.–Difference between spray transfer and short-circuiting transfer.

of separating and controlling both its static and dynamic characteristics (ref. 55). For this technique, the power source should also be equipped with a variable ac inductor in the secondary circuit which permits changes in the time constant of the short-circuiting cycle to meet changing weld requirements.

The nature of GMA welding makes this process somewhat more sensitive than GTA welding to changes in welding-equipment characteristics. Various types of constant-speed wire feeders and conventional GMA-welding, water-cooled torches are used. Most applications of this process have been set up for welding in air.

For in-air welding with the GMA process, supplemental shielding devices are not generally employed, but they can be used. Trailing shields designed for GMA welding are usually considerably longer than those used in GTA welding. When larger volumes of material are heated, they cool more slowly, and hence require better protection.

Wire-feeding equipment for GMA welding is important. The most common causes of down time are found in the wire-feed system. For feeding filler wire, a spool of wire is placed on a spindle, threaded through a straightening device and into the grip of wire-feed rolls. From the rolls, the wire is pushed through a flexible wire-feed cable, through the gun and into the arc. Hoses and plumbing to supply the gun with shielding gas and cooling water, if used, are included.

The only function of the wire feeder is to move welding filler wire to the arc so as to provide a sound porosity-free weld deposit. In a correctly designed wire-drive system, the wire is confined laterally so that it can move only in the desired direction. If the drive motor has sufficient power, the wire will move smoothly from spool to gun. Often, there are signals of impending wire-feeding failures. An alert operator becomes aware that the wire speed is varying. Before a complete stoppage occurs, a step-by-step inspection of the equipment should be made to locate and correct the trouble. Precautions that should be taken with wire-feeding apparatus are reviewed below:

(1) The wire should be snugly wrapped on the spool or coil and should be level-wound.

(2) The wire-straightening rolls should be adjusted correctly to remove the "cast" from the wire, and to prevent improper bending.

(3) The unsupported length of wire between the feed rolls and the wire-feed cable should be as short as possible.

(4) The wire should enter at the proper location on the drive rolls.

(5) The drive-roll clamping pressure should be adjusted to prevent slippage due to inadequate pressure or to prevent flattening the wire due to excessive pressure.

(6) The wire-feed cable should be clean and free of kinks to insure free movement of the wire through the cable and to prevent wire whip.

(7) The correct-size wire-feed cable and/or liner for the wire should be used.

(8) Parts showing excess wear should be replaced.

(9) The first and final test for a wire-feed system is the ease of wire movement.

The GMA-welding gun or torch is the last link in the wire-feed chain. One of its functions is to transfer welding power to the wire, preferably at the exit end of the contact tube. Its other major function is to direct a gas shield over the weld zone to exclude the adjacent atmosphere. The gun must be kept in good condition to produce good welds. Bent, worn, or broken parts should be replaced.

The contact tubes are usually made of copper or some special copper alloy. Contact tubes can malfunction due to collection of spatter and excessive wear, or they can melt when the wire burns back as a result of wire-feed failure. Burn backs are generally caused by arcing in the contact tube itself. This makes the wire stick, and then the applied voltage burns the wire back further. Worn contact tubes contribute to burn backs because, as the bore size increases, the transfer of electric power to the wire becomes erratic.

Gas coverage, the second function of the gun, is controlled by its nozzle, which is designed to produce a satisfactory gas-flow pattern. When weld spatter builds up, the shape of the gas pattern may change and, if not corrected soon enough, will cause poor welds. The proper rate of gas flow will normally produce a laminar flow at the nozzle tip. The flow rate may not be critical but a rate too low will not supply enough gas to do the job, and a rate too high will cause turbulence, which brings air into the gas shield and contaminates it. Gas leaks or cooling-water leaks can also cause porosity in welds. Bending, plugging, or improper installation of parts should be corrected.

Tooling and fixtures.—Backing of GMA welding of nickel and nickel-base alloys varies among fabricators. Backing bars are used to provide root-side shielding to facilitate control of the weld puddle, heat effects of welding, and underbead-reinforcement geometry. Backing bars also are used to minimize distortion by promoting more rapid solidification and cooling of weld metal.

Copper is the most popular material used for backup bars when manual GMA welding is done, although other materials can be used if conditions are adjusted accordingly.

Welding conditions.—The welding conditions employed in GMA welding are dependent on two separate groups of factors. First, a suitable combination of current and voltage must be selected that will produce the desired arc characteristics. The arc stability and metal transfer occurring in GMA welding are very dependent on these electrical variables and the composition of the shielding gas used. With low-current densities, metal transfer is erratic and consists of large metal globules. Large globules often contact the workpiece before they separate from the end of the filler wire. This behavior produces a short circuit which interrupts the arc. Current flow continues, however, until the globule melts sufficiently to separate from the end of the filler wire. When separation occurs, the arc reignites and the transfer process continues as before. Low-current-density GMA welding has been used for welding nickel. One important advantage is that lower currents and heat-input rates than those needed for spray-type metal transfer can be used. As the current density is increased, arc stability is improved and metal transfer changes to a characteristic spray-type transfer. High-current-density welding conditions are generally preferred in the GMA welding of most materials.

The second group of factors affecting the welding conditions includes the material thickness, joint design, weld tooling, and whether manual or machine welding techniques are being used. The first group of factors affecting welding conditions usually set minimum limits on the usable current and voltage. Variation above these minimums, combined with the possible variations introduced by the second group of factors, make it possible to produce welds of very similar appearance with many combinations of welding conditions.

With the short-circuiting technique, extreme care must be taken to avoid lack-of-fusion defects, at least when welding precipitation-hardening alloys (ref. 10). Such defects are more likely with GMA welding than with other processes because of the low-penetrating characteristics of the arc in the presence of the refractory oxides on the base metal.

Properties.—Information on properties of GMA welds in nickel and nickel-base alloys has not been reported extensively. Table 12 shows properties for a limited number of alloys (refs. 9, 55 and 56).

Applications to specific structures and materials.—GMA welding is capable of depositing welding filler metals at high rates, while shielding the parts with inert gas. It has been used successfully for welding a number of nickel-base alloys. Examples of applications are described below.

Hastelloy C has excellent formability, good weldability, and good properties for use at moderately elevated temperatures. Heat treating is relatively simple, although the recommended heat-treating temperature (2225° F) does present a problem with large parts. Tensile strength, creep, rupture, and thermal-cycling properties of GMA welds in Hastelloy C and the effects of lower-temperature heat treatments (2050° F for 2 hr, air cooled) have been reported (ref. 56). The welds were made in 0.250-in.-thick plate using the conditions shown in table 13. The first pass was made using 36 arc volts, and the second pass was made using 40 arc volts. The 2050° F heat treatment increased the tensile strength at room temperature and at 1400° F up to 10 percent, but reduced the yield strength and percent of elongation.

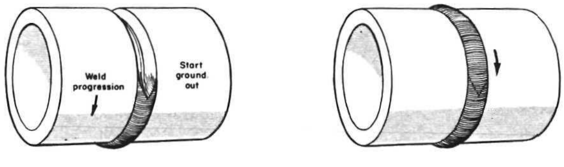
GMA welding also is used extensively for joining nickel and nickel-base-alloy pipes and tubes for nuclear, marine, cryogenic, and chemical-processing applications. Fabrication in the shop provides the most advantageous conditions where downhand welding conditions can be arranged. Field fabrication is much more difficult due to the fixed position of the parts being welded. The GMA-welding process with short-circuit metal transfer is well suited for such applications. Heat input to the weld zone is low, and large amounts of weld metal can be deposited rapidly. Some considerations that are normally observed and techniques that are used are discussed in the published literature and summarized below (ref. 52).

Lack of fusion may be experienced at weld starts because of the low-heat input, especially when welding thick materials. This can be overcome by using the design and torch-manipulating techniques shown in figures 28 and 29 (ref. 52). Inert-gas shielding such as argon or helium must be used to

TABLE 12.–*Properties of Gas Metal-Arc Welds in Selected Nickel-Base Alloys*

Base metal and thickness, in.	Test temperature, °F	Transverse ultimate tensile strength, 10^3 psi	Percent elongation in 2 in.	Location of failure	Postweld treatment	Reference
Hastelloy B,						
0.188	--	115.2	--	--	--	9
Hastelloy C,						
0.188	--	113.7	--	--	--	9
0.250	RT	116.0/122.5	47/49	Parent metal	2225° F, 20 min, air cool, 3 cycles	56
0.250	1400	75.0/77.0	43/47	Parent metal	ditto	56
Hastelloy X,						
0.125	--	103.7	--	--	--	
0.375	--	106.4	--	--	--	9
Inconel 718,						
0.250	RT	171.9	[a]7.2	--	Direct age[b]	55
0.250	RT	184.8	[a]15.8	--	Annealed and aged[c]	55
0.250	1200	144.1	12.0	--	Direct age[b]	55
0.250	1200	153.2	20.0	--	Annealed and aged[c]	55

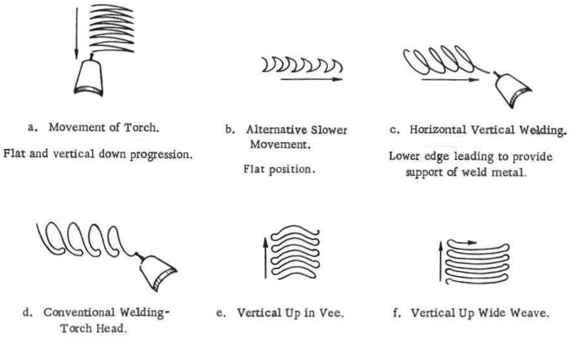
[a] In 1/2 in.
[b] 1400° F for 10 hr, furnace cool to 1200° F and hold for total aging cycle of 20 hr.
[c] 1950° F for 1 hr, air cool + 1400° F 10 hr, furnace cool and hold for total aging cycle of 20 hr.



a. First Stage

b. Second Stage

FIGURE 28.–Step-back technique for overcoming cold-start difficulties when welding pipe with the gas-metal-arc-welding process.



a. Movement of Torch.

Flat and vertical down progression.

b. Alternative Slower Movement.

Flat position.

c. Horizontal Vertical Welding.

Lower edge leading to provide support of weld metal.

d. Conventional Welding-Torch Head.

e. Vertical Up in Vee.

f. Vertical Up Wide Weave.

FIGURE 29.–Welding-torch manipulating techniques.

exclude air from the weld zones. Both weld-root and weld-face shielding should be used. Shielding the weld face is accomplished with the standard GMA-welding torch. Root shielding also must be provided; one interesting technique is the use of an inflatable bag inside the pipe as shown in figure 30 (ref. 52).

As mentioned earlier, nickel-base rocket-engine components have been welded by the short-circuiting GMA process. Several such applications are presented in reference 55. One representative example is discussed below.

The jacket for a rocket-engine thrust chamber includes four butt-welded girth joints in solution-annealed Inconel 718. The details of joint preparation, welding sequence, and operating parameters are

No deliberate pause at toe.

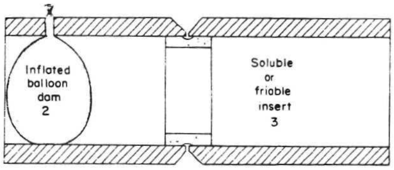


FIGURE 30.–A standard method of applying argon to the back of a weld.

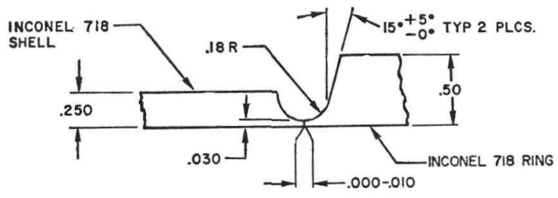
TABLE 13.–*Conditions for Gas Metal-Arc Welding of Selected Nickel-Base Alloys*

Base metal and thickness, in.	Filler metal and wire diameter, in.	Groove type	Number of passes	Welding speed, ipm	Wire-feed speed, ipm	Arc voltage, volts	Current, amp, and polarity	Shielding gas and CHF flow rate			Remarks	Reference
								Torch	Trailing	Backup		
Inconel, 1.0	MIL-EN87/RN87, 0.062	- -	- -	- -	- -	27	280 DCRP	A/- -	- -	- -	Manual	39
Hastelloy C, 0.250	Hastelloy alloy C, 0.031	60-deg single V	2	30	800	36, 40	230 - -	He/50	A/25	A/25	Mechanized	56
Inconel 718 (0.312)	Inconel 718 (0.375)	37-deg single V	- -	22-28	222	24	100 DCRP	He/50 M-1/8	- -	- -	Manual	10

shown in figure 31. These welds are completed in six passes. Since welding must be interrupted after each pass to reposition the electrode holder, there is no problem in meeting the required interpass temperature of 250° F. A rotary positioner holds the jacket components during welding, and the electrode holder is mounted in a manually adjusted rack and pinion slide fixture. This allows for in-process electrode extension and cross-seam adjustments. The use of short-circuiting GMA welding in this application provides high deposition rates and minimizes shrinkage and sinking of the inside diameter. The latter is important because of straight tolerances on the inside mold.

Arc Spot Welding

Arc spot welding has been developed for use either in applications where resistance spot welding cannot



—JOINT PREPARATION—

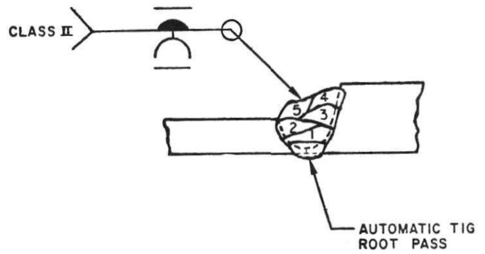


FIGURE 31.–Short-circuiting gas-metal-arc welding of the Inconel 718, J-2 thrust chamber jacket. Operating parameters: welding current–120A (dcrp); welding voltage–25V (for hot starting, 26V was maintained for 2 sec.); filler metal feed–240 ipm; travel speed–28 ipm; electrode extension–approx. 0.5 in.; inductance–approx. 700 μH; open circuit voltage–31V; short circuit current–475A; filler metal–0.035 Inconel 718; shielding gas–He @ 50 ft/hr^3 and M-1 @ 8 ft/hr^3; contact tip (i.d.)–0.043 in.; cup size–#8; weld position–40° (BTDC).

be used or as an alternative to the resistance spot-welding process. In arc spot welding either the basic GTA- or GMA-welding process can be employed. The process can be used to join combinations of thickness that are not suitable for resistance spot welding and in joints that are accessible from one side only. GTA spot welding probably will be particularly effective in the joining of overlapped materials whose total thickness does not exceed 1/4 in. GMA spot welding will be used on thicker sheet, up to a maximum of about 2 in.

The major difference between arc spot welding and either conventional GTA or GMA welding is that there is no relative lateral movement between the welding torch and the parts being joined. Starting and stopping cycles for the welding process are extremely important in arc spot welding. The total welding time generally is quite short, so that it is necessary to program welding parameters automatically to insure a smooth start and stop of the process. The shielding of arc spot welds is somewhat simpler than that of conventional GTA or GMA welds. Simple cylindrical auxiliary shields placed around the welding torch are sufficient to prevent contamination from the top surface of the weld. Shielding of the underside of the joint may not be required unless a full-penetration weld is being made. If welds are full penetration, suitable root shielding also must be provided.

The equipment used for arc spot welding is generally similar to conventional GTA and GMA welding equipment. However, some means of programming appropriate welding parameters to obtain desired starting and stopping cycles must be available. For welding thicker sheet material a means of retracting either the welding electrode or the weld-contact tube must be a part of the equipment.

Very little information is available concerning the use of arc spot welding for nickel or nickel-base alloys. The process is, however, used with materials that do not differ significantly from those used in either GTA or GMA welding. Welding conditions employed in arc spot welding are generally similar to the GTA or GMA welding conditions used in joining comparable thicknesses of materials. There are indications that the top layer that can be penetrated by GTA welding is limited.

GTA spot welding is especially adapted to making close-out joints. The process has been evaluated for use with René 41 (ref. 33), and possibly has been applied to other metals. Welds were made in two-ply pileups of 0.010-, 0.020-, and 0.040-in.-thick sheets of René 41. Four major problems were encountered—cratering, surface oxidation between sheets, sheet separation, and element segregation in the weld. Surface craters were eliminated by using downslope current control, and oxidation was reduced by using short weld times. The remaining problems are yet to be investigated.

Submerged-Arc Welding

Submerged-arc welding has been used for joining a limited number of nickel alloys. Only nickel, Monel, Inconel and Hastelloy alloys have been submerged-arc welded (ref. 9). The lack of suitable filler metals and fluxes, and the high-heat-input requirements have limited the usefulness of the process for nickel-base alloys. The process is applicable to a wide range of base-metal thicknesses, and it is adaptable to semiautomatic or fully automatic operations. In submerged-arc welding, the heat required to melt the filler metal and joint edges is provided by an arc between a metal electrode and the work. The ends of the welding electrode and the weld puddle are covered during welding with a protective submerged-arc-welding flux.

Conventional equipment is used for submerged-arc welding of nickel and nickel-base alloys. Three types of power supplies are used; variable voltage dc generators or rectifiers, constant-voltage dc generators or rectifiers, and ac transformers. Most submerged-arc welding installations require high currents at high-duty cycles. Thick sections may require welding currents as high as 4000 amp at 55 V, while thin sections may be welded at 300 amp and 2 V (ref. 57). The use of reverse polarity is preferred because it will produce a flatter bead with deeper penetration at lower arc voltage (30 to 33 V) (ref. 58). Straight polarity allows a slightly higher deposition rate, but at increased voltage (> 35 V). With straight polarity, flux consumption is increased and there is a greater chance of slag entrapment. Filler metals used with the process are bare rods or wires. Submerged-arc-welding fluxes consist of granulated mineral materials that are made according to chemical specifications and are available in a number of particles sizes. The flux that is selected for submerged-arc welding depends on the procedure that is used, joint design, and the alloy being welded.

The submerged-arc-welding operation is started by striking an arc on the workpiece beneath a blanket of flux. The arc may be initiated by touch starting, by inserting a pad of metal wool between the end of the welding electrode and the workpiece, or by the use of high-frequency current. Once the arc is initiated, the heat produced melts the surrounding flux. Submerged-arc-welding fluxes generally are electrically conductive when molten. The molten flux is necessary to permit continuous operation of the arc.

Joint designs for submerged-arc butt welding of nickel-base alloys are shown in figure 32 (refs. 17 and 18). The information available on welding conditions for nickel-base alloys is limited. Welding conditions available in the literature for Monel 400 and Inconel 600 are given in table 14. Available information on typical mechanical properties of submerged-arc welds is given in table 15 (refs. 17 to 19). Filler wires and fluxes are available for only a limited number of nickel-base alloys–wrought Monel and Inconel 600 (refs. 17 and 18). Submerged-arc welding of other nickel-base alloys probably will be realized only after suitable filler wires, fluxes, and satisfactory procedures are developed.

TABLE 14.–*Procedures for Submerged-Arc Butt Welding of Nickel-Base Alloys*

	Monel 400, up to 1-3/4 in. thick	Inconel 600, up to 2 in. thick
Electrode size, in.	0.062	0.062 and 0.093
Electrode extension, in.	7/8 to 1	7/8
Power source	Constant dc voltage, reverse polarity or straight polarity	Constant dc voltage, reverse polarity or straight polarity
Current, amp	260-280	250 (0.062-in. diam) 350-400 (3/32-in. diam)
Arc voltage	32-35	32-35
Travel speed, ipm	7-10	7
Oscillation	None	None
Joint restraint	Full restraint	Full restraint
Preheat	None	None
Interpass temperature, °F	350 max	350 max
Post-heat treatment	None	None

TABLE 15.–*Mechanical Properties of Submerged-Arc Welds in Nickel and Nickel-Base Alloys*

Base metal	Weld metal		Transverse tension tests	
	Ultimate tensile strength, psi	Percent elongation in 2 in.	Ultimate tensile strength, psi	Location of failure
Nickel	57,200	36.4	59,600	- -
Monel	68,200	48	- -	- -
	[a]74,200	[a]61		
Inconel	[b]95,000	[b]40	[c]84,400	Weld
	- -	- -	[d]83,900	Weld

[a] Monel Filler Metal 60, submerged-arc-welding flux Incoflux 5.

[b] Inconel Filler Metal 82, submerged-arc-welding flux Incoflux 4.

[c] 1/4 in.

[d] 1/16 in.

Electron-Beam Welding

Electron-beam welding also is a useful process for joining nickel and nickel-base alloys. The process is applicable to a wide range of thicknesses from about 0.0015 in. to over 2 in. One major advantage is that welding is generally performed in a high-vacuum chamber, although electron-beam welding in partial vacuum is becoming more widespread (ref. 59). Where welding is performed in a high vacuum, contamination of the weldment from external sources is essentially nonexistent. All electron-beam welding is done using mechanized equipment. Electron-beam welds made with high-power-density-type equipment exhibit a characteristic of high depth-to-width ratio for both the weld metal and the heat-affected zone. This characteristic is advantageous from the standpoint of minimizing the distortion that normally

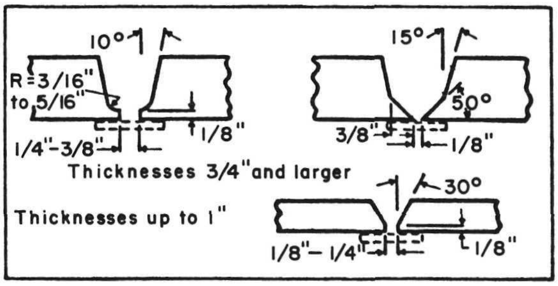


FIGURE 32.–Typical butt-weld joint design for submerged-arc welding.

accompanies welding. It may also result in welds whose properties are not altered significantly from those of the base material. Investigations of electron-beam welding in open-air atmospheres also have been made (refs. 60 through 62).

In electron-beam welding, the heat required to melt the joint edges is supplied by a focused electron beam generated in an electron gun. This beam is focused and accelerated so that it strikes the joint line parallel to the existing interface. The electron beam can concentrate a large amount of energy in a spot diameter of about 0.010 inch or less (ref. 63). Energy densities range from about 5000 to 40 000 kW/in.^{2}, compared with about 100 kW/in.^{2} in tungsten-arc welding. Electron-beam welds are usually made without the addition of any filler wire.

Equipment.—Any type of electron-beam-welding unit can be used effectively for welding nickel and nickel-base alloys. Units that characteristically produce a low-power-density beam will not produce the high depth-to-width-type weld that can be produced on high-power-density equipment. Historically, electron-beam-welding equipment is classified in two divisions—high-voltage welding, performed in the 75 000- to 150 000-volt range, and low-voltage welding, performed in the 15 000- to 30 000-volt range. Normally, the high-voltage equipment produces much narrower heat-affected zones than low-voltage equipment (ref. 64). A schematic diagram of an electron-beam-welding machine is shown in figure 33 (ref. 65). Acceptable welds, however, can be made with either type of equipment. Special electron-beam units using either clamp-on-type chambers or special electron-gun assemblies designed to allow the electron beam to be projected into the air have not normally been used on nickel alloys. Clamp-on-type chambers may be quite useful in the joining of long lengths of special shapes.

Fixtures are needed to hold the parts in position, but they need not be as heavy as those used for other welding methods (ref. 66). Copper chill bars can be used to restrict the width of the heat-affected zone and to confine and control the fusion-zone geometry (ref. 32).

Materials.—No special material requirements are involved in electron-beam welding. Because of the very high solidification rates associated with most electron-beam welding, however, it is imperative that the weld area of the parts to be joined is very clean prior to welding. The high freezing rates associated with electron-beam welding allow very little time for the escape of any gaseous impurities during welding. Thus, it might be anticipated that electron-beam welds could be somewhat more prone to porosity formation than other types of fusion welds. To date, there is very little evidence either to substantiate or to refute this supposition.

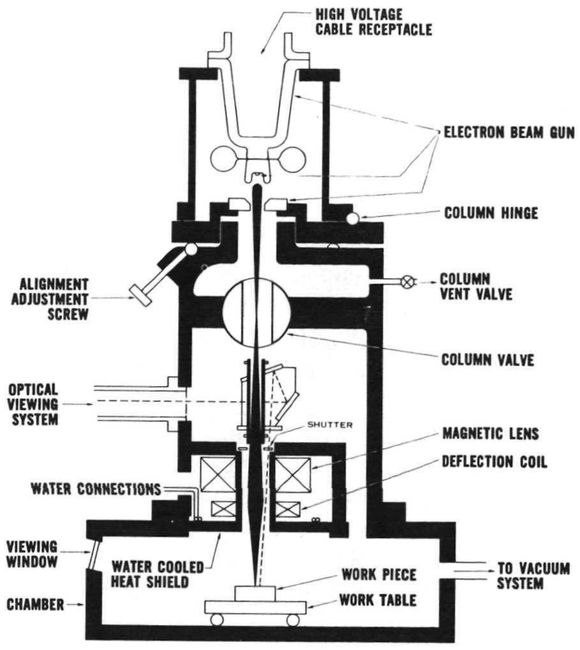


FIGURE 33.—Electron-beam welding machine.

Welding conditions.—Welding conditions used in electron-beam welding are dependent on material thickness and the type of electron gun used. For a given thickness of material, various combinations of accelerating voltage, beam current, and travel speed are satisfactory. Electrical parameters do not adequately describe the heat-input characteristics of the beam since these characteristics are affected significantly by the focus of the beam. Measurements of beam diameter are difficult to make under production conditions so that the transfer of welding parameters between different equipment units is very difficult. Fortunately, suitable welding parameters can generally be developed with only a very few trials.

In very thick material, the first pass made to penetrate the joint completely sometimes is undercut along both edges of the weld metal. This undercutting can be eliminated by a second weld pass made at somewhat lower energy levels with a slightly defocused beam. However, undercutting has been largely reduced by making minor adjustments in travel rate (ref. 32). The underside of electron-beam welds also may exhibit an undesirable contour. Some type of metal-removal operation is generally required to produce an acceptable underside contour.

The flat welding position is generally used in electron-beam welding. The welding positions that can be used are limited by the versatility of the available welding equipment. Obtaining good shielding is not a factor affecting the selection of the welding position during electron-beam welding.

Properties.—Information on properties of electron-beam welds in René 41 are given in table 16. Data on other alloys are not available.

Applications.—Electron-beam welding has been used for joining several nickel-base alloys. Applications include pressure-vessel spheres, precision assemblies, structural shapes, and other products.

Electron-beam welding has proved economical for making repairs on close-tolerance parts that might otherwise have to be scrapped (ref. 63). Figure 34 shows a modified-Tee weldment made by electron-beam-welding two pieces of Monel K-500 (ref. 68). Typical configurations for aerospace use also have been fabricated experimentally by nonvacuum techniques (ref. 60). Nonvacuum electron-beam welds in René 41 sheet have been subjected to various heat treatments before and after welding. Welding was performed in 0.010-, 0.187-, and 0.400-in.-thick material with varying degrees of success, depending on the variations in procedures. Porosity seems to be a major problem, but some control over porosity can be achieved. Copper backup bars successfully reduced porosity and undercut, particularly in thick sections. Aerospace configurations that have been welded with the nonvacuum electron-beam process included a bimetal turbine wheel consisting of René 41 and Udimet 500 turbine-blade rings welded to an A-286 alloy hub, and René 41 alloy channel sections. The Udimet 500-A286 turbine wheel is shown in figure 35 after nonvacuum electron-beam welding (ref. 60).

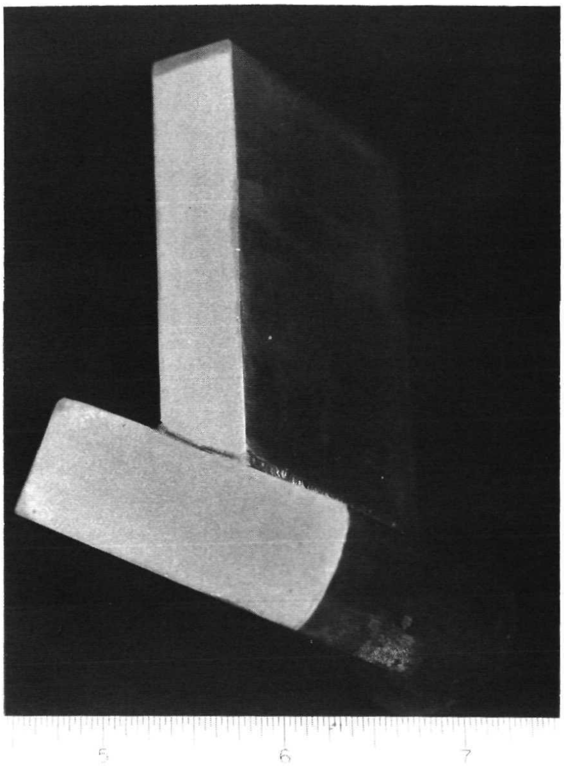


FIGURE 34.—Monel K-500 weldment made by electron-beam welding.

TABLE 16.—*Mechanical Properties of Electron-Beam Welded Nickel-Base Alloys*

Alloy	Thickness, in.	Condition[a]	Tensile strength, ksi	Yield strength, ksi	Elongation, % in 1 in.	Reduction in area, %	Reference
René 41	1	SWA	174.0	141.5	8.1	9.8	67
René 41	1	SWSA	183.2	146.5	10.0	9.5	67
René 41	1.5	SWSA	186.5	136.7	15.5	17.8	67
René	1.75	SWSA	181.5	123.9	7.0	10.0	67
Inconel 718	--	WSA_1	177.5	155.2	13.3	23.0	49

[a] S—Solution for 1 hr at 1950° F, air cool
A—Age for 16 hr at 1400° F, air cool
W—Weld
A_1—Age 8-10 hr at 1350° F, furnace cool to 1200° F, hold for total aging time of 12 hr

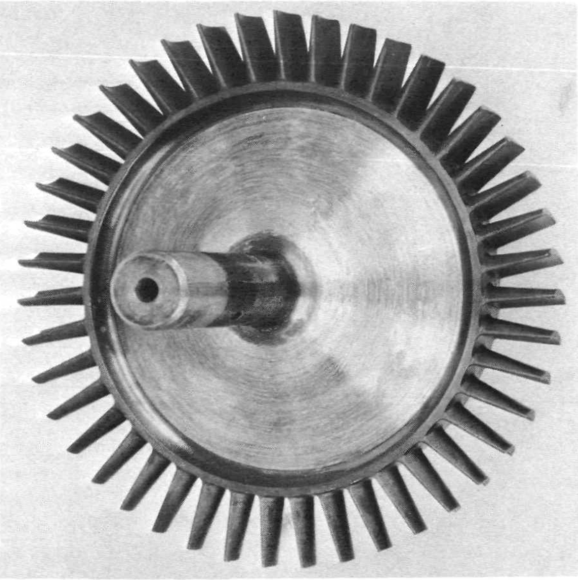


FIGURE 35.–Bimetal turbine-wheel configuration for electron-beam welding.

Plasma Arc Welding

Plasma arc welding is a method of inert-gas welding with a transferred constricted arc. The process is now used to replace GTA welding in a number of industrial applications. It offers greater welding speeds at lower current, better weld quality, greater arc stability and is less sensitive to process variables than GTA welding in certain applications. In many cases the costs also are lower. (refs. 69 to 71).

The general characteristics and electrical circuit used for plasma arc welding are shown schematically in figure 36 (ref. 69). The arc plasma, nozzle gas, or orifice gas indicated in the figure is supplied through the torch at a flow rate of 1 to 15 ft^3/hr. Suitable gases are argon, argon-hydrogen mixtures, and argon-helium mixtures, depending on the application. The gas flowing through the arc-constricting nozzle protects the electrode from contamination and provides the desired composition in the plasma jet.

Relatively low plasma-gas-flow rates are used to avoid turbulence and undesirable displacement of the molten metal in the weld puddle. Since the low gas-flow rates are not adequate for shielding the puddle, supplementary shielding gas is provided through an outer gas cup. The type and flow rate of supplemental shielding gas are determined by the welding application. Typical arc- and shielding-gas-flow rates are 4 and 35 ft^3/hr, respectively.

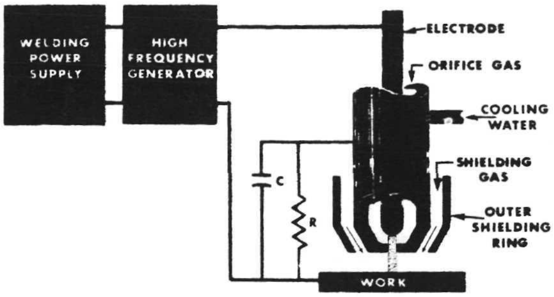


FIGURE 36.–Plasma arc welding.

In plasma arc welding, the term "keyhole" has been applied to a hole that is produced at the leading edge of the weld puddle where the plasma jet displaces the molten metal, and allows the arc to pass completely through the workpiece. As the weld progresses, surface tension causes the molten metal to flow in behind the keyhole to form the weld bead.

Keyholing is one of the chief differences between the plasma-arc and GTA processes. Presence of the keyhole, which can be observed during welding, gives a positive indication of complete penetration. It is used most effectively on nickel-base alloys in the thickness range of 0.090 to 0.300 in. (ref. 70). For materials thinner than 0.090 in., excessive drop-through and burn-through become problems. Excessive drop-through is also the limiting factor with materials thicker than about 0.300 in. In both cases, the surface tension is inadequate to support the molten metal. Plasma-arc welds can be made in thinner materials at very low currents, however, and in thicker materials with multipass techniques.

Equipment.–A mechanized plasma-arc-welding torch is shown in figure 37 (ref. 69). This torch can be operated with either straight- or reverse-polarity connections at arc currents up to 450 A. Water-cooled power cables are connected at the top of the torch to supply power and cooling water to the electrode. Fittings are provided on the lower torch body for the plasma-gas hose, the shielding-gas hose, and cooling water for the nozzle.

The two types of electrodes used in the plasma-arc torch are shown in figure 38 (ref. 69). The tungsten electrode shown on the left is used for straight-polarity operation and is available in 1/16-, 3/32-, and 1/8-in. diameters, depending on the current to be used. A water-cooled copper electrode, shown on the right in figure 38, is used for reverse-polarity operation.

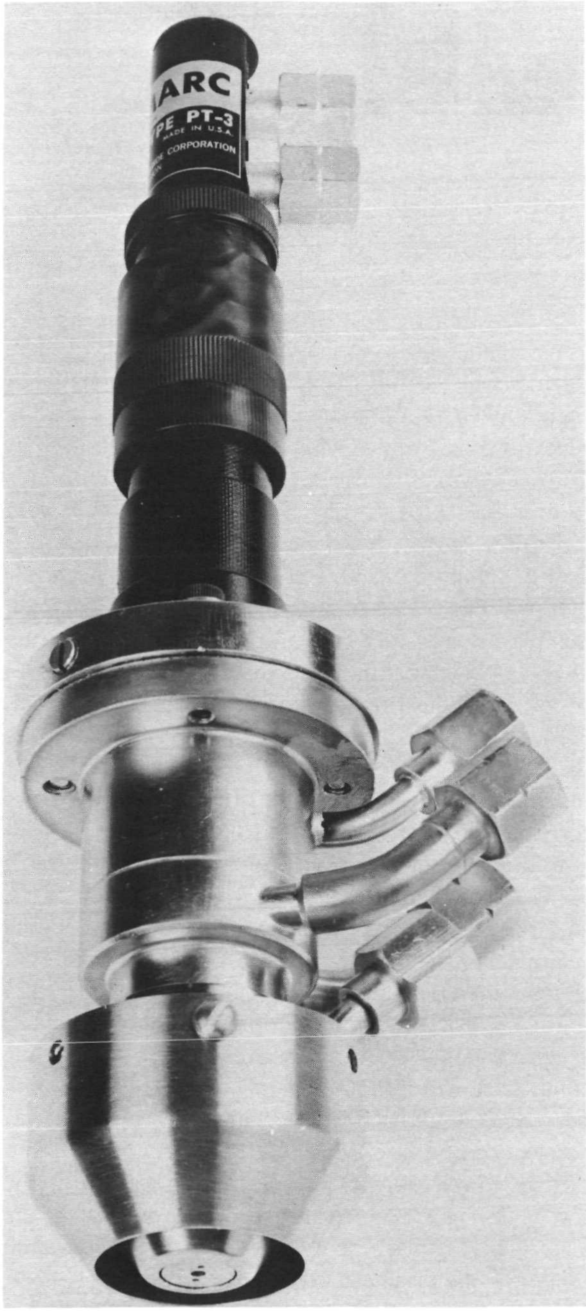


FIGURE 37.–Mechanized plasma-arc-welding torch.

Several types of multiport nozzles are available for different welding applications. The diameter of the nozzle's central port depends on the welding current and gas-flow rate. The spacing between the side gas ports is influenced by the thickness of the workpiece.

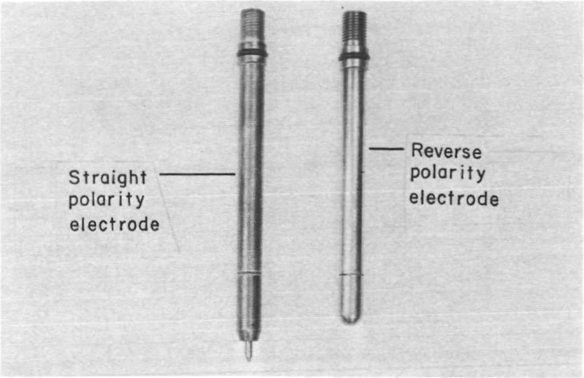


FIGURE 38.–Tungsten and copper electrodes for straight- and reverse-polarity operations.

Welding conditions and weld properties.–Filler metals are used with plasma arc where more than one weld pass is required; primarily with material too thick to be welded by the keyholing technique (ref. 70). In these cases, a keyhole root pass is made and subsequent passes are made with filler metal to fill the joint. Lower travel speeds are recommended on these filler-metal passes to avoid porosity problems. A reduced nozzle-gas flow rate may also help to reduce porosity. The use of helium for both the nozzle and shielding gases allows higher travel speeds during filler-metal passes without sacrificing quality.

For joint thicknesses that can be welded in a single pass, a square butt-joint design is best. Where filler-metal passes are required, a single-V joint with a 3/16- to 1/4-in. land and a 60° to 75° angle is recommended (ref. 71).

Plasma-arc welds can be made using either high- (150-300 amp) or low- (0.1-15 amp) current inputs depending on material thickness (ref. 71). Typical parameters for a variety of nickel-base alloys in different thicknesses are shown in table 17. Because of its high stability, the plasma arc can be operated at currents as low as 0.1 amp. This makes plasma arc suitable for welding foil materials as thin as 0.001 in.

Typical mechanical properties of plasma-arc welds in nickel-base alloys are shown in table 18.

Applications.–Plasma arc welding is in use for making circumferential joints in 70 to 30 copper nickel, Monel, and stainless steel pipe where the pipe can be rolled. It has also been used to weld stainless steel and nickel wire and nickel-base foil material in various applications. Reported advantages of the process compared with GTA welding include simplified joint preparation, higher welding speed, and backing-ring elimination.

TABLE 17.–*Plasma-Arc Welding Conditions for Nickel and Nickel-Base Alloys*

Alloy	Thickness, in.	Type of joint	Electrode diameter, in.	Travel speed, ipm	Arc current, amp	Arc voltage, volts	Gas and flow rate, ft^3/hr[a]		Reference
							Nozzle	Shielding	
Inconel 718	0.250	Square butt	1/8	6	150	23.8	--	50-A	72
Inconel 718	0.012	Square butt	--	15	6	--	20-AH	--	71
René 41	0.062	Square butt	3/32	32	90	28.5	--	50-A	72
René 41	1/8	Square but	--	7.5	100	--	15-A	15-A	71
René 41	0.008	Edge	--	7	5	--	--	20-A	71
Nickel 200	0.287	Square butt	--	10	240	31.5	10-AH	45-AH	70
Nickel 200	0.125	Square butt	--	20	160	31.0	10-AH	45-AH	70
Monel 400	0.250	Square butt	--	14	210	31.0	12.5-AH	45-AH	70
Inconel 600	0.260	Square butt	--	17	210	31.0	12.5-AH	45-AH	70
Inconel X	0.250	Square butt	--	14	230	--	14-AH	--	71
Haynes 25	0.109	Square butt	--	36	165	--	10-AH	--	71
Hastelloy X	0.020	Square butt	--	10	10	--	--	20-A	71
Hastelloy X	0.005	Square butt	--	10	4.8	--	--	20-A	71

[a] A–argon.
AH–95-percent argon–5-percent hydrogen.

TABLE 18.–*Properties of Plasma-Arc Welds in Nickel and Nickel-Base Alloys*

Alloy	Thickness, in.	Ultimate strength, ksi	Yield strength, 0.2%, ksi	Joint efficiency, %	Elongation, % in 2 in.	Reference
Inconel 718	0.250	185.6	153.8	98.0	17.2	72
Nickel 200	--	59.5	--	98.0	31.0	70
Inconel 600	--	82.5	--	91.5	19.0	70

Resistance Spot Welding

Resistance spot welding has been used extensively for joining nickel and its alloys in a wide range of thicknesses. The thickness that can be welded in any given application is limited only by the power and force capacity of the equipment. In the process, all the heat required for joining is supplied by the passage of an electric current between two opposed electrode tips that contact the surfaces of the parts to be joined. In conventional spot-welding practice, a localized volume of metal at the sheet-to-sheet-interface region melts, and then solidifies to form the weld. There are techniques also to make welded joints in which no melting is involved; such welds may be called solid-state welds. Joints of this type are similar to conventional resistance welds except that no molten metal is formed during the joining process. Even conventional spot welds in many materials contain an area around the molten nugget that is diffusion-bonded. The bond in this area may be strong enough to make a significant contribution to the load-carrying capacity of the spot weld.

Nickel and nickel-base alloys are spot welded in much the same manner as other metals. In many respects, these alloys are easy to resistance spot-weld. The configurations involved in spot welding and the relatively short time periods used with the process tend to preclude any contamination from the atmosphere. As a result, there appears to be little need to consider auxiliary shielding of nickel during resistance spot welding. The thermal and electrical conductivities, and the mechanical properties of nickel and nickel-base alloys vary depending on the alloy and its condition. Conditions for spot welding are adjusted to account for these variations. For example, electrical resistivity is low for low-carbon nickel and high for Inconel X. The low-resistivity materials require higher current, but usually less pressure. Several combinations of welding variables can produce similar and acceptable results.

Equipment.—Nickel and nickel-base alloys have been welded successfully on almost all types of conventional resistance-spot-welding equipment. Spot-welding equipment normally provides accurate control over the basic spot-welding parameters: weld current, weld time, and electrode force. Various data indicate that each of these parameters may vary to a certain degree without appreciably reducing weld quality. It is desirable, however, to have enough control over the parameters to obtain reproducible results, once the optimum settings are obtained for a given application. Thin sheet (under about 0.035 in.) can be welded with most of the 30-kVA, 60-cycle, single-phase, rocker-arm-type machines. For thicker sheet and for the harder alloys, larger press-type machines are more suitable because higher currents and electrode forces are required. Upslope controls are used to help prevent expulsion, but downslope and postweld heat controls have not demonstrated any advantages when used in welding these alloys. No significant changes in welding characteristics or static weld properties have been reported that can be attributed to the use of any specific type of resistance-welding equipment.

Electrode alloys generally recommended for spot-welding nickel and its alloys include RWMA classes 2 and 3 and a molybdenum-tipped electrode. In conventional practice, internally cooled electrodes improve tip life. For small parts, the electrodes often are not water cooled. Both flat-face and spherical-radius tip geometries are used. Full-domed electrodes should not be used for high-nickel-base alloys because these alloys resist indentation and prevent proper forging. Although weld strengths may be high when domed electrodes are used with certain nickel-base alloys, the resulting welds show cracks extending inward from the weld periphery. These cracks are caused by the reduced pressure exerted by domed electrodes at the edges of the weld nugget (ref. 73). With the soft nickel or nickel alloys, a low level angle will reduce sticking to a minimum. The amount of indentation and weld strength when these alloys are spot welded can vary from weld to weld because of slight variations in sheet temper.

When designing sheet-metal assemblies for resistance spot welding, the factors that should be considered are the same as those for other materials. They include

(1) Joint overlap—A sufficient amount of overlap should be provided to contain the weld. Suggested minimum joint-overlap values range from 0.250-in. for 0.005-in.-thick sheets to 1.875 in. for 0.125-in.-thick sheets.

(2) Accessibility—Spot welds should be placed in locations that are accessible with the equipment to be used.

(3) Flatness—Forging pressure will be inadequate if part of it is used to form the parts to provide proper contact.

(4) Weld spacing—Insufficient spot-weld spacing causes reduced current at the desired location due to shunting of some current through previously made welds. Recommended minimum spot-weld-spacing values for annealed nickel range from 0.50 to 2.25 in. for 0.005 and 0.125-in.-thick sheets, respectively.

Welding conditions.—Resistance spot-welding conditions are controlled primarily by the total thickness of the assembly being welded, and to a rather large degree by the welding machine being used. Similar welding conditions may be perfectly suitable for making welds in the same total thickness where the number of layers differs significantly. However, for any given thickness or total pileup, various combinations of welding current, time, and applied force may produce similar welds. Other variables such as electrode size and shape are important in controlling such characteristics as metal expulsion, sheet indentation, and sheet separation. The use of slope controls to obtain preheat, postheat, and additional weld forging is reported for some high-strength alloys such as René 41 (refs. 74 and 75).

Nickel and nickel-base alloys that have properties similar to steel behave like steel when welded. However, most nickel alloys are harder and stronger than low-carbon steel, particularly at elevated temperatures. Greater pressures are therefore required during spot welding. The time of current flow should be as short as possible. For very thin sheet and fine wires, weld time usually is less than 2 cycles and often is less than 1 cycle (60-cycle current). Current is set at a value that is somewhat above the value that produces a weak or just "stuck" weld, but below values that produce expulsion. Upslope controls that gradually increase current to final values are used to help reduce expulsion.

Table 19 lists spot-welding conditions used for nickel and some selected nickel-base alloys.

TABLE 19.—*Resistance-Spot-Welding Conditions and Properties for Nickel and Selected Nickel-Base Alloys*

Thickness, in.	Dome diameter, in.	Electrode force, lb	Weld time, cycles	Welding current, amp	Fused zone or weld diameter, in.	Average shear strength, lb	Tension/ shear ratio, %	Reference
Annealed nickel sheet								
0.005/0.005	5/32	100	3	7,100	0.10	40	--	76
0.031/0.031	3/16	900	4	15,400	0.18	950	--	76
0.125/0.125	3/8	3300	20	31,000	0.37	7000	--	76
TD nickel								
0.050		(Solid-state, back brazed)				1585/1595	--	34
0.050		(Fused nugget, back brazed)				1580/1590	--	34
Annealed Monel sheet								
0.005/0.005	5/32	220	2	5,000	0.10	70	--	76
0.031/0.031	3/32	700	12	10,000	0.17	1056	--	76
0.125/0.125	1/2	5000	30	30,000	0.47	7300	--	76
Annealed Inconel sheet								
0.005/0.005	5/32	300	2	7,000	0.11	90	--	76
0.031/0.031	3/16	700	12	6,700	0.18	1150	--	76
0.125/0.125	7/16	5270	30	20,100	0.44	8000	--	76
Hastelloy R-235								
0.030/0.030	7/32	[b]1200/2700	[b]8/2/2	20,000	0.156	1255	64.6	9
0.063/0.063	5/16	[a]2000/4000	[b]10/2/8	21,500	0.250	3268	80	9
0.094/0.094	3/8	4000/8000	[b]10/2/4	28,600	0.344	5780	67.5	9
Hastelloy X								
0.030/0.030	7/32	[a]900/2500	[b]8/2/2	18,900	0.156	1379	63.2	9
0.063/0.063	5/16	[a]2500/4000	[b]10/2/10	21,700	0.266	3286	59.4	9
0.094/0.094	3/8	[a]4400/7500	[b]9/2/4	30,500	0.344	4816	89.0	9
Inconel X								
0.010/0.010	5/32	300	2	730	0.11	[c]320/460	[c]81.4/39.2	77
0.031/0.031	7/32	1750	8	9,900	0.17	[c]1400/1800	[c]71.5/37.7	77
0.062/0.062	5/16	4400	14	16,350	0.29	[c]4300/5600	[c]79.1/42.8	77

[a] Top value—welding force, bottom value—forging force.

[b] Weld time/cool time/number of pulses.

[c] Top value—as welded; bottom value—after aging at 1300° F, 4 hr.

Properties.—The quality of spot welds is measured by several testing methods. In addition to cross tension and tension-shear-strength requirements, many specifications, such as company specifications and the military specification MIL-W-6858B (ref. 78) place certain restrictions on weld penetration, sheet separation, electrode indentation, and weld diameter (ref. 74).

Many properties and characteristics of resistance spot welds in nickel and nickel-base alloys have been determined. Those that are most common are listed in table 19. Additional information is available in the published welding literature. In many instances, complex testing procedures are required to determine the behavior of spot welds under special conditions. The fatigue properties of spot welds are low, but this behavior is more characteristic of the joint type than of the material.

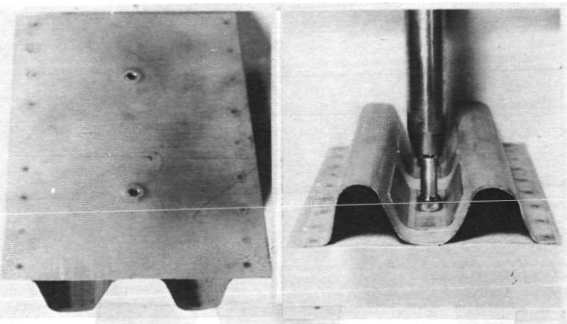
Applications.—Resistance spot welding has been used for many years for joining the familiar nickel and nickel-base alloys. It is an important joining method for these alloys, for the newer nickel-base alloys, and for applications to new products. The process is especially important in electronic and aerospace components. Spot welding is used principally for joining sheet metals in thicknesses ranging from about 0.001 to 0.250 in.

Extensive information is available in the published literature on spot welding of the nickel-base alloys. Much effort has been placed on spot-welding developments for some high-strength alloys. Spot welding of René 41, for example, was investigated in conjunction with the X-20 airplane program, and special techniques were developed (ref. 74). René 41 required preheat and rigid control of heat buildup and molten nugget formation during welding. In addition, forging pressure was needed during a postheat time to prevent weld cracking. When these techniques were observed during welding, a diffusion-bonded ring was formed around the molten weld metal, which helped minimize expulsion. These techniques also helped eliminate weld-metal-shrinkage cracks. The effects of weld quality on static mechanical properties, fatigue properties, and vibration testing at room and elevated temperatures were determined. Thickness combinations greater than 2.5 to 1 were difficult to weld by conventional techniques because of insufficient penetration into the outer sheet (ref. 75). Metal shims permit successful joining of unequal thicknesses up to 8 to 1. Past experience has shown, however, that resistance welding of alloys like René 41 and Hastelloy X can be performed with conventional equipment (ref. 33). In the spot welding of these alloys, oscillographic equipment should be used to insure that the machine is set up and operating properly. Metal fit is extremely important. If any portion of the electrode force is used to produce metal contact, weld properties will be reduced. Lack of complete cleanliness also results in a deterioration of weld properties.

TD nickel has been resistance spot-welded using both solid-state and fusion techniques (ref. 32). This alloy has very desirable properties for aerospace applications. The properties of spot welds for some applications of TD nickel have been cause for concern, however, partly because of the unfavorable stress pattern around the weld. Back-brazing techniques have been successful in alleviating this condition in prototype jet-engine components when the resistance welds are subject to fatigue. This technique is promising for making usable joints with TD nickel.

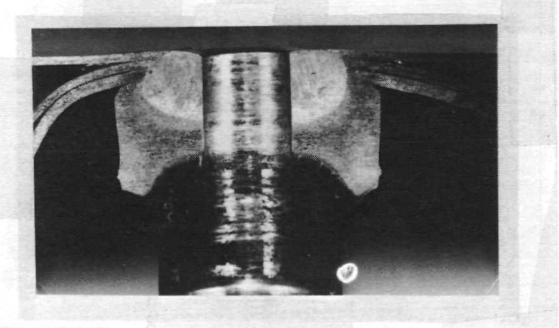
Resistance spot welding has also been used to join interconnecting nickel ribbon to electrical component leads in the world's first orbiting telescope (ref. 79). There are approximately 30 000 welded current interconnections in the control electronics package of the instrument. After one telescope had been on qualification testing for over two years and another tested and orbited, there had been no failures attributable to the welded interconnections.

Additional spot-welding applications for nickel and nickel-base alloys are illustrated in figures 39 (ref. 75), 40 (ref. 33), and 41 (ref. 74).



a. Top View of Panel

b. Bottom View of Panel Ready for Welding



c. Cross Section of Spot-Welded Fitting

FIGURE 39.—M-252 port-fitting attachment spot-welded to a three-ply pileup of René 41.

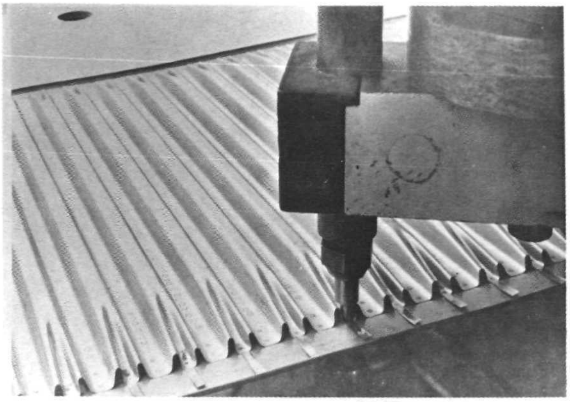


FIGURE 40.–Spot-welding creased-edge corrugation to skin and doubler.

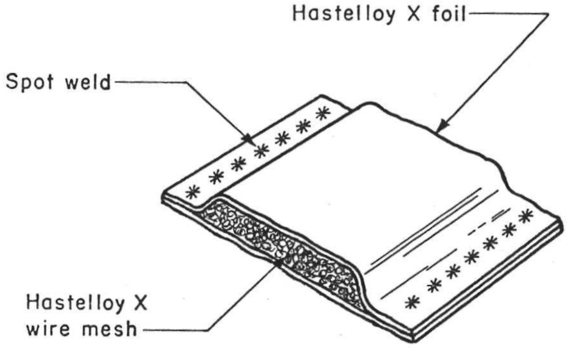


FIGURE 41.–Spot-welded window-seal assembly for supersonic aircraft.

Roll Resistance Spot Welding

Roll resistance spot welding is similar in most respects to standard spot welding. The major difference is that wheel-shaped electrodes are used in roll resistance spot welding, instead of the cylindrical-type electrode used in conventional spot welding. The use of the wheel electrodes provides a convenient means of indexing the parts between each individual spot weld. Rotation of the wheels is intermittent with the wheel electrodes being in a fixed position during the actual welding cycle. Electrode wear is more uniformly distributed with a wheel-type electrode than it is with a conventional cylindrical electrode; thus, it is possible to make many more welds without dressing of the electrodes. However, there is somewhat less flexibility with roll-spot-welding techniques than with those of conventional spot welding.

Equipment for roll spot welding differs from conventional spot-welding equipment primarily in that provision must be made to accommodate the wheel-shaped electrodes. Also, a suitable drive and indexing mechanism must be provided. Usually, however, roll resistance spot welding is performed with resistance-seam-welding machines.

Roll-spot-welding conditions have not been found in the literature. It is expected that these conditions would be very similar to those of conventional spot welding.

Resistance Seam Welding

Seam welding also is similar to spot and roll spot welding. Its principal advantage is that it can be used to produce leaktight joints. The principal disadvantage is that there is much more distortion with seam welding than with other types of resistance welding.

Equipment.–In seam welding, wheel-type electrodes instead of spot-welding electrodes are used. Individual overlapping spots are created by coordinating the welding-current time and wheel rotation. Seam welds can be made with conventional spot-welding techniques; however, it is much more common to use commercially available equipment designed specifically for seam welding. In the process, the wheels usually can be rotated continually or intermittently. The use of continuous seam welding limits the weld-cycle variations that can be used. For example, a forge-pressure cycle is not possible during continuous seam welding because of the continuous rotation of the electrodes. Forging pressure can be used with intermittent motion.

Weld conditions and properties.–Selected data on seam-welding conditions and characteristics of seam-welded joints are given in table 20 (ref. 9). Additional information on mechanical properties of seam welds in nickel-base alloys is available in published literature (refs. 9, 19, and 74 through 78). The high-strength alloys such as Hastelloy R-235 and Inconel X usually are welded by using forging force and intermittent drive. When the completed weldment is intended for applications requiring leaktight seams, suitable pressure or leak tests are used. Many of the tests applicable to spot welds also are applicable to seam welds.

Applications.–Seam welding is used for welding sheet-metal components requiring gastight or leaktight seams. Nickel and many of the nickel-base alloys

TABLE 20.–*Resistance-Seam-Welding Conditions for Selected Nickel-Base Alloys*

Thickness, in.	Wheel		Electrode force, lb	Timing		Weld spacing, welds per in.	Wheel speed, in./min	Weld current, amp	Width of fused zone, in.	Weld overlap, percent
	Face width, in.	Radius, in.		On, cycles	Off, cycles					
Monel 400										
0.031/0.031	3/16	6	700	4	12	12	19	10,000	0.15	20
0.062/0.062	3/8	6	2500	8	12	9	20	19,000	0.17	10
Inconel 722										
0.031/0.031	3/16	3	2300	4	8	10	30	9,700	0.17	20
0.062/0.062	1/4	6	[a]4000	8	16	12	12.5	14,400	0.24	10
Inconel X-750										
0.031/0.031	3/16	3	2300	4	8	10	30	8,500	0.17	- -
0.062/0.062	3/16	6	[a]4000	8	16	12	12.5	10,300	0.18	- -

[a] Not optimum but satisfactory where sufficient force is not available.

have been resistance-seam-welded but, unfortunately, only limited information is available in the published literature. Recommended seam-welding schedules for selected thicknesses of Monel and Inconel X-750 and-722 are given in table 20 (ref. 9). Most of the available published literature contains information pertaining to the development of seam-welding schedules for particular nickel-base alloys (refs. 74 through 76 and 79). It seems that suitable seam-welding schedules can be developed when needed for nickel-base alloys.

Distortion found in seam-welded thin-sheet assemblies can be minimized or eliminated by using special tooling or heat-treating techniques. For weld Inconel X-750, distortion can be minimized by heat treating before welding. Reaging after welding improves joint properties (ref. 80).

Flash Welding

Flash welding is used extensively for joining nickel and nickel-base alloys. Typical products include Monel pickling chains and hot-water tanks, and Inconel rings for jet engines.

In two respects, flash welding is better adapted to the high-strength, heat-treatable alloys than are arc, spot, or seam welding. First, molten metal is not retained in the joint, so cast structures that might be corroded are not present. Second, the hot metal in the joint is upset, which may improve the ductility of the heat-affected zone. Flash welding has several other important advantages. Welding speeds are very rapid, heavy sections can be joined, and high production rates can be achieved. Filler metal is not added. Extruded shapes can be flash-welded and, with suitable designs, machining costs can be reduced.

Equipment.–Equipment for flash welding is considerably different from equipment used for spot or seam welding. The parts are held firmly in two copper-alloy dies, one or both of which are movable. Current from a welding transformer passes through the dies and into the work. With the current on, the parts are advanced toward each other. At their first contact, the current causes melting of the metal and violent expulsion, which continues until the base metal is heated to welding temperature. Then, the parts are forged together to complete the weld. Welding current usually is shut off at the time forging takes place.

The machine capacity required to weld nickel and nickel alloys does not differ greatly from that required for steel. This is especially true for transformer capacity. The upset-pressure capacity for making flash welds in nickel-base alloys is higher than that required for steel. Figures 42 and 43 show the transformer and upset capacity required for welds of

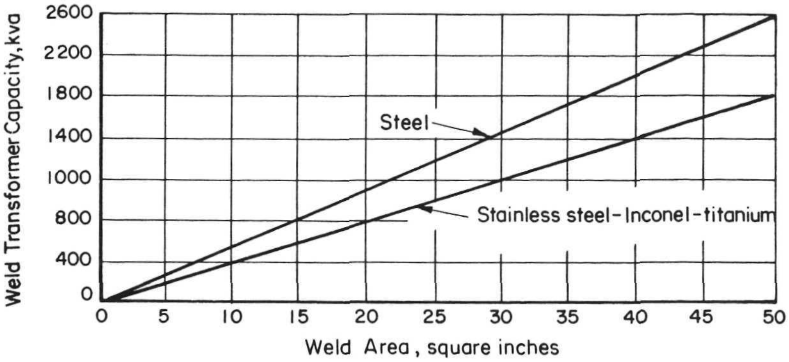


FIGURE 42.–Transformer capacity versus weld area for flash welding.

different cross sectional areas in Inconel (ref. 81). Transformer-capacity requirements vary from one machine to another, depending upon the coupling between the parts and transformer.

Joint design and joint preparation.–Joint designs for nickel flash welds are similar to those used for other metals. Flat, sheared, or saw-cut edges and pinch-cut rod or wire ends are satisfactory for welding. For thicker sections, the edges are sometimes beveled slightly. The overall shortening of the parts due to metal lost during welding should be taken into account so the finished parts will be the proper length. Figure 44 shows the metal allowances used in making flash welds in several materials including Inconel (ref. 80). The allowances include the metal lost in the flashing and upsetting operations.

The flash-welding conditions that are of greatest importance are flashing current, speed and time, and upset pressure and distance. With proper control of these variables, molten metal, which may be contaminated, is not retained in the joint, and the metal at the joint interface is at the proper temperature for welding. Generally, high flashing speeds and short flashing times are used when it is desirable to minimize weld contamination. Also, the use of a parabolic flashing curve is more desirable than the use of a linear flashing curve because maximum joint efficiency can be obtained with a minimum of metal loss.

Flash-welding variables vary from machine to machine and application to application. Table 21 illustrates welding conditions for several nickel-base alloys (ref. 9). Welding current is not given, but welding current and arc voltage depend on the transformer tap that is used.

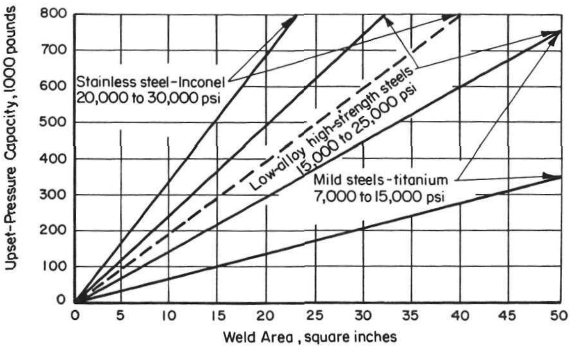


FIGURE 43.–Maximum machine upset-pressure requirements versus weld area for flash welding.

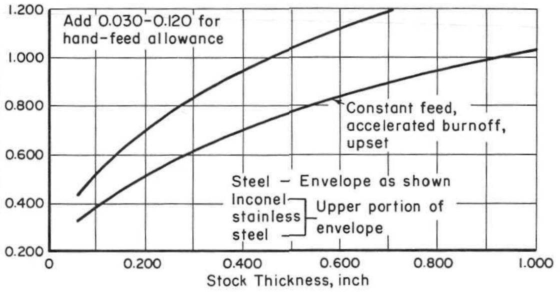


FIGURE 44.–Total metal allowance versus stock thickness.

Properties of flash welds.–Flash welds that have mechanical properties approaching those of the base metals are being regularly produced in conventional machines. Joint efficiencies of 95 percent or better are common for flash welds.

The static-tension-test properties of flash-welded joints are summarized in table 21 (ref. 76). The static properties of flash-welded joints in nickel and nickel-base alloys are good. Most tension specimens fail away from the weld centerline with strengths that almost equal or exceed those of the base metals.

TABLE 21.–*Welding Conditions and Properties for Flash Welds in Nickel and Some Nickel-Base Alloys*

Material	Rod diameter, in.	End preparation[a]	Flashing distance, in.	Flashing time, sec	Duration during upset, cycles	Current upset distance, in.	Watt hr/weld	Weld tensile strength, psi	Rod strength, psi	Reference
Nickel	1/4	Pointed	0.442	2.5	1-1/2	0.125	2.15	58 000	65 100	76
Nickel	3/8	Pointed	0.442	2.5	2-1/2	0.145	4.87	65 600	66 500	76
Monel	1/4	Pointed	0.442	2.5	1-1/2	0.125	1.93	68 500	70 500	76
Monel	3/8	Pointed	0.442	2.5	2-1/2	0.145	5.55	80 300	84 700	76
"K" Monel	1/4	Pointed	0.442	2.5	1-1/2	0.125	2.02	93 900	100 000	76
"K" Monel	3/8	Pointed	0.442	2.5	2-1/2	0.145	4.79	98 800	99 000	76
Inconel	1/4	Pointed	0.442	2.5	1-1/2	0.125	2.15	101 200	109 800	76
Inconel	3/8	Pointed	0.442	2.5	2-1/2	0.145	5.19	102 000	106 000	76
TD nickel	[b]0.050	--	--	--	--	--	--	[c]4 100	--	29
TD nickel	[b]0.125	--	--	--	--	--	--	63 800	--	82
TD nickel	[b]0.125	--	--	--	--	--	--	8100/9060	--	82

[a] 110° included angle. [b] Sheet thickness. [c] At 2000° F.

Applications.–Flash welding has been used for joining nearly all of the nickel-base alloys in a variety of forms and shapes (refs. 76 and 83). It is used for butt-welding sheet, strip, rod, and extruded sections. The process also is used for joining rings such as jet-engine rings, wheel rims, and chain links. Applications of the process for joining some of the nickel-base alloys are described below.

Flash welding is used extensively for fabricating rings and wheels. A typical jet-engine ring fabricated by flash welding is illustrated in figure 45 (ref. 83). These rings are fabricated by ring rolling of extruded sections and flash welding.

TD-nickel has been flash-welded experimentally to develop information on flash-weld performance at high temperatures (ref. 32). Welding conditions were developed that produced good welds that had 100-percent joint efficiency. However, joint efficiency in the proposed operating temperature range is only 30 to 40 percent because of loss of thoria dispersion in the weld zone and reorientation of grains in the heat-affected zone. Agglomeration of thoria and delamination in the weld area also cause problems.

Magnetic-Force Welding

Another process that produces a diffusion weld and resembles flash butt welding in principle is magnetic-force welding (ref. 84). The process is not yet widely used, but it is particularly adaptable to dispersion-strengthened material, such as TD nickel, and has also been used successfully with nickel and Incoloy (ref. 85).

Although resembling flash welding, magnetic-force welding uses much higher current and shorter times. For example, TD nickel is joined at a peak current of 1 500 000 amp/in.^{2} with a current on-time of 4 msec (ref. 85). Pressure during welding is maintained by electromagnets. The very short welding time minimizes grain growth because the workpieces are not melted. The process also reduces the susceptibility of the weld to corrosion and/or cracking.

Commercially, magnetic-force welding has been used for end capping nuclear fuel rods (ref. 84). One end closure can be made every 2 min. compared to one every 30 min. with conventional diffusion-welding techniques.

Explosive Welding

Explosive welding (refs. 86 through 89) is one of the newer joining processes that has been successfully used with nickel-base alloys. This process utilizes the force of an explosive charge to bring the surfaces to be joined into sharp, intimate contact. Although some melting occurs, joining does not depend on fusion. As the plates collide, kinetic energy causes an effect known as jetting. This jetting obliterates surface films on the colliding plates and allows such intimate contact that the cohesive forces of each surface interact to produce a metallurgical bond. The resultant joint has an extremely thin bond area, and

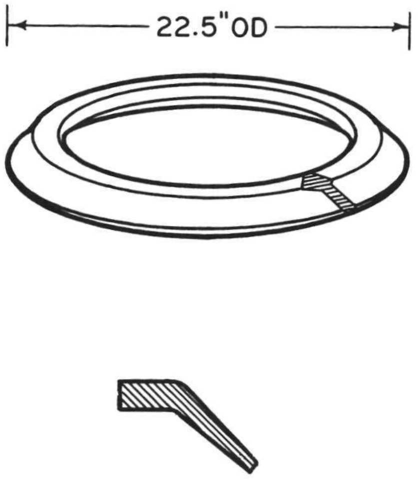
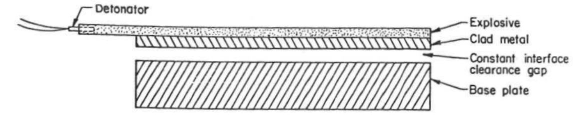
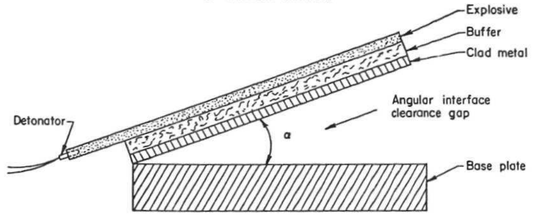


FIGURE 45.–A flash-welded L-605 jet-engine ring.



a. Constant Interface



b. Angled Interface

FIGURE 46.–Explosive-metal geometries utilized to accomplish explosive bonding.

there is very little disturbance of surrounding metal and its mechanical properties.

Welding conditions.–The important explosive-welding parameters are (1) type and loading of explosives, (2) mass and mechanical properties of the moving material, and (3) the distance through which this material accelerates before colliding with the base metal.

A variety of explosives have been used in welding. The most important consideration in selecting the explosive is its detonation velocity, which must fall within the limits necessary to produce the required impact velocity between the two metals being welded. The explosives that have been used vary both in detonation velocity and in physical form. Whatever explosive is used, welding should not be undertaken without someone experienced in its handling being on hand. The explosives are generally detonated with a standard commercial blasting cap, often in conjunction with a line-wave generator for larger explosive charges.

There are two basic joint geometries used for explosive welding as shown in figure 46 (ref. 89). The constant interface is generally used with low- and medium-detonation velocity explosives. In this case, no buffering material is required between the explosive and cladding metal. With high-velocity explosives, the explosive and cladding material are separated by buffers such as rubber or acrylic sheet. The angled interface is normally used with these materials, although a variation of the constant-clearance design, with buffering, may be used.

The bond interface in explosive welds is usually wavy or rippled, due to instability of the jet at the collision point between surfaces. Some melting does occur and can be detrimental, especially with metal combinations that form brittle intermetallic compounds. Melting also creates a danger of shrinkage voids that can act as crack initiators. Careful control of welding parameters, however, can keep melting to a minimum.

An advantage of explosive welding is that surface preparation need not be as careful as with other processes. However, surfaces should have no machining marks, and they should be smooth to within 0.001 in. in areas where the weld is expected.

Materials and applications.–All four types of nickel and nickel-base alloys have been explosive-welded in both similar and dissimilar combinations. Reference 89 presents a list of metals that have been joined by this process. The widest use of the process to date has been in the area of cladding and of joining flat sheet to plate. However, tubular transition joints, seam and lap welds, rib-reinforced structures, and spot welds have also been made. Explosive spot welding is particularly attractive because the small explosive charges that are required can be packaged and used with a hand-held tool. Joints have been reported in plates up to 10 in. long and in thicknesses ranging from 0.002 to 0.33 in. Plates as large as 20 ft by 7 ft have been clad by explosive welding. All of the specific applications of explosive welding to nickel-base alloys that have been reported to date relate to dissimilar metal combinations. Some of these applications are discussed in the section of this report entitled "Dissimilar Metals."

Laser Welding

Another of the newer welding processes adaptable to nickel alloys is pulsed-laser welding (refs. 90 through 93). In this process, the energy of a laser beam is used to melt and fuse the base materials. The coherent laser light beam is focused at the area to be welded and with each pulse of light the weldment is moved to refocus the light one-half spot away. The pulse duration normally is 1 to 10 msec. Solidification occurs long before the next pulse is generated, and there is no heating effect on the subsequent area to be welded.

The very low heat input of laser welding results in a very small heat-affected zone and minimal thermal damage. The low heat input also minimizes shrinkage and distortion; laser welds generally have about one-tenth the distortion of electron-beam welds (ref. 91). Another advantage is that normally inaccessible joints can be welded since contact with the work is unnecessary. Laser welds can also be made through transparent materials (glass, plastic), which makes controlled-environment welding and welding of toxic or radioactive materials a relatively simple procedure. The process is very adaptable to the welding of small-diameter electronic leads, since laser spot welds may be less than 0.001 in. in diameter.

Heat-resistant nickel-base alloys, such as Hastelloy C, Inconel X, and René 41 have poor thermal diffusivity that limits their laser weldability (ref. 90). Because of vapor depletion on the weld surface, single-pass laser welds in these materials have been limited to a depth of about 0.04 in. With the development of laser equipment with longer pulse durations, this situation is improving, however.

René 41 has been successfully welded in 0.025-in. thickness (ref. 93). The ease with which these specimens were welded and the weld penetration achieved at low peak-power levels, indicated that joints could be obtained in material up to at least 0.060 in. thick. In 0.005-in.-thick laser-welded specimens, room-temperature tensile strengths of 124.3 ksi have been obtained (ref. 92).

One other relatively new process that has been used to some extent on nickel-base alloys is inertia welding. Because its use to date has been primarily in joining dissimilar metals, the discussion of this process is included in the section on that subject.

SOLID-STATE WELDING

In solid-state welding, all components of the joint are maintained as solids. Welds can be made if two metallic surfaces, properly prepared, are brought together under an applied pressure at a suitable temperature for a sufficient length of time. Deformation and diffusion are important mechanisms of solid-state welding. It is convenient to subdivide discussions on this type of welding on the basis of whether deformation or diffusion is predominant. Both mechanisms probably always operate to some extent during the formation of a solid-state weld, but there are significant differences in the extent to which these two mechanisms control a given welding process. Deformation may be limited to very small surface areas during welding that is controlled primarily by diffusion. When considerable deformation is used during the welding operation, diffusion can be quite limited. Both deformation and diffusion welding as well as magnetic-force welding, which is essentially a diffusion-controlled process have been applied successfully only to a limited number of nickel alloys.

The term "solid-state welding" as used in this report applies to all joining processes in which either diffusion or deformation plays a major roll in the formation of the joint and in which a liquid phase is absent during welding.

Diffusion Welding

Solid-state diffusion welding is a joining method in which metals are welded by the application of pressure and heat. Pressure is limited to an amount that will bring the surfaces to be joined into intimate contact. Very little deformation of the parts takes place. Solid-state diffusion welding does not involve melting of the surfaces to be joined. Once the surfaces are in intimate contact, the joint is formed by diffusion of some element or elements across the original interfaces.

Some of the merits of the process that make it attractive as a method of manufacturing are as follows:

(1) Multiple welds can be made simultaneously.

(2) Welds can be made that have essentially the

same mechanical, physical, and chemical properties as the base metal.

(3) Welding can be done at temperatures below the recrystallization temperature of most materials.

(4) The formation of brittle compounds can be avoided provided that proper materials and welding conditions are selected.

(5) For each material combination, there are several combinations of parameters that will produce welds.

(6) Segregation and dilution of alloying or strengthening elements is eliminated. This is important when joining TD nickel.

Diffusion welding is primarily a time- and temperature-controlled process. The time required for welding can be shortened considerably by using a high welding pressure or temperature because diffusion is much more rapid at high temperatures than at low temperatures. Both the welding time and temperature often can be reduced by using an intermediate material of different composition to promote diffusion. This procedure reflects the increase in diffusion rate that is obtained by the introduction of a dissimilar metal.

The steps involved in diffusion welding are as follows:

(1) Preparation of the surfaces to be welded by cleaning or other special treatments

(2) Assembly of the components to be welded

(3) Application of the required welding pressure and temperature in the selected welding environment

(4) Holding under the conditions prescribed in step 3 for the required welding time

(5) Removal from the welding equipment for inspection and/or test.

The preparation steps usually include chemical etching and other cleaning steps similar to those employed during fusion welding or brazing. In addition, the surfaces to be welded may be coated with some other material by plating or vapor deposition to provide surfaces that will weld more readily. Coatings such as ceramics are sometimes applied to prevent welding in certain areas of the interface. Methods used to apply pressure include using simple presses containing fixed and movable dies, evacuating sealed assemblies so that the pressure differential applies to a given load, and placing assemblies in autoclaves so that high gas pressures can be applied. A variety of heating methods also can be used in diffusion welding. Generally, the temperature is raised by heating with some type of radiation heater. Resistance-spot-welding equipment also is used (ref. 94). As suggested above, the environment during welding is important.

The alloying elements contained in nickel-base alloys have been shown to affect diffusion-welding efficiency (ref. 95). Iron, titanium, and aluminum cause distinctly harmful effects. The effects of chromium, columbium, molybdenum, and cobalt, however, are small. In this same study, the effects of seventeen different elements used as intermediate diffusion aids were investigated. All except tantalum improved the shear strength of René 41 joints. The greatest strength improvements were obtained with boron, nickel, palladium, and manganese, as shown in table 22.

Diffusion-welded joints have been made in a limited number of nickel alloys under the conditions encompassed by the following ranges:

Temperature	1600° to 2200° F
Time	0.2 min. to 23.3 hr
Pressure	about atmospheric to 24 000 psi.

TD nickel, which is difficult to weld by fusion methods because the thoria particles agglomerate in the weld area, can be satisfactorily welded by the

TABLE 22.–*Effect of Elemental-Interface Diffusion Aids on the Shear Strength of René 41 Joints*

Element	Shear strength, psi	
	Avg value	Max value
Ag	7 000	8 500
B	27 400	54 500
Cb	5 400	8 500
Co	8 800	9 800
Cr	5 400	9 600
Cu	9 900	12 200
Fe	9 200	10 500
Mn	14 800	15 400
Mo	9 400	12 000
Ni	27 500	31 600
Pd	16 500	20 600
Si	12 600	23 200
Ta	2 700	3 600
Ti	11 600	12 900
V	8 100	12 700
W	11 900	12 700
Zr	6 600	10 500
Bare alloy, no interface aid	5 000	

TABLE 23.–*Summary of Diffusion-Welding Processes for Nickel-Base Superalloys*[a]

Alloy	Surface preparation	Bonding parameters			Atmosphere	Reference
		Time, min	Temperature, °F	Pressure, psi		
Nimonic 90[b]	Degrease, abrasion (500-grit abrasive)	15	2000	4 000	Protective	100
TD nickel	- -	1/5	2200	10 000	Inert	101
TD nickel	- -	1440	2050	Low	- -	101
TD nickel	Degrease	1/6	2200	20 000	Inert	102
TD nickel	Acetone and water	1	2000	12 500	Vacuum or inert	99, 103
TD nickel	Acetone and water	1	2150	7 500	Vacuum or inert	99, 103
TD nickel[c]	Polish, degrease, pickle, rinse	90	2000	9 000	- -	82
René 41	- -	4	1950	700	Vacuum	95

[a] Stop weld not used.
[b] 0.002-in. nickel-foil intermediate used.
[c] Includes lap joints and lap joints with nickel- and molybdenum-foil intermediates.

diffusion process (refs. 96 and 97). Shear strengths of 52 000 psi (about 93 percent of parent-metal strength) have been obtained in TD-nickel joints bonded for 1 min at 2000° F and 8000 psi (ref. 96). In another application, diffusion spot bonds with tensile strengths equal to those of the parent metal were obtained in 0.05-in.-thick TD nickel with a three-phase resistance welder (ref. 94).

Welding conditions reported in the published literature are given in table 23. Applications for diffusion welding are illustrated in figures 47 and 48 (ref. 99).

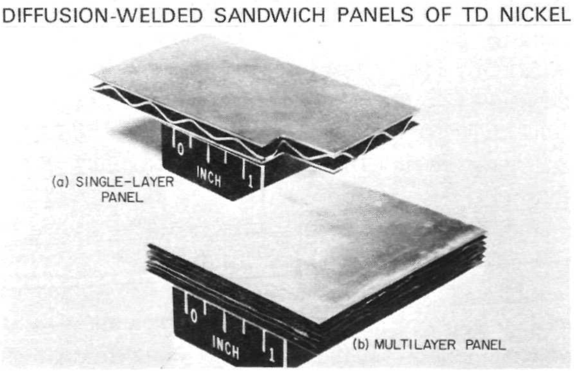


FIGURE 47.–Diffusion-welded structural panels.

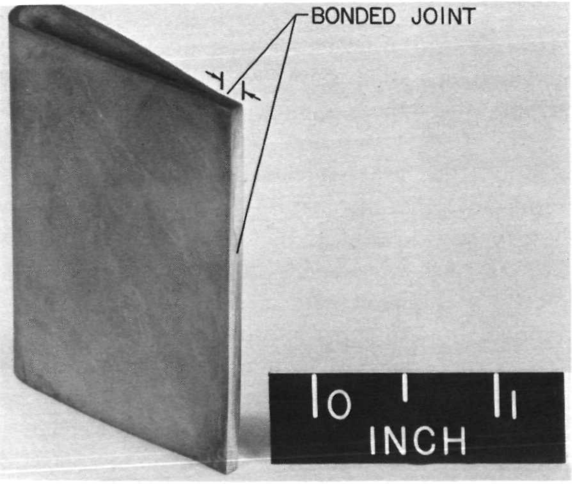


FIGURE 48.–Diffusion-welded jet-engine blade.

Deformation Welding

Deformation welding differs from diffusion welding primarily in that a large amount of deformation takes place in the parts being joined. This deformation makes it possible to produce a weld in much shorter times and frequently at lower temperatures than possible during diffusion welding. When sealed assemblies are joined at elevated temperatures, bonding pressures and atmospheres often differ considerably from room-temperature values because of such factors as outgassing and softening of the materials. Arrangements must be made to control these factors under actual bonding conditions. Welding deformations as great as 95 percent may be used. The steps involved in deformation welding are very similar to those used in diffusion welding.

Roll welding is a solid-state deformation-welding process that has been used for the fabrication of structural shapes and sandwich panels (refs. 104 through 106). Materials that have been investigated and found to be suitable for this method of fabrication include René 41, Inconel, and other nickel-base alloys. Examples of products made by roll welding are illustrated in figure 49 (refs. 104 and 107).

Pressure gas welding (refs. 108 through 110) is a welding process in which the joint is formed simultaneously over the entire area of abutting surfaces by heating with gas flames and by the application of pressure without the use of filler metal. Pressure gas welding may or may not be a solid-state welding process, depending on the actual welding procedure used. The two procedures in common use are the closed-joint and the open-joint methods. In the closed-joint method, the clean faces of the parts to be joined are abutted together under pressure and heated by gas flames until a predetermined upsetting of the joint occurs. This method of pressure gas welding has been used only experimentally for welding a limited number of nickel-base alloys (ref. 111). In the open-joint method, the faces to be joined are individually heated by the gas flames to the melting temperature and then brought into contact for upsetting. There are no known applications of the open-joint method for welding nickel alloys. The process in both methods is ideally adapted to a mechanized operation, and practically all commercial applications are either partially or fully mechanized. The process also is adaptable to the welding of low- and high-carbon steels, low- and high-alloy steels, and several nonferrous metal alloys.

Pressure gas welding produces a forged-butt weld by upsetting the faying surfaces under heat and pressure. The heating system in one facility consists of a multiorifice circular oxyacetylene torch equipped with suitable pressure regulators and flowmeters to provide a controlled heating rate at the joint. The circular torch is oscillated so that the individual pinpoint flames are oscillated circumferentially around the joint to avoid local overheating. The welding pressure is supplied by a hydraulic system of a size sufficient to produce the required forging pressures. Welding pressures vary depending on the material and weld area. An overall view of a pressure-gas-welding machine is shown in figure 50 (refs. 110 and 111). Although the equipment used for pressure gas welding is a conventional machine for heating and applying pressure, details of the equipment such as the circular heating-torch design are considered proprietary.

A typical pressure-gas-welding cycle is as follows:

(1) The parts to be welded are aligned in the machine.

(2) A controlled welding force is applied.

(3) The torch is ignited.

(4) Heating is continued until sufficient forging has been produced to upset the joint a predetermined amount to complete the joint.

(5) The gas flame is extinguished.

(6) Hydraulic welding force is released.

(7) The part is removed from the machine after cooling to a predetermined temperature.

After welding, the completed weldments are heat-treated as required.

BRAZING AND SOLDERING

Nickel and nickel-base alloys are selected for applications that require either good corrosion resis-

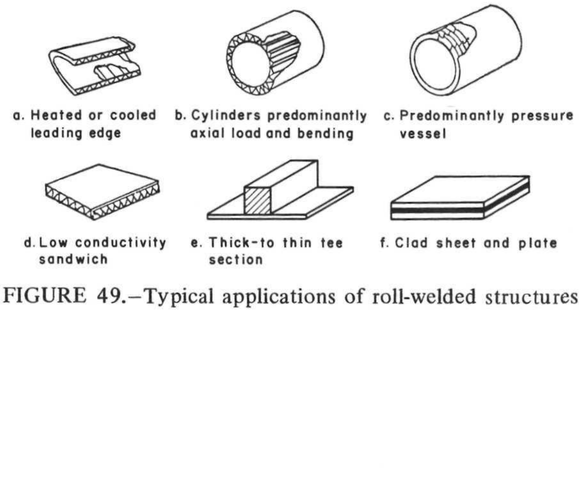

a. Heated or cooled leading edge
b. Cylinders predominantly axial load and bending
c. Predominantly pressure vessel
d. Low conductivity sandwich
e. Thick-to thin tee section
f. Clad sheet and plate

FIGURE 49.–Typical applications of roll-welded structures.

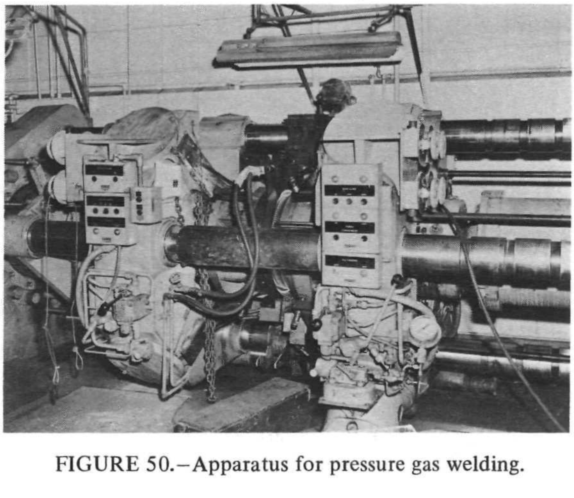


FIGURE 50.–Apparatus for pressure gas welding.

tance or good corrosion resistance combined with useful mechanical properties at elevated temperatures. Brazing is a suitable method for joining parts or assemblies to meet these requirements. Soldering also is used, but the uses of soldered joints are limited to low-temperature-service application.

Brazing has a three-part definition: (1) the joining of two or more parts by heating to temperatures of 800° F or above, (2) the use of a filler metal having a melting temperature range that is below that of the base metal, and (3) the wetting of the base-metal surfaces by the filler metal. Soldering is similar to brazing, but the base metals are heated to temperatures below 800° F. Heating can be performed with torches, furnaces, radiation heaters, self-resistance heating, and by other means.

When selecting a brazing procedure it is important to consider the behavior of (1) the base metal and (2) the brazed joint during brazing and under service conditions. Some nickel and nickel-base alloys can be brazed by using conventional brazing procedures, while other alloys require great care. During brazing, residual or applied tensile stress should be kept as low as possible. Certain molten brazing filler metals can cause stress-corrosion cracking. Also, inherent stresses present in the age-hardenable alloys can lead to stress-corrosion cracking. Stress relieving or annealing prior to brazing is advisable. Special treatments, filler metals, and procedures also are necessary for some alloys. For example, nickel alloys that contain chromium, aluminum, or titanium have tenacious oxides on their surfaces. These oxides form easily and cannot be reduced readily by pure hydrogen or by fluxing.

Materials

Brazing filler metals for nickel and nickel-base alloys include: (1) filler metals that are normally used for brazing ferrous materials and (2) special-purpose filler metals developed by individual organizations. Some typical brazing filler metals for nickel and nickel-base alloys are listed in table 24 (refs. 12, 112, and 113). The proper filler is determined by service requirements, compatibility of the brazing filler metal with the base metal at brazing temperatures, availability of suitable brazing alloys, and postbrazing heat-treating requirements.

Brazing and soldering alloys should not interact excessively with the base metal. Much effort has been expended to overcome problems resulting from interactions of nickel-alloy filler metals with nickel-alloy base metals. No completely satisfactory solutions have been found. Brazing filler-metal alloys that contain phosphorus, aluminum, and magnesium are not used because these elements have a strong tendency to form brittle compounds or alloys. Lead, bismuth, and antimony, frequent constituents of solders and threading compounds, also have embrittling effects on nickel and nickel-base alloys at elevated temperatures. Nevertheless, conventional solders are often used. Tin also is used for some highly corrosive service applications.

Cleanliness is extremely important when brazing nickel and nickel-base alloys. This applies to the base metal, filler metal, atmospheres, and fluxes. All elements that cause contamination or interfere with brazing should be eliminated. All forms of surface dirt such as paint, oil, chemical residues, and scale should be removed by using suitable procedures such as those described earlier in the section on cleaning. The formation of refractory oxides on nickel-base alloys that contain elements such as aluminum and titanium should not be permitted. Procedures that prevent the formations of oxides before and during brazing include special treatments of the surfaces to be joined or brazing in a controlled atmosphere. Surface treatments include copper plating, nickel plating, and reducing the oxides to metallic form. Dry, oxygen-free atmospheres that are used include inert gases, hydrogen, and vacuum. The brazing atmosphere, whether gases or vacuum are used, should be free from harmful constituents, such as sulfur, oxygen, and water vapor.

Brazing flux is needed to "combine with, dissolve, inhibit, or otherwise render ineffective those unwanted products of the brazing operation which would otherwise impair the braze or totally prevent brazing" (ref. 12). This applies to soldering fluxes also. Fluxes are not designed for primary cleaning, which should be performed conventionally. There are no known fluxes suitable for nickel-base alloys containing large amounts of titanium and/or aluminum. For nickel-base alloys having only minor amounts of aluminum or titanium, brazing fluxes containing chlorides, fluorides, borates, and wetting agents can be used. These fluxes should be selected with care, considering the filler and base metals and brazing conditions. For soldering operations, acid fluxes only are recommended. The cleaning actions of

TABLE 24.–*Commonly Used Filler Metals for Brazing Nickel and Nickel-Base Alloys*

Composition, weight %						Temperature, ° F		
Ag	Cu	Zn	Cd	Ni	Others	Solidus	Liquidus	Brazing range
					Silver-brazing alloys			
35	26	21	18	--	--	1125	1295	1295-1550
45	15	16	24	--	--	1125	1145	1145-1400
50	15.5	16.5	18	--	--	1160	1175	1295-1550
50	15.5	15.5	16	3	--	1195	1270	1270-1500
56	22	17	--	--	5.0Sn	1145	1205	1205-1400
60	30	--	--	--	10.0Sn	1095	1325	--
					Copper-brazing alloys			
--	99.90	--	--	--	0.04O	--	1981	2000-2100
--	99.92	--	--	--	--	--	1981	2000-2100
					Nickel-brazing alloys			
--	--	--	--	93	3.5Si, 2B	--	--	1950-2150
--	--	--	--	91	4.5Si, 3B	--	--	1850-2000
--	--	--	--	90	10P	--	--	1750-1950
--	--	--	--	82	7Cr, 3Fe, 4Si, 3B	--	--	1850-2000
--	--	--	--	72	16Cr, 4Fe, 4Si, 3.8B	1850	1950	1900-2100
--	--	--	--	39	33Cr, 24Pd, 4Si	1820	2150	2150
					Gold-brazing alloys			
--	--	--	--	18	82 Au	1750	--	1830

rosin fluxes are too mild, so they are not used. As in welding, it is important to remove fluxes after the joining operation.

Equipment for brazing nickel and nickel-base alloys is of the same type as that used for brazing other common material. Standard equipment is available commercially for torch, furnace, induction, resistance, and vacuum brazing. The equipment should be capable of controlling important factors such as heating and/or cooling rate, temperature, time at temperature, and atmosphere when desired.

Heating Methods

Many methods are used for heating the parts to brazing or soldering temperatures. The entire joint must be heated uniformly for a time sufficient for the alloy to flow and fill the joint area. Heating methods and procedures are summarized in the published literature (ref. 12) and below. The selection of a heating method will depend upon factors such as the size of assembly, configuration of the parts, types of metals involved, production requirements, and available equipment.

For manual brazing, gas torches or radiation heaters are used. Air and city gas, air and other fuel gases, oxyacetylene, or oxyacetylene and other gases may be used for torch brazing. A large, soft reducing flame is preferred. The flame is played on the work to heat the joint area to a uniform temperature of 50° to 100° F higher than the melting temperature of the brazing alloy employed. Then the brazing alloy is applied. The alloy will flow toward the hotter part if the parts are clean. When the alloy has flowed completely, the flame should be removed and the joint allowed to cool undisturbed. Solidification of the alloy can be observed by a sudden change from very shiny to less shiny appearance of a fillet. At this time the joint has very low strength and if moved a cracked joint might result.

Furnaces, either electrical-, oil-, or gas-fired, may also be used for brazing. Usually such brazing is done in large batches. Careful control of temperature is necessary to prevent overheating or underheating. If the furnace is too small to heat the parts rapidly, an oxygen-free atmosphere is helpful in extending the life of the flux. Induction heating also is a good heating method. Very heavy parts can be heated so rapidly that the outside surfaces become hot without appreciable heating of the center. In such instances, thermal stresses can be developed and cause stress cracking. Resistance heating also is used for small parts and for the assembly of small parts to large parts where pressure on the parts can be applied. Salt-bath brazing may be employed, but is seldom applied to nickel and nickel alloys. Metal-bath brazing is limited to applications in fine wire and very small parts.

Another method of heating is the use of quartz infrared lamps (ref. 115). The commercial process, known as "Nortobrazing", uses these lamps as a heat source and a separate set of chill forms for cooling. This setup, used for honeycomb structures, minimizes heavy tooling by heating and cooling the assembled structures with maximum speed. The process has been used on Inconel 702 and René 41. Heating for soldering can be performed in the same manner as that prescribed for brazing, and by using the many forms of manual soldering tools that are available commercially.

Additional details of brazing and soldering procedures are determined by considering the particular alloy, base metal, and intended service. Producers of the base metal and brazing filler-metal alloys, and the published literature should be consulted in this determination.

Brazed- and soldered-joint quality are evaluated by conventional methods (ref. 12). However, when the assembly is intended for elevated-temperature service, quality requirements are so rigid that additional tests usually are required.

Detailed information on properties of brazed and soldered connections are not included here. Published literature, standard handbooks, and manuals should be consulted for these data.

Applications

Practically every form of brazing has been used in joining nickel and nickel-base alloys for a broad range of service. In recent years, considerable information has been developed for brazing applications involving assemblies to operate at high temperatures. An inherent problem when brazing many high-temperature alloys with nickel filler metals is the harmful effect of the high temperatures on base metals. Reaction of the brazing filler metals with the base metal is a problem with some alloys.

Quantitative data on the effects of brazing thermal cycles on base-metal strength show that strength losses and microstructural changes occur to varying degrees. A study of eight superalloys showed that generally the weakest high-temperature alloys had the greatest strength losses. The strongest alloys had the least loss of properties and, in most instances, responded well to postbrazing heat treatments (ref. 116).

The good heat-transfer characteristics of nickel make it a useful material for heat exchangers. One difficulty, however, is intergranular penetration by the brazing alloy, particularly when brazing thin sheet. Many of the conventional brazing alloys that are recommended for use with nickel-base alloys contain nickel, chromium, silicon, iron, and boron. Nickel is the major element. A widely used brazing filler metal contains 73.25-percent nickel, 14-percent chromium, 3.5-percent boron, 4-percent silicon, 4.5-percent iron, and 0.75-percent maximum carbon. Wide experience developed by users has revealed how to minimize the effects of base-metal filler-metal reactions with this alloy. Another brazing alloy recommended for some applications of thin nickel-base alloys contains 77-percent nickel, 13-percent chromium, and 10-percent phosphorus. This alloy has low solubility with nickel-base alloys, and erosion of the base metal can be controlled quite readily (ref. 12). Also, an alloy of 65-percent nickel, 23-percent manganese, 7-percent silicon, and 5-percent copper has been developed to cope with the penetration problem (ref. 116). The manganese addition inhibits intergranular attack by nickel-phosphorus and nickel-silicon alloys.

The age-hardenable nickel alloys, because of their high strength and good corrosion resistance, are often used for fuel-assembly grids in nuclear reactors. In one case, Inconel-718 fuel grids have been brazed in a vacuum or hydrogen atmosphere using a Ni-14Cr-10P filler metal (ref. 117). Before brazing, the grid straps were cleaned and electroplated with 0.0005 to 0.001 in. of nickel. Furnace brazing was done in either a vacuum of 5×10^{-4} torr or in hydrogen at 1850° to 1900° F. At least one hour at brazing temperature was needed to achieve adequate strength. It was found, however, that ductility could be improved by holding the assembly at brazing temperature for up to 3 hours. The use of a vacuum or hydrogen atmosphere minimizes oxidation of the titanium and aluminum in the base metal, thus enabling the filler metal to wet and flow.

Inconel 718 has also been used for complex tubular assemblies in the Phoebus-2A reactor (ref. 114). Brazing was done at approximately 1830° F in a resistance-heated furnace and argon atmosphere by using an Au-18 Ni brazing alloy. The Inconel-718 parts were plated with 0.0002 to 0.0005 in. of nickel prior to brazing. Of nearly 2000 assemblies brazed in this manner, less than one percent were rejected because of poor braze joints.

Brazing appears to be a process well suited for joining TD nickel and TD nickel-chromium. Numerous brazing filler alloys have been investigated for joining these alloys for service temperatures in the 1400° to 2400° F range. Brazing alloys that provide adequate strength, good flow and wetting behavior, and a range of brazing temperatures have been identified (refs. 57, 94, 98, 118, 119, and 120). Diffusion effects at 2000° F and preferential oxidation of diffusion zones are primary problems. Jet-engine components of TD nickel-chromium, brazed with a TD-6 alloy (Ni-16Cr-4Si-17Mo-5W), have performed successfully in full-scale tests (ref. 98).

An example of products made by brazing of nickel and nickel-base alloys is shown in figure 51 (refs. 112, 113 and 121).

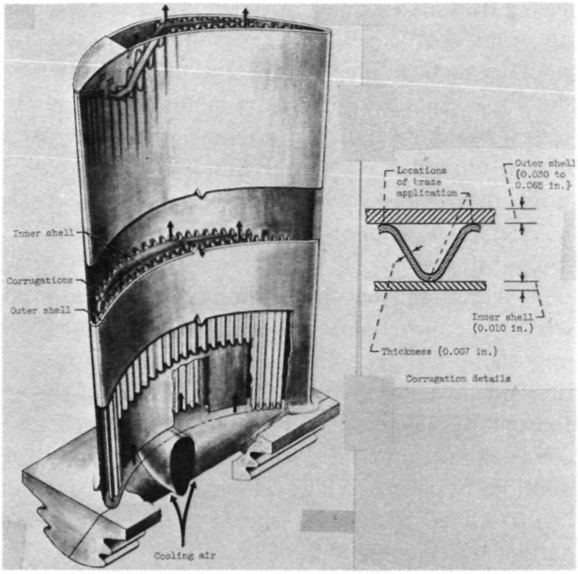


FIGURE 51.—Air-cooled turbine blade of nickel-base alloy fabricated by brazing.

DISSIMILAR METALS

Sometimes it is necessary to join the nickel-base alloys to alloys of lower nickel content or to other metals such as stainless steel and carbon steel. This may be done by welding, brazing, or soldering, or may be done mechanically. The preferred methods are welding and brazing. Soldering is usually suitable only for joints that carry very little or no load at room temperature.

The problems that arise when joining dissimilar metals depend mainly on the differences in composition between the alloys. If they are similar or are metallurgically compatible over a wide composition range, problems will not be great, assuming that good welding practice is used. An example of the ideal metallurgical situation is the welding of pure nickel to Monel. These metals are completely compatible. Consequently, they can be welded to one another without difficulty by any process in which compatible filler material is used. Dissimilar metal combinations that are often joined to nickel and nickel-base alloys are (refs. 9 and 11)

- Monel 400 to:
  - Steel
  - Low-alloy steel
  - Stainless steel (304)
  - 70/30 copper-nickel
  - Hastelloy B
- Nickel 200 to:
  - Steel
  - Low-alloy steel (8630)
  - Stainless steel (304)
  - Monel 400
  - 70/30 copper-nickel
  - Hastelloy B
- Inconel 600 or Incoloy 800 to:
  - Steel
  - Low-alloy steel (8630)
  - Stainless steel
  - Monel 400
  - Nickel 200
  - 70/30 copper-nickel
  - Hastelloy B

In other situations, a dilution of the nickel-base alloy with a dissimilar metal during welding can be tolerated only to a limited degree (ref. 122). If stainless-steel filler wires are used to join Monel to austenitic stainless steel, any significant copper pickup from the Monel will cause hot shortness and cracking in the weld. Thus, stainless-steel filler wire should be avoided for this combination when processes that cause much dilution are used. Likewise, a Monel filler wire is not useful because chromium from the stainless will cause cracking. A special Inconel filler wire or nickel is best, but neither is foolproof.

It is apparent that the dilution obtained during the welding of nickel-base alloys to other metals is very important. Processes that cause a minimum of dilution should always be used. Manipulation of the arc to impinge mainly on the base metal that is nearest in composition to the filler wire will assist in minimizing dilution. Suppliers of filler wire and electrodes should be consulted before a choice is made for any particular combination of dissimilar metals. The following weld compositions should be avoided:

(1) A ferritic weld deposit, if dilution by nickel, chromium, or copper is to be encountered

(2) The 18-8-type weld deposit, if dilution by more than 3-percent copper is to be encountered

(3) A high-carbon Monel deposit, if dilution by iron is to be encountered

(4) Any Monel deposit, if dilution by more than 6- to 8-percent chromium is anticipated

(5) The 18-8-type deposit, if dilution by nickel and chromium is sufficient to cause the crack-sensitive 35Ni-15Cr weld composition.

Joining of Nickel and Steel

Arc welding of Inconel to Type 304 stainless steel, to carbon steel, and to itself has been investigated (ref. 123). Base-metal plate thicknesses from 0.75 to 2.63 in. were welded using the shielded-metal-arc, inert-gas tungsten-arc, and inert-gas metal-arc processes. Welds that met the stringent requirements for nuclear-power-plant service were obtained by all processes. Included in the published data are strength at room temperature and at 650° F, hardness, and bend ductility. This study also included overlaying of Inconel on other base metals. A similar study was made of the welding of heavy Inconel plate to carbon steel by utilizing specific nickel-base electrodes, MIL-4N85 for welding with covered electrodes, and MIL-EN87/RN87 for gas metal-arc welding (ref. 39). The weld-deposit compositions of these electrodes that are used when welding or overlaying are given in table 25.

The effects of welding position, heat treatment, high restraint, and use over other filler-metal-alloy weld deposits were investigated in this study. Crack- and porosity-free welds were obtained under every condition examined.

Another electrode was reported useful for making transition welds between Inconel and stainless steel (ref. 124). A titanium-manganese-modified Inconel weld wire was used with the gas-metal-arc process to produce high-quality welds in heavy plate. Age-hardened Inconel W, 1-inch thick, has been welded to Inconel of the same thickness using the manual and gas-tungsten-arc processes. For the production of retorts for high-temperature furnaces, Hastelloy X is welded to itself, to Inconel, and to mild steel (ref. 125). The same practice is used for the dissimilar-metal systems as that for welding Hastelloy X to itself, but a different filler metal is used (Inco-Weld A). Heat input is kept at a minimum by careful joint design, single-pass welding, minimum weaving, and high travel speeds. The thicknesses welded are 0.25 and 0.38 in.

Although arc welding is most commonly used to weld nickel-base alloys to steel, such joints have been resistance spot welded. For example, procedures for spot welding Inconel 718 to Type 301 stainless steel have been developed (ref. 126). Shear and tensile strengths of experimental spot welds in these materials were adequate at 75°, – 320° and – 423° F.

TABLE 25.—*Electrode Weld-Deposit Combinations*

Electrode	Composition, %										
	Ni	Cr	Fe	Mn	Cb + Ta	C	Ti	Si	S	Cu	Co
MIL-4N85	67.0	14.7	7.5	7.7	2.0	0.04	0.40	0.50	0.007	0.03	0.07
MIL-EN87/RN87	72.0	20.0	1.0	3.0	2.6	0.03	0.30	0.30	0.009	0.02	0.04

Joining of Nickel and Titanium

Inconel 600 has been diffusion-welded to Ti-8Al-1Mo-1V with and without diffusion aids (ref. 127). Specimens welded without an intermediate heat treatment at 1625° F for 15 min. in vacuum had acceptable shear strengths at all test temperatures. Silver or nickel plating of the base metals did not improve the joint strength but did permit lower welding temperatures. During this same program, these materials were also roll-welded at 1050° F without a diffusion aid.

Fusion welding of nickel-base alloys to titanium is more difficult because of the formation of brittle intermetallic compounds. However, successful gas tungsten-arc and electron-beam welds have been made by using columbium and high-copper alloy inserts (ref. 128). In this case, the titanium was welded to the columbium insert, the nickel-base alloy was welded to the copper-alloy insert, and the two inserts were welded together.

Joining of Other Dissimilar Metals

Explosive welding has a distinct advantage over other processes for joining dissimilar metals and is most widely used in this area. Because of the very short duration of the process, intermetallic compounds do not form in dissimilar-metal joints when proper variables are chosen. Explosive welding has been used to fabricate heat-exchanger tube sheets (ref. 89) in which both nickel and Monel tube sheets have been bonded on steel. Inconel tubes have also been joined to steel tube sheets by explosive welding. A list of dissimilar-metal combinations that have been explosively welded is given in reference 89.

Inertia welding is a relatively new process that has been used to join nickel-base alloys to other metals (refs. 129 and 130). Inertia welding is a solid-state process in which the stored kinetic energy of a rotating flywheel is employed for all of the heating and much of the forging of the weld. One feature of inertia welds is a very narrow heat-affected zone; about 0.02 to 0.25 in. for most materials and sizes. Only a small amount of upset is required so that stock is shortened only about 0.020 in. in most cases. The process requires only about 1/50 the energy of flash-butt alloys, such as Inconel 713C and 718, to carbon and alloy steels. Such welds have shown joint efficiencies of 100 percent, with failure occurring in the weaker of the two base metals.

Diffusion-welding techniques can be used to join TD-nickel to precipitation-hardening alloys (ref. 96). Diffusion welding has also been used to join Nichrome (80Ni-20Cr) to Cb-35UO_2 cermets at 2190° F and 12 000 psi (ref. 131).

In summary, two considerations are important when welding nickel-base alloys to other metals, viz., dilution of the weld metal and proper choice of the filler metal. These two factors are strongly interrelated and have led to the development of new and altered filler metals as indicated. The welding of the age-hardenable nickel-base alloys to other metals is not well covered in the literature. Such joints are made, however, with considerable success as long as the accepted procedures and proper filler metals are used. Hastelloy W has been used widely as a filler metal for welding dissimilar combinations. It was developed for this purpose. The composition of Hastelloy W is essentially the same as that of Hastelloy B, but with 5-percent additional chromium. This composition provides an ideal matrix when used to weld many different dissimilar age-hardenable-alloy combinations.

CHAPTER 4

Joint Quality

Joints in nickel and nickel-base alloys often may have undesirable features that will interfere with proper operation in service. Suitable inspection techniques and repair methods must be used that will detect those undesirable features and enable their repair. It is also necessary to determine the causes of the undesirable features so that proper remedial and repair procedures can be developed.

INSPECTION

Joints in nickel and nickel-base alloys usually are inspected by several methods. Nondestructive inspections are almost always performed. Destructive inspection, however generally is not performed on completed product joints. It is often necessary and desirable to check changes in dimensions that may have resulted from welding. The visual- and measurement-type inspections performed for this purpose may also include checks of weld-joint profile and measurements of the weld thickness. Various inspection procedures also are used to insure that the joints produced are of satisfactory quality. The most commonly used techniques in this area include visual, dye penetrant, and X-ray. Various types of leak tests are used on components designed to contain gases or fluids.

DEFECTS

The definition of joint defects is arbitrary. Many years of experience have been gained with welding codes and specifications that either prohibit or allow certain features characterized as defects. Features recognized as defects are generally limited in accordance with conservative practices. This approach to defects has been quite successful in the past, but is of some concern when dealing with many of the newer materials being used in various types of fabrication. This concern is based on the belief that the removal of certain types of features classified as nonallowable defects often results in more damage to the serviceability of a structure than the damage that might be done by allowing the feature to remain. The reluctance of many welding engineers to repair certain features is based on this feeling, not on a desire to make the welding job easier.

The fabrication of defect-free welds is highly dependent on the quality requirements of applicable specifications and on the inspection methods that are used. For example, hardly any welding code or specification allows cracks in a weld. However, cracked welds can and do get into service if inspection methods that will insure detecting all cracks present in a weld are not required.

The only reliable way to determine what weld features are truly defects is to evaluate the effects of such features in a test program. Such an evaluation must include tests that are representative of the service conditions. Many defect-like weld features have no effect on the static-tension properties of the weld. However, these same features may degrade performance seriously in a fatigue test.

With the knowledge currently available about the performance of fusion weldments, a conservative engineering approach to defects should be followed. Typical arc-weld features that are sometimes classified as defects are shown in figure 52.

Porosity

Porosity has been encountered to some extent in fusion welds in nickel and nickel-base alloys. Measures to control cleanliness and the employment of good welding techniques have successfully reduced the occurrence of porosity. It is known that carbon monoxide and nitrogen are the primary causes of porosity in nickel-base alloy weldments (ref. 132). The addition of strong oxide formers such as alumi-

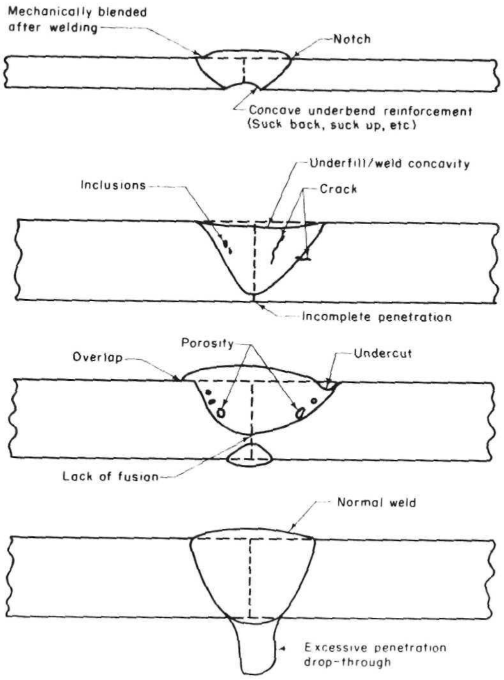


FIGURE 52.–Arc-weld defects.

num, titanium, and columbium will significantly reduce the tendency toward porosity. Some factors known to cause porosity in nickel and nickel-base alloy welds include

(1) Improper filler metals
(2) Incorrect arc length
(3) Low welding speed
(4) Insufficient sheet thickness
(5) Air in shielding gas
(6) Moisture
(7) Improper cleaning.

Porosity in welds can be controlled if the procedures that have been developed are followed.

Folds and Surface Pits

Fluorescent and dye-penetrant indications are obtained from folds and pits at the surface of the weld metal. Often, these features are not considered detrimental to weld quality. They do not necessarily indicate the presence of subsurface cracks or porosity (ref. 45).

Fissures

Intergranular cracking is characteristic of a wide range of metals and alloys. The degree of cracking ranges from readily detected macrocracks to nearly undetectable microcracks. In nickel-base alloys, microcracks are usually called fissures. For many applications, the presence of weld-metal fissures is not considered serious. In one investigation of fissuring in Inconel 600 weldments (ref. 133), it was stated that local fissure densities as high as 70 fissures per square inch had no measurable effect on fatigue life when the weld was tested at a constant-strain amplitude of 0.3 percent. The size of the largest fissure (not fissure density) appeared to be the major factor affecting fatigue life. In specimens 0.600-in. wide by 0.100-in. thick, disk-shaped fissures up to 0.070 in. in effective diameter had no measurable effect on fatigue life. However, fissures 0.110 in. in effective diameter caused a reduction in fatigue strength by a factor of 2.3.

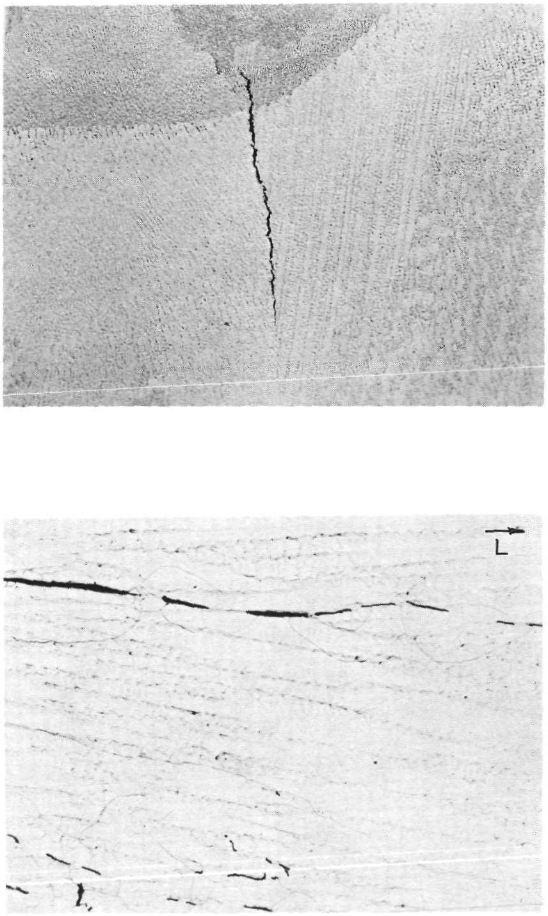


FIGURE 53.–Weld fissures in a nickel-chromium-iron alloy.

In nuclear applications, steam-power plants, and numerous aerospace applications, fissures are a critical problem if only because the specifications used prohibit their presence. In one study (ref. 134), intergranular fissuring was attributed to grain-boundary segregation that was present in large amounts when (1) the original impurity concentration in the alloy was high and (2) when large grains were formed in the microstructures at high temperatures. Figure 53 illustrates the appearance and small size of typical weld fissures in a nickel-chromium-iron alloy (ref. 135).

Information developed on microfissuring in Inconel 718 is also of interest (ref. 136). This study indicates that manganese in excess of 0.20 percent in combination with silicon in excess of 0.25 percent reduces the tendency to microfissuring in Inconel 718 GTA welds. A possible explanation of this phenomenon is that the manganese unites with "free" sulfur. This union minimizes the reaction of sulfur with other elements and consequent hot shortness. In this study, there were no heats with high-manganese and low-silicon contents, or vice versa, so the individual influence of each element could not be evaluated. Magnesium in amounts above 20 ppm was also shown to offer some resistance to microfissuring. Finally, this study indicates that material with a grain size coarser than ASTM No. 2 is slightly more susceptible to microfissuring than material with finer grains. This is true even when the manganese and silicon content is high.

Strain-Age Cracking

Strain-age cracking is an intergranular cracking that occurs in the precipitation-hardenable high-temperature nickel-base superalloys during the initial heat treatment following fabrication by welding or cold working. The problem is particularly severe when repair welding is conducted on aged material. The defect seriously limits the use of these alloys in applications where they are otherwise well suited. The cracks are relatively large, with the greater part of the crack in the base metal (ref. 134).

The severity of strain-age cracking varies considerably among different alloys. It is rarely, if ever, encountered in solid-solution-hardening, nonaging, nickel-base alloys such as Inconel and Nimonic 75. On the other hand, such alloys as Udimet 500 and Udimet 700 are nearly impossible to weld due to strain-age cracking (ref. 10). René 41 presents considerable difficulty, particularly when manual welding techniques are applied.

Strain-age cracking in Inconel X and René 41 has been investigated and appears to be related to metallurgical reactions during aging that cause grain-boundary embrittlement. Studies of manual and automatic arc-welding techniques for minimizing strain-age cracking in René 41 sheet showed that

(1) High-heat-input welds are more susceptible to strain-age cracking than low-heat-input welds.

(2) Aged material is the most crack-susceptible condition investigated.

(3) Preheating at 600° F prior to welding did not reduce crack susceptibility on subsequent aging at 1400° F. Reduction of residual welding stresses was not apparent.

(4) Shot peening was effective as a means for reducing strain-age cracking during aging of 0.032- and 0.500-inch material due to changes in residual stresses.

(5) Minimum restraint on the weld joint is desirable in minimizing strain-age cracking (refs. 137 and 138).

(6) Resistance to strain-age cracking is improved by the use of high-purity raw materials (iron, silicon, and managanese) during melting of René 41 (ref. 138).

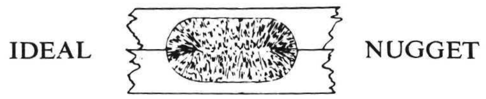
(7) Resistance to strain-age cracking is improved by using electron-beam rather than gas tungsten-arc welding (ref. 138).

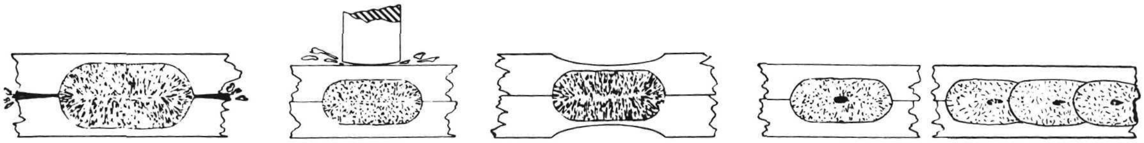
(8) Resistance to strain-age cracking decreases with increasing thickness.

(9) Postweld annealing in an oxygen-free atmosphere reduces the tendency toward strain-age cracking (ref. 139).

Defects in Resistance Welds

Characteristics described as defects in resistance welds are difficult to assess. Defects in resistance welds are generally categorized as external and internal defects. With the exception of cracks that are exposed to the exterior of the sheets, which are obviously undesirable, the remaining external defects are probably considered as such because they indicate that the welding conditions may not have been exactly right. External defects in this category are sheet preparation, surface pits, metal expulsion, tip pickup, and excessive indentation. Regarding internal



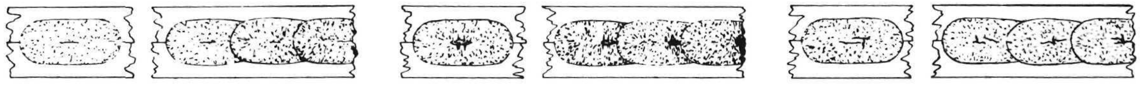


I. Excessive expulsion at interface.
  1. Insufficient electrode force.
  2. Excessive current or "on" time.
  3. Electrode dressing too sharp.
  4. Foreign matter at interface.

II. Surface expulsion.
  1. Electrode dressing too sharp.
  2. Excessive current for electrode force.
  3. Foreign matter on surface.
  4. Insufficient coolant on electrodes.

III. Excessive indentation.
  1. Electrode dressing too sharp.
  2. Insufficient electrode width.
  3. Excessive electrode force.
  4. Excessive current.
  5. Excessive "on" time.
  6. Insufficient coolant on electrodes.

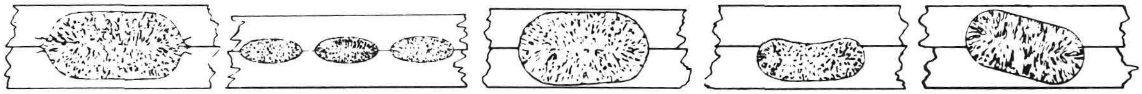
IV. Void in nugget.
  1. Insufficient electrode force.
  2. Excessive current or "on" time.
  3. Electrode dressing too flat.
  4. Insufficient "off" time.
  5. Excessive roll speed.



V. Cracks in nugget.
  A. Horizontal cracks in center.
    1. Insufficient electrode force.
    2. Insufficient "off" time.
    3. Electrode dressing too flat.
    4. Excessive current.
    5. Excessive roll speed.

V. Cracks in nugget.
  B. Vertical cracks with voids.
    1. Excessive current or "on" time.
    2. Insufficient "off" time.
    3. Insufficient electrode force.
    4. Electrode dressing too flat.

V. Cracks in nugget.
  C. In crack sensitive metal.
    1. Insufficient electrode force.
    2. Electrode dressing too flat.
    3. Insufficient "on" time.
    4. Excessive current.
    5. Insufficient "off" time.
    6. Excessive roll speed.



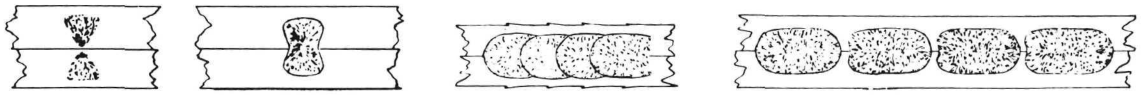
VI. Cracks in parent metal.
  1. Insufficient electrode width for nugget diameter.
  2. Electrode dressing too sharp.
  3. Excessive current or "on" time.
  4. Insufficient "off" time.
  5. Excessive roll speed.

VII. Undersize nugget.
  1. Insufficient current.
  2. Insufficient "on" time.
  3. Excessive electrode force.

VIII. Excessive penetration.
  1. Excessive current.
  2. Excessive "on" time.
  3. Electrode dressing too sharp.
  4. Insufficient coolant on electrodes.
  5. Insufficient electrical or thermal conductivity of electrodes.

IX. Unequal penetration.
  1. Unequal electrode dressing.
  2. Unequal electrical or thermal conductivity of electrodes.
  3. Unequal distribution of coolant on electrodes.

X. Unbalanced nugget.
  1. Misalignment of electrodes.
  2. Off center dressing of electrodes.



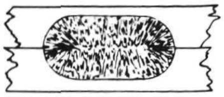
XI. Concave sides of nugget.
  1. Insufficient "on" time.
  2. Insufficient current.
  3. Insufficient width of electrodes.

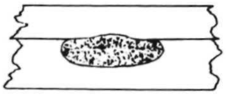
XII. Scuffing.
  1. Insufficient coolant on electrodes.
  2. Excessive current.
  3. Insufficient electrode force.
  4. Insufficient electrical or thermal conductivity of electrodes.
  5. Electrode dressing too sharp.
  6. Rolls not synchronized (when both rolls are driven).

XIII. Lack of tangency or overlap.
  1. Insufficient current.
  2. Excessive "off" time or roll speed.
  3. Insufficient "on" time.

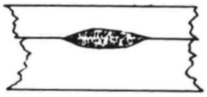
FIGURE 54.–Common defects in resistance spot and seam welds and their causes. Prevalent causes are in order of importance. (Courtesy of Allegheny Ludlum Steel Corp.)

IDEAL NUGGET

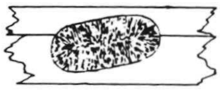




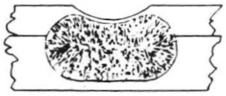
I. Lack of penetration in thin sheet.
  1. Electrode dressing too flat on thin sheet.
  2. Excessive electrode force.
  3. Excessive electrical or thermal conductivity of electrode on thin sheet.
  4. Insufficient electrical or thermal conductivity of electrode on heavy sheet.



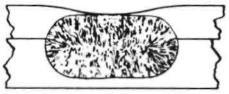
II. Lack of penetration in both sheets.
  1. Electrode dressing too flat.
  2. Excessive electrode force.
  3. Insufficient current.
  4. Insufficient "on" time.



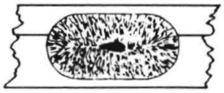
III. Unbalanced nugget.
  1. Misalignment of electrodes.
  2. Off-center dressing of electrode faces.



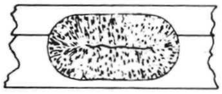
IV. Excessive indentation.
  1. Electrode dressing too sharp at indentation.
  2. Excessive electrode force.
  3. Excessive current or "on" time.
  4. Insufficient width of electrode at indentation.



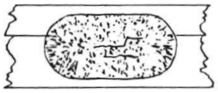
V. Excessive penetration.
  1. Electrode dressing too sharp on thin sheet.
  2. Insufficient electrode force.
  3. Excessive current or "on" time.
  4. Insufficient electrical or thermal conductivity of electrode.
  5. Insufficient coolant.



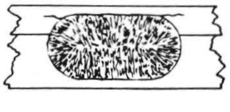
VI. Void in nugget.
  1. Insufficient electrode force.
  2. Excessive current.
  3. Excessive "on" time or roll speed.
  4. Electrode dressing too flat.
  5. Insufficient "off" time.



VII. Cracks in nugget.
  A. Horizontal cracks at center.
    1. Insufficient electrode force.
    2. Insufficient "off" time.
    3. Electrode dressing too flat.
    4. Excessive current or "on" time.



VII. Cracks in nugget.
  B. In crack sensitive metal.
    1. Insufficient electrode force.
    2. Electrode dressing too flat.
    3. Insufficient "off" time.
    4. Insufficient "on" time.



VIII. Cracks in parent metal.
  1. Insufficient electrode width for nugget diameter.
  2. Electrode dressing too sharp.
  3. Excessive roll speed.
  4. Excessive current or "on" time.
  5. Insufficient "off" time.
  6. Insufficient electrode force.

FIGURE 54.–Concluded.

defects, cracks are obviously undesirable, but there is very little evidence that porosity in minor amounts is harmful to properties. The same is true of either insufficient or excessive penetration. Typical defects in resistance spot and seam welds and their causes are given in figure 54 (ref. 140).

REPAIRS

During the development of procedures for joining nickel and nickel-base alloys, consideration should always be given to the possibility that repairs may be necessary. This is especially true in the case of the solid-solution-hardening and age-hardening alloys, where the cost of the base metal and its preparation for joining is very high, and unnecessary scrap losses cannot be afforded. The complex structures usually involved may necessitate repairs because they are not amenable to complete stress analysis prior to welding.

Available information on joining repairs is largely limited to repairing arc-fusion welds by arc-fusion welding techniques. The following discussion, therefore, is confined to repair of fusion welds by arc welding.

Repair of weldments is not desirable. However, it is an almost inevitable occurrence in production operations. When repair welding is necessary it is important to determine what caused the defect; not only for its value in minimizing the need for subsequent repairs, but also in determining a suitable repair-welding procedure.

The repair of the nonaging nickel-base alloys does not usually present serious problems. Analysis of the cause of the defect, its complete removal, and then repair by the original welding procedure altered to eliminate the cause of the defects will usually suffice. Most of the weldments in solid-solution- and age-hardening nickel-base alloys are much more difficult to repair. The extra thermal cycling due to rewelding and the heat treatments necessary must be carefully developed for the situation at hand.

A few general rules applicable to repairing welds in all nickel-base alloys are outlined below. If they are followed, problems will be minimized.

(1) Inspect for repairable flaws immediately after joining and before any subsequent treatment. Multipass welds and products requiring multiple joints should be inspected after each step in the joining operation.

(2) Determine the cause of flaws before repairing so that procedure or design modifications can be made if necessary.

(3) Determine whether or not the flaw can or should be repaired; the repair weld is a heterogeneous area and, as such, may continue to function as a flaw.

(4) Remove the entire flaw and prepare the joint area as in the original or modified procedure.

(5) Insure that metal in the area to be repaired is in the most suitable condition for making the repair.

(6) Provide for local or complete stress relief where necessary.

(7) Develop repair procedures on an experimental basis when repairs must be made on material that has been given its final heat treatment.

Much of the literature on the repair of joints in nickel-base alloys indicates the need for successful repair welds in these alloys. However, very little has been published on the details of the procedural changes required. This suggests that successful repair is an art that depends on the skill and experience of the personnel involved.

Two postweld procedures that were effective in insuring adequate service life for repair-welded René 41 are (ref. 27):

(1) Locally solution-treat the repair weld at 1950° F for 5 min.

(2) Cold-work the surface of the repair weld by hammer peening at room temperature.

Both operations were performed before aging of the repair weld. The effect of hammer peening was to refine the grain size, and perhaps reduce residual stresses.

Three other repair-weld heat-treatment sequences for René 41 have been reported:

(1) Repair, solution-treat, then use a double aging treatment, 1650°/1400° F.

(2) Repair, anneal at 1800° F, air-cool, then age.

(3) Repair, age, then furnace-cool.

The particular attributes of these treatments were not given.

The repairability of René 41 on test assembly parts containing lap joints has been studied (ref. 33). Attempts to make these repairs in the aged alloy were not successful when René 41 filler metal was used. Sound joints were obtained by using Hastelloy W filler metal. Manual welding was used. Synthetic defects were filled with weld metal while the heat input was gradually tapered off to produce suitable weld contours.

Tests on the repair welding of Astroloy revealed some difficulty in producing crack-free original welds in a restrained specimen (ref. 27). By peening immediately after welding and after solution treatment, suitable welds were made. Then, crack-free repair welds on the aged specimens were obtained by peening for 1 min. before reaging.

Important considerations when repair-welding age-hardenable alloys include (ref. 141)

(1) Weld heat input

(2) Weld-backing media

(3) Filler-material selection
(4) Postweld heat treatments
(5) Special welding and grinding equipment.

Specially shaped furnaces for heating only those areas that have been repaired are normally used for many repair welding applications.

Inconel 718 is a nickel-base high-strength alloy that can be repair-welded with relatively little difficulty. Because of its particular age-hardening characteristics, Inconel 718 can be welded in the age-hardened or solution-annealed condition (ref. 142) and in more highly restrained conditions than other alloys.

For Hastelloy X, semiautomatic techniques are preferable to manual procedures for rewelding (ref. 47). Manual methods impose concentrated heat input and thus localized thermal stresses on a weld. These in turn induce cracking in Hastelloy X. This may result in multiple manual rewelds, compounding the original problem. In addition, manual rewelds introduce another variable—that of individual welder's technique.

Very little information is available concerning the repair of defective spot welds. A number of the defects classified as external defects can be repaired by very light machining of the external weld surfaces. The repair of cracked resistance welds must be accomplished by either a fusion-weld process or the use of a mechanical fastener.

CHAPTER 5

Conclusions and Recommendations

With few exceptions, nickel and nickel-base alloys are joined effectively by using conventional joining procedures. To prevent cracking, contamination of the weld joint and adjacent areas by potentially harmful foreign materials must be avoided. Welded joints in some of the high-strength age-hardenable alloys are susceptible to cracking unless the base metal is properly heat-treated prior to joining. The following recommendations are made to cover areas in which available information is limited or inadequate to solve the existing problems.

Contamination.—Many chemical elements that have harmful effects on welds in nickel-base alloys have been identified and remedies have been developed. There is a need, however, to develop nondestructive techniques for detecting the presence and possibly the amount of foreign material on surfaces in or near areas to be joined. Limits for cleanliness of the materials involved in joining also need to be established.

Welding metallurgy.—Additional information is needed on the welding metallurgy of some of the high-strength age-hardenable nickel-base alloys so that more satisfactory joining procedures and techniques can be developed. Studies should be undertaken to obtain the needed information. Studies of the effects of processing variables on joint properties such as prior thermal and working history, welding thermal history, intermetallic reactions, and microstructures should be included. A thorough knowledge of the welding metallurgy of these alloys will be useful in the development of filler metals and joining procedures and for preventing defects and contamination.

Welding conditions.—Conditions for joining and related processing need to be extended for some alloys and processes. Useful information is limited on fabrication of nickel-base alloys by solid-state-joining techniques, plasma arc welding, electron-beam welding, and even MIG and resistance seam welding. Submerged-arc welding has limited applications for nickel-base alloys, partly because of the lack of suitable fluxes and filler metals. The additional developmental work that is needed would be determined by the material that is selected and by processes that are potentially useful, to include some of the relatively new processes such as laser welding, inertia welding, explosive welding, and magnetic-force welding.

Brazing.—The brazing of nickel-base alloys has been studied extensively, but no completely satisfactory brazing filler metals have been developed for high-temperature applications of nickel-base alloys. Fluxes are needed in cases where it is impractical to braze in controlled atmospheres. Prospects for developing more satisfactory filler metals and fluxes for the nickel-base alloys should be determined and, if favorable, followed with the required development programs.

Cracking.—Methods for preventing fissuring or strain-age cracking in some nickel-base alloys need to be developed. Fissures in nickel-base-alloy weldments often are potentially serious defects; their presence is prohibited for many nuclear, steam-power-plant, and aerospace applications. Strain-age cracking also seriously limits the use of some age-hardenable high-temperature nickel-base alloys. Additional research to study the causes and mechanisms of cracking would provide useful information for developing crack-prevention procedures. Such factors as prior thermal history, weld heat-input rates, and postweld heating procedures have important effects; however, overall solutions to the cracking problems are yet to be developed.

Repair welding.—Literature on repair of joints in nickel-base alloys indicates the need for improved repair-welding procedures. Available information on joint repairs is limited to repair procedures for arc-fusion welds by arc-fusion welding. Practically no published information is available on the repair of brazed joints or resistance spot or resistance seam welds. The development of repair procedures by other joining processes also needs to be considered, particularly with some of the high-strength age-hardenable nickel alloys. It appears that information on repair-welding procedures may contribute useful information for developing welding procedures after tack welding.

TD nickel.—TD nickel has some very desirable properties for high-temperature applications, and much work is in progress to develop suitable joining processes for this material. Difficulties in joining TD nickel appear to be related to agglomeration of thoria particles when the metal is melted and to delamination during or after welding. Successful diffusion welding and brazing techniques for TD nickel are now well developed and progress has been made on GTA procedure that may overcome many of the problems. However, studies aimed at developing methods for preventing delamination by procedure or material modifications might still be worthwhile for this kind of material.

Dissimilar metal joining.—It is often desirable to join one nickel-base alloy to a different one or to a completely different material. Problems consequently arise in the proper choice of filler metal and from various heat treatments involved. A great amount of effort has been expended on such joints, but very little data are available in the literature. A few filler-metal alloys have been developed for fusion-welding dissimilar alloys, but the details of procedure and heat-treatment compromise are not often available. The acquiring of available data on joining particular nickel-base alloys to other alloys and the filling of the gaps in these data by experimental programs would be worthwhile.

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APPENDIX

Cross Reference of Present and Previous Trade Designations for Nickel and Nickel-Base Alloys[a]

Designation	Previous designation
Nickel 200	"A" Nickel
Nickel 201	Low Carbon Nickel
Nickel 204	Nickel 204
Nickel 205	"A" Nickel (electronic grade)
Nickel 211	"D" Nickel
Nickel 212	"E" Nickel
Nickel 220	"220" Nickel
Nickel 225	"225" Nickel
Nickel 230	"230" Nickel
Nickel 233	"330" Nickel
Nickel 270	New Product
PERMANICKEL alloy 300	PERMANICKEL alloy
DURANICKEL alloy 301	DURANICKEL alloy
MONEL alloy 400	MONEL alloy
MONEL alloy 401	MONEL "401" alloy
MONEL alloy 402	MONEL "402" alloy
MONEL alloy 403	MONEL "403" alloy
MONEL alloy 404	New Product
MONEL alloy R-405	"R" MONEL alloy
MONEL alloy 406	LC MONEL alloy
MONEL alloy K-500	"K" MONEL alloy
MONEL alloy 501	"KR" MONEL alloy
INCONEL alloy 600	INCONEL alloy
INCONEL alloy 604	INCONEL "600" alloy
INCONEL alloy 625	New Product
INCONEL alloy 700	INCONEL "700" alloy
INCONEL alloy 702	INCONEL "702" alloy

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[a] From Handbook of Huntington Alloys, Huntington Alloy Products Division, The International Nickel Company, Inc., Huntington, W. Va., 2nd Ed. (May, 1963).

Designation	Previous designation
INCONEL alloy 718	INCONEL "718" alloy
INCONEL alloy 721	INCONEL "M" alloy
INCONEL alloy 722	INCONEL "W" alloy
INCONEL alloy X-750	INCONEL "X" alloy
INCONEL alloy 751	INCONEL "X-550" alloy
INCOLOY alloy 800	INCOLOY alloy
INCOLOY alloy 801	INCOLOY "T" alloy
INCOLOY alloy 804	INCOLOY "804" alloy
INCOLOY alloy 805	INCOLOY "805" alloy
NI-O-NEL alloy 825	NI-O-NEL alloy
INCOLOY alloy 901	INCOLOY "901" alloy
NI-SPAN-C alloy 902	NI-SPAN C alloy
NIMONIC alloy 75	NIMONIC 75 alloy
NIMONIC alloy 80A	NIMONIC 80A alloy

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