NASA-SP-5087

TECHNOLOGY UTILIZATION

WELDING OF PRECIPITATION-HARDENING STAINLESS STEELS

An AEC/NASA HANDBOOK

ATOMIC ENERGY COMMISSION UNITED STATES OF AMERICA

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA

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NASA-SP-5087
METALS, CERAMICS, AND
MATERIALS (TID-4500)

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER

WELDING OF PRECIPITATION-HARDENING STAINLESS STEELS

by

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Prepared for

Manufacturing Engineering Laboratory

In Cooperation with

Technology Utilization Office

Under the Supervision of

Redstone Scientific Information Center
U. S. Army Missile Command
Redstone Arsenal, Alabama
MSFC Order No.
Report No. RSIC-598

Subcontracted to

Battelle Memorial Institute
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

Contract No. DA-01-021-AMC-11651(Z)

ABSTRACT

The state of the art of the welding of precipitation-hardening stainless steels is reviewed. Welding preparations, specific welding processes, welding dissimilar metals, and joint quality are discussed.

FOREWORD

Precipitation-hardening stainless steels are potentially useful wherever corrosion resistance and high strength at high temperatures are needed. They were developed initially to meet urgent requirements in World War II, but new alloys and methods of processing have since been introduced to assist engineers concerned with missiles and space vehicles and with various applications in the field of nuclear science and technology.

The Atomic Energy Commission and National Aeronautics and Space Administration have established a cooperative program to make available information, describing the technology resulting from their research and development efforts, which may have commercial application in American industry. This publication is one of the many resulting from the cooperative effort of these agencies to transfer technology to private industry.

This survey is based on information contained in a series of reports originally prepared by Battelle Memorial Institute for the Manufacturing Engineering Laboratory of the George C. Marshall Space Flight Center. The original information has been updated and revised in writing the current, seven volume survey. These volumes were prepared under a contract with the NASA Office of Technology Utilization which was monitored by the Redstone Scientific Information Center.

PREFACE

This report is one of a series of state-of-the-art reports being prepared by Battelle Memorial Institute, Columbus, Ohio, under Contract No. DA-01-021-AMC-11651(Z), in the general field of materials fabrication.

It reviews practices for joining precipitation-hardening stainless steels. Discussions are presented to provide

(1) Information on joining preparations

(2) Information on joining processes

(3) Information on joint quality.

Techniques and special considerations that are normally followed when joining these steels are described.

The information covered was obtained from producers of precipitation-hardening stainless steels, equipment manufacturers, technical publications, reports from Government contracts, and from interviews with engineers employed by major fabricators and producers of these stainless steels. Data from reports and memoranda issued by the Defense Metals Information Center also were used. Experience gained during the preparation of previous reports in the series has also helped in the preparation of this report.

The literature search for this program began with 1955. In accumulating the information necessary to prepare this report, the following sources within Battelle were searched, covering the period January, 1955, to the present:

Defense Metals Information Center

Main Library

Slavic Library

Technical Journal Indexes for the period of 1955 to the present also were searched (Ref. 1), and information was obtained from sources outside of Battelle, viz., the Redstone Scientific Information Center (Refs. 2 and 3), the Defense Documentation Center (Ref. 4), and the NASA Scientific and Technical Information Facility (Ref. 5).

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The authors wish to thank each of these individuals and their organizations for contributions. They also wish to thank Vernon W. Ellzey and John A. Gibson of Battelle, Project Technical Coordinators, and D. Hauser, H. W. Mishler, and H. E. Pattee, who contributed to this report.

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WELDING OF PRECIPITATION-HARDENING STAINLESS STEELS

SUMMARY

The precipitation-hardening stainless steels can be welded by many of the familiar welding processes. Because of the cost of these materials and the critical uses to which they are applied, more care is usually taken in joining than with carbon steels. All of these steels are hardenable by heat treatment. Therefore, it is important that proper filler metals be used if it is intended that the welds have the same heat-treatment response as the base material. It is important also that good cleaning procedures be used to prevent contamination of the weld and the heat-affected zone.

The precipitation-hardening stainless steel alloys can be divided into three types: martensitic, semiaustenitic, and austenitic. Little difficulty is experienced in welding the martensitic and semiaustenitic types. However, the use of joining processes such as gas tungsten-arc or gas metal-arc, which may depend on melting metal of the same composition as the base material should be avoided when the austenitic types are joined.

In general, welding of the precipitation-hardening stainless steels is similar to the more common nonhardenable austenitic stainless steels. When proper techniques are used, joints of excellent quality and high strength can be produced in the precipitation-hardening alloys.

INTRODUCTION

The precipitation-hardening stainless steels were developed during World War II as the result of a need for stronger corrosion-resistant materials than were then available. Knowledge of their properties became available generally between 1946 and 1948 but new alloys and improved heat treatments continued to appear at least until the late 1950s. Newer modifications of the original alloys, usually developed for particular applications, continue to appear periodically. The welding metallurgy of these alloys is discussed by Linnert and Harkins (Refs. 6 and 7).

This report summarizes the information on joining of precipitation-hardening stainless steels that has become available since 1955. In it, the subject is discussed very briefly from the viewpoint of the materials themselves and much more extensively from the viewpoint of joining processes and their applications to these particular materials. Individual joining processes, dissimilar alloy joining, and those special considerations which must be taken when joining the various alloys are described. Inspection techniques and the effects of defects are also described.

The precipitation-hardening stainless steels are used in applications where both high strength and resistance to corrosion or oxidation are desired. They have been used extensively in the aircraft industry for at least ten years. There are also many applications of these steels to boosters and missile systems. The steels have many attributes which make them desirable in a wide variety of structures and components. The precipitation-hardening stainless steels maintain both oxidation resistance and strength to relatively high temperatures. They are among the most fabricable of the high-strength materials. They can be worked by most conventional methods such as rolling, machining, or forging when in a quite low strength condition and then hardened by modest heat treatments subsequent to working. With the exception of the austenitic precipitation-hardening alloys these steels also have good weldability. Most of the common welding processes and a number of other joining processes are usable with these steels. In general, the precautions which have to be taken during welding are no more difficult than those which are required for the common nonhardenable austenitic stainless steels.

The precipitation-hardening stainless steels are relatively high cost and used where a high degree of reliability is needed. Therefore, it is often necessary to choose processes and procedures (shielded metal-arc, electron-beam, brazing) which lead to the production of high-quality joints and minimize scrap losses. Since the corrosion resistance of these steels is one of their major attractions it is necessary to be sure that the joining procedures do not detract from this property. The strength of these steels is obtained through heat treatment. The final heat treatments are such that they can be carried out either during or after the joining operation. However, to obtain optimum properties, it is important that the recommended heat-treating procedures be adhered to.

MATERIALS

The precipitation-hardening stainless steels, when properly heat treated, have good corrosion and oxidation resistance and fracture toughness in addition to high strength. They also have good properties at moderately high temperatures, 1300 F for some of the types available.

TYPES, HEAT TREATMENT, PROPERTIES

The precipitation-hardening stainless steels are grouped into three types (Ref. 7):

(1) Martensitic

(2) Semiaustenitic

(3) Austenitic.

This classification is based on the behavior of the steel when it is cooled from an appropriate austenitizing (solution treating) temperature.

In martensitic types the austenite transforms to martensite on cooling. This transformation causes some hardening. Additional strength is obtained by aging at the proper temperature.

After cooling from the austenitizing temperature to room temperature the semiaustenitic types remain austenitic. Reheating to an appropriate temperature conditions the austenite so that it transforms to martensite on cooling to room temperature or lower. Subsequent aging at proper temperature increases strength over that obtained by the austenite-martensite transformation.

The austenitic types do not transform on cooling to room temperature. Strengthening is obtained by aging the austenitic structure at an appropriate temperature.

A thorough knowledge of the specific strengthening treatment applicable to the particular precipitation-hardening alloy being fabricated is needed in order to attain the full potential of the alloy. Welding procedures must be adapted to these treatments in such a way that loss of strength is minimized or that subsequent strengthening is possible.

For reader convenience, Table I shows the compositions of a number of precipitation-hardening stainless steels. Table II gives some idea of the forms in which these steels can be obtained. Table III shows the heat treatments used to produce different properties in these steels. The reasons for the difference and number of heat treatments is complex. It has been treated in some detail by Ludwigson and Hall (Ref. 8). The properties of the various steels in various conditions of heat treatment are given in Table IV.

WELDING FILLER WIRES

For the fusion-welding processes, filler wires having the same composition as the base plate are generally used for welding the martensitic and semiaustenitic steels to themselves. Welds between these materials and other metals, such as nickel-base alloys, are usually made with stainless steel filler wires of the 300 class. Coated electrodes can only be used with those materials which do not contain aluminum or titanium if the weld is expected to respond to heat treatment.

The austenitic types of precipitation-hardening steels are usually considered to be nonweldable by fusion-welding processes. When they are welded, filler wires developed for this purpose and having quite different composition than the base

TABLE I. COMPOSITIONS OF COMMERCIAL PRECIPITATION-HARDENING STAINLESS STEELS (Refs. 7,9,10,11,12)

Alloy	Composition, percent							
	C	Mn	Si	Cr	Ni	Al	Mo	Other Elements
				Martensitic Types				
Stainless W	0.12 max	1.0 max	1.0 max	16.0-18.0	6.0-8.0	1.0 max	--	1.0Ti max, 0.2N max, 1.0Al max
17-4 PH	0.07 max	1.0 max	1.0 max	15.5-17.5	3.0-5.0	--	--	3.0-5.0Cu, 0.15-0.45Cb+Ta
15-5 PH	0.07 max	1.0 max	1.0 max	14.0-15.5	3.5-5.5	--	--	2.5-5.5Cu, 0.15-0.45Cb+Ta
414 Ti	0.08 max	1.0 max	0.75 max	10.5-12.5	1.5-3.5	--	--	0.75Ti max
ALMAR 362 (typical)	0.03	0.3	0.20	14.5	6.5	--	--	0.80Ti
ALMAR 363	0.05 max	0.3 max	0.15 max	11.0-12.0	4.0-5.0	--	--	10XC min Ti
				Semiaustenitic Types				
17-7 PH	0.09 max	1.0 max	1.0 max	16.0-18.0	6.5-7.75	0.75-1.50	--	--
PH 15-7 Mo	0.09 max	1.0 max	1.0 max	14.0-16.0	6.5-7.75	0.75-1.50	2.0-3.0	--
AM-350	0.12 max	0.90	0.50 max	16.0-17.0	4.0-5.0	--	2.5-3.25	0.10N
AM-355	0.15 max	0.95	0.50 max	15.0-16.0	4.0-5.0	--	2.5-3.25	0.10N
				Austenitic Types				
A-286	0.08 max	1.0-2.0	0.40-1.00	13.5-16.0	24.0-28.0	0.35 max	--	1.0-1.5Ti, 0.10-0.50V
17-10P	0.10-0.14	0.50-1.00	0.60 max	16.5-17.5	9.75-10.75	--	--	0.25-0.30P
HNM	0.30	3.50	0.50	18.50	9.50	--	--	0.25P

TABLE II. FORMS IN WHICH THE PRECIPITATION-HARDENING STAINLESS STEELS ARE AVAILABLE (Refs. 9,10,11,12,13,14,15,16)

Alloy	Forms Available
	Martensitic Types
Stainless W	Sheet, plate, bar
17-4 PH	Sheet, strip, plate, bar, wire, castings, forgings
15-5 PH	Sheet, strip, plate, bar, wire, forgings (heavy sections in plate and bar not recommended)
414 Ti	Sheet, strip
ALMAR 362	Bars, hollow bars, wire, billets
ALMAR 363	Sheet, strip
	Semiaustenitic Types
17-7 PH	Sheet, strip, plate, bar, wire, forgings (heavy sections in plate and bar not recommended)
PH 15-7 Mo	Plate, bar, wire, billets
AM 350	Sheet, strip, foil, welded tubing, bar, wire
AM 355	Sheet, strip, bars, castings, forgings
	Austenitic Types
A 286	Sheet, strip, plate, bar, wire, billets, tubing
17-10 P	Plate, bar, wire, billets
HNM	Plate, bar, billets

TABLE III. HEAT TREATMENTS USED WITH COMMERCIAL PRECIPITATION-HARDENING STAINLESS STEELS (Refs. 7,9,10,11,12)

Alloy	Anneal	Hardening Treatments	Designation of Condition
		Martensitic Types	
Stainless W	1850-1950 F, air cool	950-1050 F for 30 min, air cool	Aged
17-4 PH	1900 F, oil or water quench	900 F for 1 hr, air cool	H900
15-5 PH	1900 F, oil or air cool	900 F for 2 hr, air cool	H900
	Ditto	925-1150 F for 4 hr, air cool	H925-H1150
	"	1400 F for 2 hr, air cool, 1150 F for 4 hr, air cool	H1150M
414 Ti	Used in condition furnished by mill		--
ALMAR 362	1500 F, one hr per inch	900 F for 4 hr, air cool	--
	Ditto	1100 F for 3 hr, air cool	--
ALMAR 363	1500 to 1700 F	Stress relieve at 900-1000 F	--
		Semiaustenitic Types	
17-7 PH	1950 F		Annealed or Condition A
	Ditto	1400 F for 1-1/2 hr, cool to 60 F, 1050 for 1-1/2 hr, air cool	TH1050
	"	1750 F for 10 min, air cool, -100 F for 8 hr, 950 F for 1 hr, air cool	RH950
	"	Cold roll 60%, 900 F for 1 hr, air cool	CH900
15-7 Mo	Same as 17-7 PH	Same as 17-7 PH	Same as 17-7 PH
AM-350	1950 F, cool rapidly		Annealed or Condition A
	Ditto	1710 F, rapid cool, -100 F for 3 hr, 850 F for 3 hr, air cool	SCT
	"	1375 F for 3 hr, air cool, 850 F for 3 hr, air cool	Double age
	"	Cold roll, 850 F for 3 hr, air cool	CRT
AM-355	1875 F, cool rapidly		Annealed or Condition A
	Ditto	1710 F, cool rapidly, -100 F for 3 hr, 850 F for 3 hr, air cool	SCT
	"	1710 F, 1375 F for 3 hr, air cool, 850 F for 3 hr, air cool	Double age
	"	Cold roll, 850 F for 3 hr, air cool	CRT
	"	1710 F, cool rapidly, -100 F for 3 hr, cold roll, 850 F for 3 hr, air cool	SCCRT

TABLE III. (Continued)

Alloy	Anneal	Hardening Treatments	Designation of Condition
		Austenitic Types	
A-286	1800 F or 1650 F, oil quench		Annealed
	1800 F or 1650 F, oil quench	1325 F for 16 hr, air cool	Aged
17-10P	2050 F for 30 min water quench	--	Annealed
	Ditto	1300 F for 24 hr, water quench	Aged
	"	1300 F for 12 hr, water quench, 1200 F for 24 hr, water quench	Double aged
HNM	2050 F, cool rapidly	--	Annealed
	Ditto	1350 F for 16 hr, air cool	Aged

TABLE IV. PROPERTIES OF COMMERCIAL PRECIPITATION-HARDENING STAINLESS STEELS (Refs. 7,9,10,11,12)

Alloy	Condition	Size and Shape	Ultimate Tensile Strength, 1000 psi	0.20 Percent Offset Yield Strength, 1000 psi	Elongation, percent in 2 inches	Modulus of Elasticity, 10^6 psi	Hardness
			Martensitic Types				
Stainless W	Aged 950 F	Sheet, 0.030-0.060 in.	195-225	180-210	3-4	28.0	R_C 39-47
17-4 PH	H 900	Bar stock	195	180	13	28.5	R_C 43
15-5 PH	H 900	Bar stock	200	185	14	28.5	R_C 44
	H 1150	Bar stock	145	125	19	28.5	R_C 33
	H 1150M	Bar stock	125	85	22	28.5	R_C 27
414 Ti	As received	Sheet and strip	110	95	15	29.0	R_B 100
ALMAR 362	Aged 900 F	Bar	188	182	13	28.5-30.0	--
	Aged 1050 F	Bar	152	144	18	--	--
ALMAR 363	As received	Strip	123	106	12	27.9	--
			Semiaustenitic Types				
17-7 PH	TH 1050	Sheet, 0.020 in. and over	200	185	9	29.0	R_C 43
	RH 950	Sheet, 0.020 in. and over	235	220	6	29.0	R_C 48
	CH 900	Sheet, 0.020 in. and over	265	260	2	29.0	R_C 49
PH 15-7 Mo	TH 1050	Sheet, 0.020 in. and over	210	200	7	29.0	R_C 44
	RH 950	Sheet, 0.020 in. and over	240	225	6	29.0	R_C 48
	CH 900	Sheet, 0.020 in. and over	265	260	2	29.0	--
AM-350	SCT	Strip	201	172	13	--	--
	Double aged	Strip	195	155	10	--	--
	CRT	Strip	226	220	5	--	--
AM-355	SCT	Strip	216	181	11	--	--
	Double aged	Strip	195	155	10	--	--
	CRT	Strip	245	240	8	--	--
	SCCRT	Strip	290	280	2	--	--

TABLE IV. (Continued)

Alloy	Condition	Size and Shape	Ultimate Tensile Strength, 1000 psi	0.20 Percent Offset Yield Strength, 1000 psi	Elongation, percent in 2 inches	Modulus of Elasticity, 10^6 psi	Hardness
			Austenitic Types				
A-286	Aged	Bar stock	146	100	25	29.1	293 Bhn
17-10P	Aged	Bar stock	137	68	25	29.0	286 Bhn
	Double aged	Bar stock	143	77	20	29.0	302 Bhn
HNM	Aged	Bar stock	168	124	20	29.0	R_C 38

metal are used. When filler wires of the same composition as the base plate are used, serious weld-metal cracking may occur.

Table V shows the filler wire recommended for use with the various steels.

MATERIAL CONDITION FOR WELDING

Production of satisfactory joints in any material depends on proper selection of joining method, on proper joint design, and on proper cleaning of the material prior to making the joint. In some materials, including the precipitation-hardening stainless steels, satisfactory joints also depend on the material being in the proper metallurgical condition prior to joining and proper treatment of the material after joining. Choice of process and joint design will be discussed in following sections of this report. Prewelding condition and postweld conditioning will also be discussed.

It is necessary to be sure that corrosion and oxidation resistance of these alloys are not lowered during fabrication operations. Corrosion resistance can be seriously affected by contamination during joining or heat-treating operations of either base metal or weld metal by dirt, oils, grease, crayon marks, etc. on the surface (Ref. 17). Carbon pickup from surface contaminants can adversely affect heat-treatment response as well as corrosion resistance. Sulfur pickup can affect both corrosion resistance and properties. Other materials can affect various properties adversely. Consequently, the surfaces of all parts must be clean before joining or heat treatment is undertaken.

Dirt and films of oil and grease can be removed by washing or by degreasing operations. Soaps can be removed with hot water. Removal of soluble oils, tallow and fats require a hot alkaline solution wash followed by a hot water rinse.

Oxide films of two types are encountered on precipitation-hardening stainless steels (Refs. 9,10,11,14). Light oxide films are produced by the aging or

TABLE V. ELECTRODES RECOMMENDED FOR WELDING PRECIPITATION-HARDENING STAINLESS STEELS (Refs. 7,9,10,11,12,14,16,18)

Alloy	Coated Electrodes	Filler Wires	Dissimilar Joints
		Martensitic Types	
Stainless W	Timken 16-25-6 Timken 16-25-6	A-286 Hastelloy W	Hastelloy W[a] Type 309[b]
17-4 PH	W 17-4 PH Type 308[c]	W 17-4 PH Type 308	Type 309[d] Type 309 Cb[d]
15-5 PH	W 17-4 PH Type 308	W 17-4 PH Type 308	Type 309 Type 309 Cb
414 Ti	Type 308, Type 309	414 Ti	Type 309
ALMAR 362	Type 308, Type 309	ALMAR 362[e]	--
ALMAR 363	Type 308, Type 309	ALMAR 363	--
		Semiaustenitic Types	
17-7 PH	W 17-4 PH, Type 308 Type 309	W 17-7 PH W 13-9 PH[f]	Type 310[g] Inco Weld A[h] Inconel 82[h]
PH 15-7 Mo	Type 308, Type 309	WPH 15-7 Mo (sheet) WPH 13-7 Mo (plate)[i]	Type 310 Type 309
AM 350 and AM 355	AM 355 Type 308 Type 309 Type 310	AM 350 AM 355	Type 308 Type 309
		Austenitic Types	
A 286	Type 309 Type 310	Inco 92 Hastelloy W	Type 309 Type 310
17-10 P	Arc welding not recommended.		
HNM	Arc welding not recommended.		

Footnotes for Table V

(a) Nickel-base electrode or filler wire corresponding to American Welding Society E NiCr-1 or ER NiCrFe-7. In general, when electrodes or filler wires are used whose composition differs from the base plate, the weld cannot be expected to have high strength even if heat treated after welding.

(b) Stainless steel electrode or filler wire of about 25Cr-12Ni corresponding to AWS E309 or ER309.

(c) Stainless steel electrode or filler wire of about 20Cr-10Ni corresponding to AWS E308 or ER308.

(d) Type 309 electrode containing Cb to improve corrosion resistance of weld deposit.

(e) Special filler wire analysis containing a maximum of 0.40 Ti is recommended.

(f) As special analysis to be used when it is expected that a lot of dilution will occur.

(g) Stainless steel electrode or filler wire containing about 25Cr-20Ni corresponding to AWS E310 or ER310

(h) Nickel-base electrodes corresponding to AWS E Ni1 and ER Ni3.

(i) A modified filler composition containing less chromium than 17-7 PH designed for use in joints where a large amount of filler wire is to be deposited.

conditioning heat treatments. Light to heavy scales are produced by solution annealing treatments and hot-working operations. Light oxides can be removed by acid pickling treatments. A typical treatment recommended for 15-5 PH (Ref. 9) is a few minute pickle in 10% nitric-2% hydrofluoric acid (by volume) at 110-140 F.

Heavier oxide coatings and scales may be removed by grit or sand blasting or by a descaling operation carried on at moderate temperatures. The procedure suggested for 15-5 PH (Ref. 9) is to loosen the scale in a caustic-permanganate solution at 160-180 F. This takes about 60 minutes and is followed by a water rinse. The scale is then pickled off using the acid solution given above for removing light oxides. Fused salt descaling processes should not be used since the temperatures required may age these steels.

Acid pickling times should be closely controlled for the precipitation-hardenable steels. In the heat-treatment condition which is best for fabrication operations some of these steels may be somewhat susceptible to stress-corrosion cracking.

If, after cleaning, parts are exposed to the open atmosphere they may become recontaminated. Dust and fine particles of foreign material may settle on them. In shop atmospheres they may become coated with oil, grease, or similar contaminants from the air. Joint areas may be cleaned of this type of contamination by wiping with lint-free cloths dampened with a solvent such as methyl-ethyl ketone. However, it may be advisable to prevent recontamination after cleaning. This can be done by using the cleaned materials within a short time after cleaning. If this cannot be done, they can be protected by covering with lint-free and oil-free wrappings.

The effectiveness of a cleaning operation can be evaluated by various methods. Contact resistance measurements can be used although this technique is not widely used. A common method of evaluating the effectiveness of descaling and pickling operations is to observe water breaks during the rinsing operation. If the cleaned surface is uniformly wet by the water the surface is considered clean. If the water collects in drops or patches it is said to "break". The presence of a water break indicates that the surface has not been well cleaned.

More detailed descriptions of metal cleaning processes and techniques can be found in the literature (Ref. 19). Typical solutions and procedures for use after complete removal of soils such as oil and grease are given in Tables VI and VII.

Most of the precipitation-hardening steels have a preferred heat-treatment condition in which joining operations are undertaken. (Ref. 14). For arc welding, this condition is usually the one which permits hardening by postwelding heat treatment. When brazing, the brazing cycle may be adjusted to accomplish part of the heat treatment. For other joining procedures, the hardened condition may be preferred since it may not be desirable to heat treat after joining. Table VIII indicates the preferred base-metal conditions for a number of joining processes.

JOINT PREPARATION

The method of joint preparation for the precipitation-hardening stainless steels can be any one of the following: machining (all types), shearing, grinding, flame cutting (iron powder or flux) and plasma cutting. The applicable machining, shearing, and grinding techniques are those used for most stainless steel shaping and will not be covered here. Flame cutting techniques which utilize either iron oxide or special fluxes in the cutting flame to melt or react with the chromium oxide that is formed have been developed for cutting the stainless steels. These, however, have been largely replaced by plasma-arc cutting. The plasma-arc provides the necessary heat to melt the chromium oxide which is the main hinderance to normal flame cutting of the stainless steels. The high-speed gas (plasma) stream also blows the molten metal away from the cutting face. The plasma arc can be used to cut any material that is electrically conductive. Therefore, this method is commonly used to cut metals that are difficult or impossible to cut efficiently by conventional metal-cutting methods such as the oxyacetylene cutting process.

TABLE VI. TYPICAL SEQUENCE OF PROCEDURES FOR PICKLING PRECIPITATION HARDENING STAINLESS STEELS (Ref. 19)

Cycle		Solution: Composition, % by volume[a]	Solution: Operating temperature, F	Solution: Immersion time, min[b]
1	Sulfuric acid dip	15 to 25 H_2SO_4[c]	160 to 180	30 to 60
2	Water rinse[d]	--	Ambient	--
3	Nitric-hydrofluoric acid dip	5 to 12 HNO_3; 2 to 4 HF	120 max	2 to 20
4	Water rinse[d]	--	Ambient	--
5	Caustic-permanganate dip[e]	18 to 20 NaOH; 4 to 6 $KMnO_4$[f]	160 to 200	15 to 60
6	Water rinse[d]	--	Ambient	--
7	Sulfuric acid dip	15 to 25 H_2SO_4[c]	160 to 180	2 to 5
8	Water rinse[d]	--	Ambient	--
9	Nitric acid dip	10 to 30 HNO_3	140 to 180	5 to 15
10	Water rinse (dip)	--	Ambient[g]	--

(a) Acid solutions are not inhibited.
(b) Shorter times are for lower-alloy steels; longer times are for more highly alloyed types, such as 309, 310, 316, 317, and 318.
(c) Sodium chloride (up to 5% by weight) may be added.
(d) Dip or pressure spray.
(e) Sometimes used to loosen scale.
(f) Percent by weight.
(g) Boiling water may be used to facilitate drying.

(Note: In the precipitation-hardened condition, the high hardness and the nature of the structure make the steel susceptible to strain cracking during pickling. Therefore, the immersion time in the acid solutions should be as short as possible.)

TABLE VII. COMPOSITIONS OF ELECTROLYTIC PICKLING SOLUTIONS FOR VARIOUS STEELS (Ref. 19)

Material being pickled	Electrolytic unit	Acid in solution, % by volume			
		HCl	H_2SO_4	HNO_3	H_3PO_4
Low-carbon sheets	A-c bipolar	2 to 3	--	--	--
Low-carbon continuous strip	A-c bipolar	2 to 3	--	--	--
	D-c direct contact	--	5 to 15	--	--
Plain carbon steel couplings	D-c direct contact	--	1	--	--
Ferritic and martensitic stainless	A-c anodic	--	3 to 5	1	--
		--	--	1	3 to 5

TABLE VIII. PREFERRED BASE-METAL CONDITION FOR JOINING (Refs. 9,10,11,12,14)

Alloy	Arc Welding[a]	Resistance Welding	Brazing
	Martensitic Types		
Stainless W	Annealed	Aged	--
17-4 PH	Annealed for light sections, overaged for heavy sections	Aged	--
15-5 PH	Annealed for light sections, overaged for heavy sections	Aged	--
414 Ti	As received	Aged	--
ALMAR 362	Annealed	Annealed or aged	--
ALMAR 363	As received	As received	--
	Semiaustenitic Types		
17-7 PH	Annealed	Transformed or aged	Annealed or aged
PH 15-7 Mo	Annealed	Transformed or aged	Any
AM-350	Annealed or aged	Annealed or aged	--
AM-355	Annealed or aged	Annealed or aged	--
	Austenitic Types		
A-286	Not recommended[b]	Annealed or aged	--
17-10P	Not recommended	Aged	--
HNM	Not recommended	--	--

(a) Conditions given are those which should be used to get maximum strengths when welding these alloys to themselves.

(b) May be welded with specially designed filler metals; Inco 92 or Hastelloy W.

Plasma-Arc Cutting. For cutting metals, the plasma arc is established between the electrode and the workpiece; various gases are used to form the plasma, depending on the particular metal being cut. In contrast to the oxy-acetylene process, where the cutting speed is limited by the rate at which the chemical reaction between oxygen and iron proceeds, the cutting speed of the plasma arc is limited only by the power available for cutting and the quality of the cut itself. The quality of cutting is governed largely by the choice and/or magnitude of the following process variables: (1) type of plasma gas, (2) gas flow rate, (3) cutting speed, and (4) stand-off distances. Torch parameters such as the size of the cutting tip and the selected power level are more in the nature of dependent variables. Once they are selected, the process variables can be adjusted to produce acceptable cutting. Care must be exercised in making such adjustments when optimum cutting conditions are required, since minor variations affect the smoothness of the cut surface, the amount of dross adhering to the cut, and the production of an undesirable bevelled surface.

Applications. There is no indication in the literature that plasma-arc equipment has been used to cut the precipitation-hardening stainless steels. However, one of the equipment producers reported that two commercial steel supply firms had cut such materials. (Ref. 20). Contact with one of these organizations revealed that considerable quantities of 17-4 PH steel have been cut on a production basis for general industrial use. (Ref. 21). Contoured shapes and blanks have been cut without difficulty and, apparently, joint preparations for subsequent welding operations were cut as well. Some evidence of edge cracking was noted when a square blank was cut too close to the edges of a plate. Thicknesses up to one-inch were cut. The second firm also reported cutting 17-4 PH steel with plasma-arc equipment. (Ref. 22). Bar stock, about 2 inches thick by 3 inches wide was cut for use in fabricating helicopter bell cranks. Although no difficulty was experienced in cutting this stock, cracks were evident in the finished part.

However, it is not known when the cracks were first evident, since the bar stock was ground, drilled, and machined to form the bell crank. The parts were also heat treated after fabrication. When materials are cut with the plasma arc, a heat-affected zone exhibiting microstructural changes from that of the original base metal occurs; depending on the heat input, the zone may be as wide as 0.010 inch.

Experience in plasma-arc cutting of precipitation-hardening stainless steels indicated that the cutting conditions are similar to those established for cutting Type 304 stainless steel. These conditions are as follows:

TABLE IX. PLASMA-ARC CUTTING CONDITIONS FOR TYPE 304 STAINLESS STEEL (Ref. 21)

Thickness, in.	Tip Diameter, in.	Plasma Gas Flow Rate, cfh			Power, kw	Cutting Speed, ipm
		N_2	H_2	A		
1/4	3/32	90	5	--	30	35
1/2	3/32	90	5	--	30	25
1	7/64	120	10	--	50	30
1	9/64	150	20	--	100	55
1	1/8	--	20	145	30	25
1-1/2	9/64	150	20	--	100	30
1-1/2	1/8	--	20	145	50	20
2	9/64	150	20	--	100	15
2	7/32	--	60	110	100	30
3	3/16	200	20	--	150	10
3	7/32	--	60	110	100	25
4	3/16	200	20	--	200	6
4	7/32	--	60	110	100	25
5	7/32	--	70	130	150	10
6	7/32	--	70	130	150	6
8	7/32	--	70	130	150	4

Note: For a given plate thickness there is more than one set of conditions that will produce acceptable cuts.

DISTORTION CONTROL AND TOOLING

Because of the pattern of heating and cooling which develops during welding, any welded part is subject to a certain amount of distortion. The amount of distortion occurring in welded precipitation-hardening stainless steels may be greater than that encountered with other materials, particularly low-alloy steels. This is because the precipitation-hardening stainless steels expand more on heating and do not conduct the heat of the arc away from the weld area nearly as fast as do low-alloy steel and other metals. Precipitation-hardening stainless steels also are subject to growth and contraction during heat treatment. For these reasons, greater care is required to control distortion in precipitation-hardening stainless steel than is required for other metals.

Ling-Temco-Vought measured the shrinkage across GTA weld joints in various thicknesses of PH 15-7 Mo sheet (Ref. 23). The sheet thicknesses and the welding conditions used were:

Sheet Thickness, inch	Voltage, volts	Current, amp	Travel Speed, ipm	Filler Wire Size, inch	Wire-Feed Speed, ipm	Heat Input, joules per inch
0.040	12	100	15	0.030	25	4,800
0.060	12	160	14	0.030	29	8,230
0.085	12	190	10	0.030	35	13,680
0.125	12	190	6	0.030	40	22,800

The amount of shrinkage that occurred in these welds is shown in Figure 1. A formula was developed for calculating the shrinkage as a function of the sheet thickness. This formula is:

$$\text{Weld shrinkage (inch)} = 0.183 \times \text{sheet thickness (inch)} + 0.00045$$

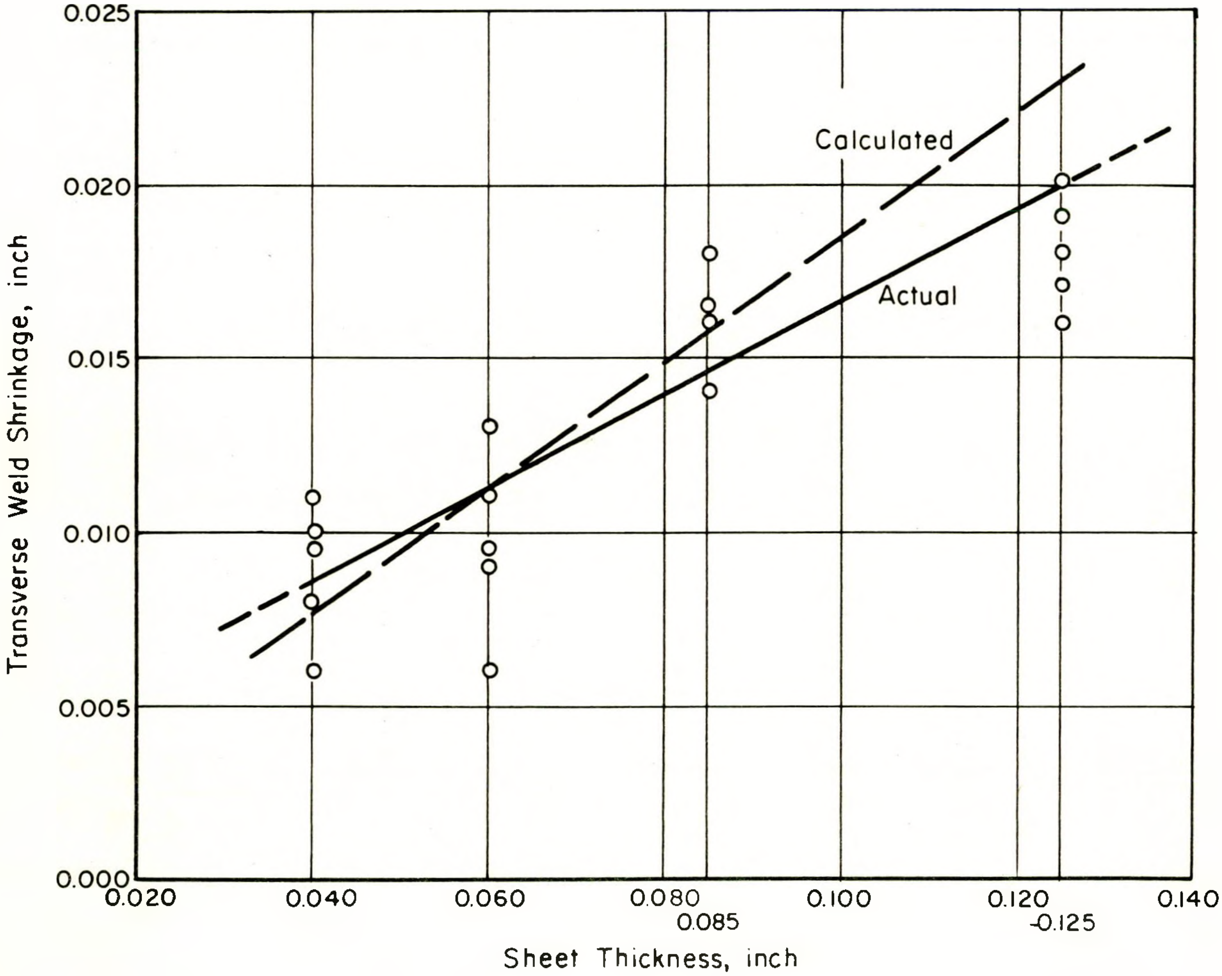


FIGURE 1. SHRINKAGE OF GTA WELDS IN PH 15-7 Mo SHEET (Ref. 23)

The calculated values also are plotted in Figure 1. These shrinkage values would be affected by changes in any of the welding parameters and in the type of jigging. For these welds, the pieces were held in a 3-foot-long stake welder fixture. Spacing between hold-down clamps on opposite sides of the joint was 0.215 inch. A copper backing strip with a groove width of 0.140 inch also was used. Ling-Temco-Vought cautions that these values should not be extended to other materials, thicknesses beyond this range, or the use of other welding parameters.

The type of welding process used also will influence the amount of weld shrinkage. This is because different heat inputs and different amounts of metal melted are associated with different welding processes. The most striking example is that of electron-beam welding where the weld joint is much narrower than the joints produced by arc-welding processes. In Figure 2, the shrinkage across the weld joint for both electron-beam and GTA welds in PH 15-7 Mo is plotted (Ref. 24). The shrinkage of electron-beam welds tends to be independent of material thickness. This is because the width of electron-beam welds is relatively constant for material in this thickness range.

A butt weld in precipitation-hardening stainless steel sheet will become bowed in the direction of the weld. This is due to the lengthwise shrinkage of the weld metal and is called the "drawstring effect". The weld also shrinks across its width and, in so doing, will cause the two pieces being welded to draw together and close up the joint ahead of the weld. Surprisingly, plates and sheets may spread apart if the welding travel speed is high enough. Welds in plate do not bow appreciably because the restraint is so high. However, they are subject to angular distortion. This type of distortion occurs in plate because a beveled joint and a number of passes are used. The opening at the top of the joint is considerably wider than at the bottom of the joint. Moreover, the root pass acts as a pivot, keeping the parts from pulling in uniformly across the joint width. Then, as each pass after the root pass is put in and shrinks, it will pull the two

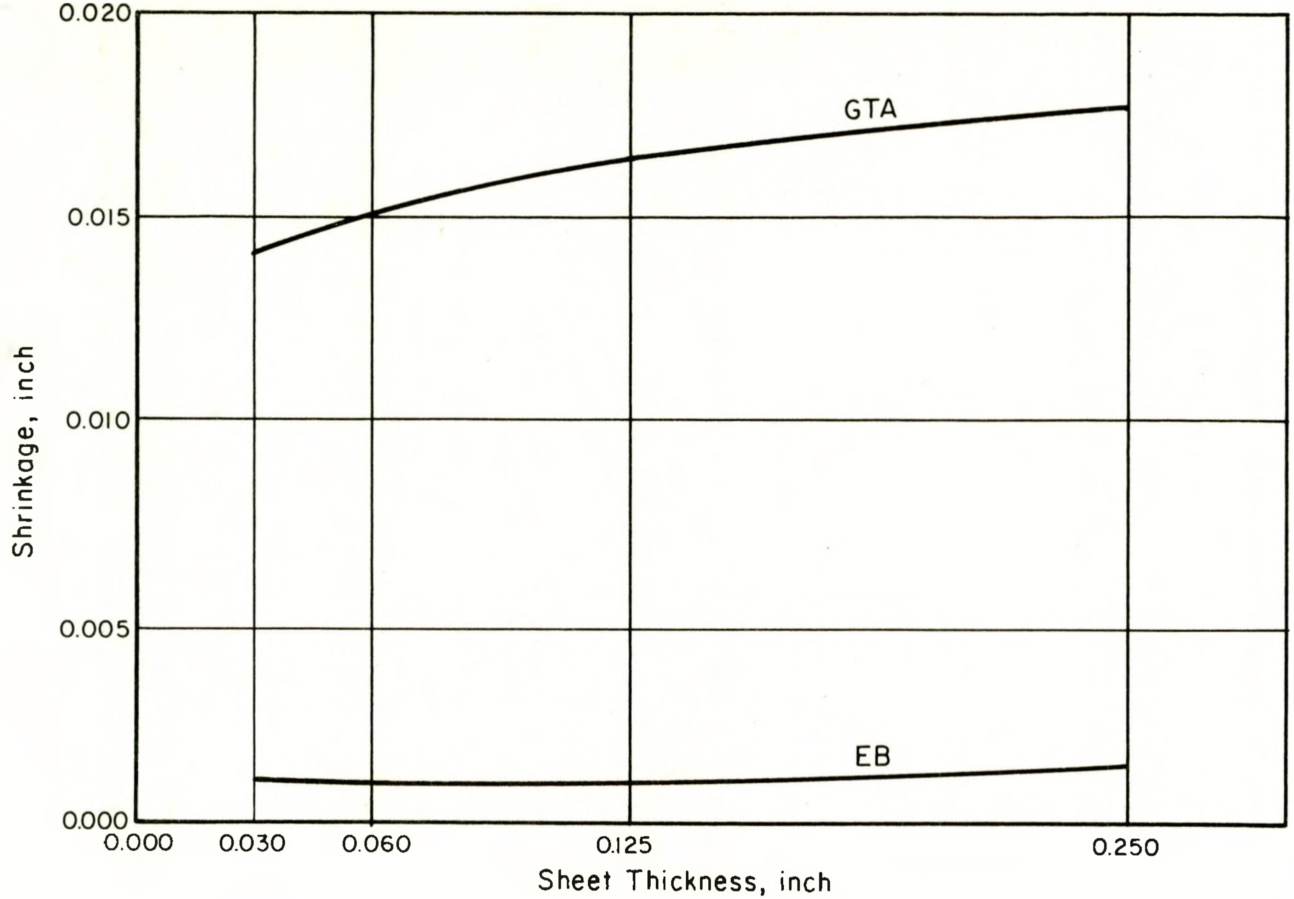


FIGURE 2. TRANSVERSE WELD SHRINKAGE (ELECTRON BEAM AND GTA WELDS IN PH 15-7 Mo) (Ref. 24).

pieces together at an angle. Fillet, lap, and corner welds also are subject to similar distortions.

Growth or contraction occurring during heat treatment of these alloys is a very important factor, especially in laying out parts to be fabricated in the annealed condition and subsequently heat treated. The typical dimensional changes occurring during heat treatment of these alloys are as follows (Ref. 25):

Alloy	Treatment	Dimensional Change	
		Type	Amount, in./in.
17-7 PH	Transformation treatment (1400 F)	Growth	0.004
	Aging treatment (950 or 1050 F)	Contraction	0.0004 to 0.0007
	Condition A heated at 1750 F for 10 minutes, air cooled, plus -100 F for 8 hours	Growth	0.0045 to 0.0051
	Heating Condition R 100 for 1 hour at 950 F	Contraction	0.00028 to 0.00032
AM 350	Subzero cool and temper	Growth	0.0045
	Double age	Growth	0.004
17-4 PH	Aging at 900 F	Contraction	0.0004 to 0.0006

There are three basic methods of controlling distortion caused by welding: (1) reduce shrinkage forces by controlling weld-bead sequence and heat input, (2) offset the parts, and (3) restrain the joint by tacking and by using jigs and fixtures.

DISTORTION CONTROL BY REDUCTION OF SHRINKAGE FORCES

Shrinkage forces cannot be eliminated. However, there are methods for reducing the distortion caused by shrinkage forces. These methods include avoiding overwelding, being sure of good fit-up, using backstep and skip welding, and controlling heat input and preheat.

Excess weld metal may increase distortion because there is more metal to shrink. Ideally, the surface of a butt weld should be flush with the surface of the base metal. This is difficult to do, so butt welds are made with a small amount of reinforcement. However, the amount of reinforcement should be kept as small as possible. For a fillet or lap weld, the strength of the joint is determined by the throat depth of the weld. Excess weld metal does not increase the strength here, for once the fillet is large enough the base metal becomes the weakest link in the chain. The size of lap and fillet welds should not exceed the size indicated in specifications or on drawings. The surface of these welds should be as flat as the welder can make them.

One way to avoid excess weld metal and, thus, reduce distortion is to use correct joint spacing (gap or root opening). Use a joint opening wide enough for good penetration, but no wider. If the opening is too wide, more weld metal will be needed to fill the gap and more shrinkage will occur. Correct joint gap usually is no more than 1/16 inch regardless of the welding process or thickness. No gap is possible with many processes and thin materials.

Backstep and skip welding can be used for long continuous welds. In both of these methods, short intermittent welds are made. For backstep welding, each bead is started some distance ahead of the previous bead and is welded back to join the beginning of the previous bead. A skip weld is a series of short beads made some distance apart. The gaps between the beads are welded in after the beads have cooled. These techniques usually are used with shielded metal-arc welding or with manual GMA welding.

When welding thin material, lengthwise or "drawstring" bowing of the part is usually the most serious type of distortion. This can be reduced by using as small an electrode size (shielded metal-arc and GMA welding) and as low a current setting as is practical. In thicker material, crosswise or angular distortion is more apt to occur. This can be reduced by cutting down the number of passes, making the passes heavier and increasing the welding travel speed.

DISTORTION CONTROL BY OFFSETTING PARTS AND BALANCING SHRINKAGE FORCES

If the operator can estimate the amount of shrinkage or distortion that will occur in a particular weld joint, he can correct for this distortion by offsetting the parts. The welding distortion then will pull the parts into the correct position or alignment.

This method is particularly good for T-joints. The "leg" of the T is offset before the weld is made. The shrinkage of the weld pulls the leg to its proper 90-degree position. If two welds are to be made, one on each side of the leg, the "cap" of the T could be bent slightly before the welding with the same results after the welds are complete. Butt welds and corner welds made from one side can be offset before welding to compensate for distortion. The amount of offset required will vary greatly, depending on the material thickness, welding parameters, welding process, and welding technique. No specific data are available for the amount of offset required for precipitation-hardening stainless steels.

Offsetting or prebending usually is used for short welds and simple shapes. For long welds, or for welds in complex structures, these methods may become too complicated to give satisfactory results.

Shrinkage forces can often be balanced against each other to prevent distortion. Double V- or U-joints can be welded without angular distortion if the proper welding sequence is used. If the beads are deposited alternately on opposite sides of the joint, the shrinkage of one bead will be balanced against the shrinkage from the bead made on the other side of the joint and the parts should remain flat. The same results can be obtained in T-welds by making short intermittent welds on opposite sides of the leg.

DISTORTION CONTROL BY TACK WELDING AND JIGGING

Usually the most practical way to prevent distortion is to fasten or clamp the parts rigidly before welding so that they cannot move. For simple welds, this can be done by tacking before welding. For large parts for complex shapes or for critical assemblies, jigs or fixtures are needed.

Tack Welding. Tack welds are used chiefly to keep the parts from drawing together or spreading apart during welding. In other words, they are used to maintain the right joint alignment and gap. They will not prevent angular or lengthwise distortion or bowing. Tack welds should always be used when the parts are not clamped in a jig and sometimes they are useful even with a jig. The spacing between tack welds depends on the thickness of the material--the thinner the material the closer the tack welds. They may be as close as 3/4 inch, if necessary.

Tack welds, however, can be a source of defects when the subsequent welds are made. Tack welds are subject to cracking if they are too small. For this reason, they should always be inspected and, if cracked, ground out before subsequent welding. Sound tack welds should be ground to a smooth contour that blends evenly into the base metal. This will facilitate complete melting of the tack weld into the subsequent weld.

Jigging. Jigs are used for two purposes: (1) to hold the pieces during welding, and (2) to prevent distortion. For holding pieces together for welding, jigs can be used with any thickness of material. To control distortion, though, jigging is not very effective for material over about 1/4 inch thick. The shrinkage forces that develop in welds of thick material become so great that a jig to hold these forces would be too bulky to be practical. Thus, other means of controlling distortion should be used when welding thick stainless steel sections.

Jigs can be simple or complex, depending on the shape of the parts being welded. The complex jigs usually are intended for only one specific job run. Simple jigs, though, can be used for a wide variety of welding jobs.

The simplest jig consists of a backup bar, two hold-down bars, and some C-clamps (Figure 3). The backup bar should be grooved so that proper weld penetration can be obtained. This groove should be about 3/32-inch deep and about 10 times wider than the sheet thickness but never less than 3/16-inch wide. Copper

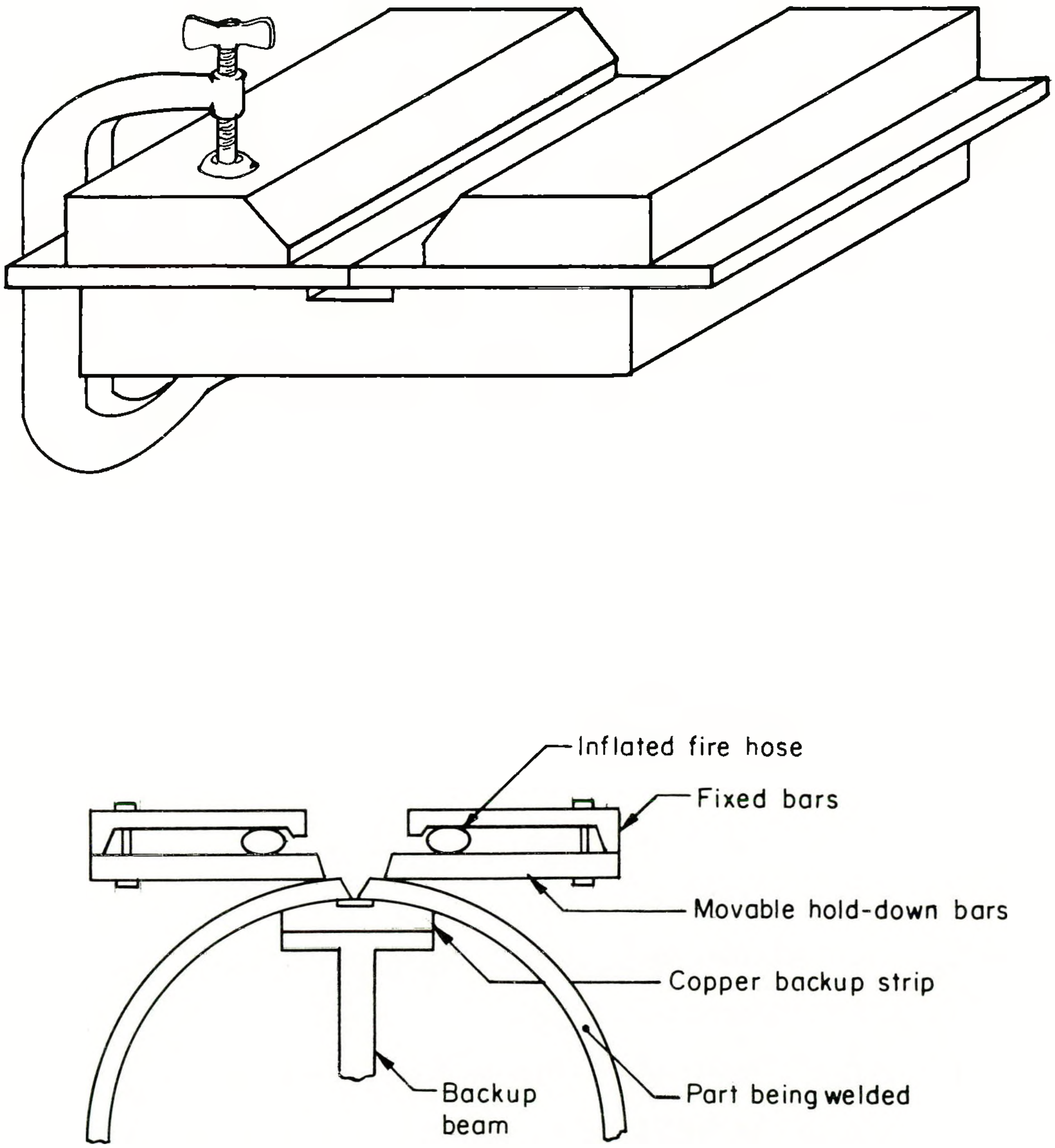


FIGURE 4. SCHEMATIC SKETCH OF "FIRE-HOSE" JIGGING

is the best material for the backup bar. The weld metal will not fuse to the copper and the copper will act as a chill bar to cool the weld joint quickly to aid in reduction of distortion. The hold-down bars may be of steel or copper with copper preferred if rapid cooling is desired. Water-cooled jigs are sometimes used to confine the welding heat and promote fast cooling. The edges of the hold-down bars are beveled so that there is room to weld.

Both the hold-down and backup bars should be rigid so that the weld shrinkage will not bend the jig parts. The bars should be at least 1/2 inch thick. A good practice is to make the backup bar of steel with a grooved copper insert. Added rigidity can be obtained by using angles, T-sections, or T-beams for the hold-down and backup bars.

Where long welds are to be made, these simple jigging systems often become awkward to use. If the pieces being welded are also wide, it may be possible to apply clamps only at the ends of the joint. To clamp the center of the joint would require C-clamps with impractical throat depths. For such applications, special jigs have to be built or purchased commercially. One jigging method uses common fire hose as the clamping device. The fire hose is inflated with air under pressure to force the clamping fingers against the parts being welded (Figure 4). Other jigs use various types of mechanical fingers to apply the clamping pressure and are called stake welders or stake fixtures (Figure 5).

Fillet welds and corner welds can be jigged using the simple "angle-iron and C-clamp" equipment. The sharp corners on the angle pieces should be ground off so that good fitup can be obtained. As with butt welds long fillet or corner joints will require special jigs. The examples given for butt welds can be modified easily for fillet and corner welds. The same jigging principles also apply to edge and lap welds.

The tooling used in resistance welding precipitation-hardening stainless steels is generally similar to tooling used in resistance welding other materials. Resistance-welding tooling consists of suitable fixtures or jigs to hold the parts

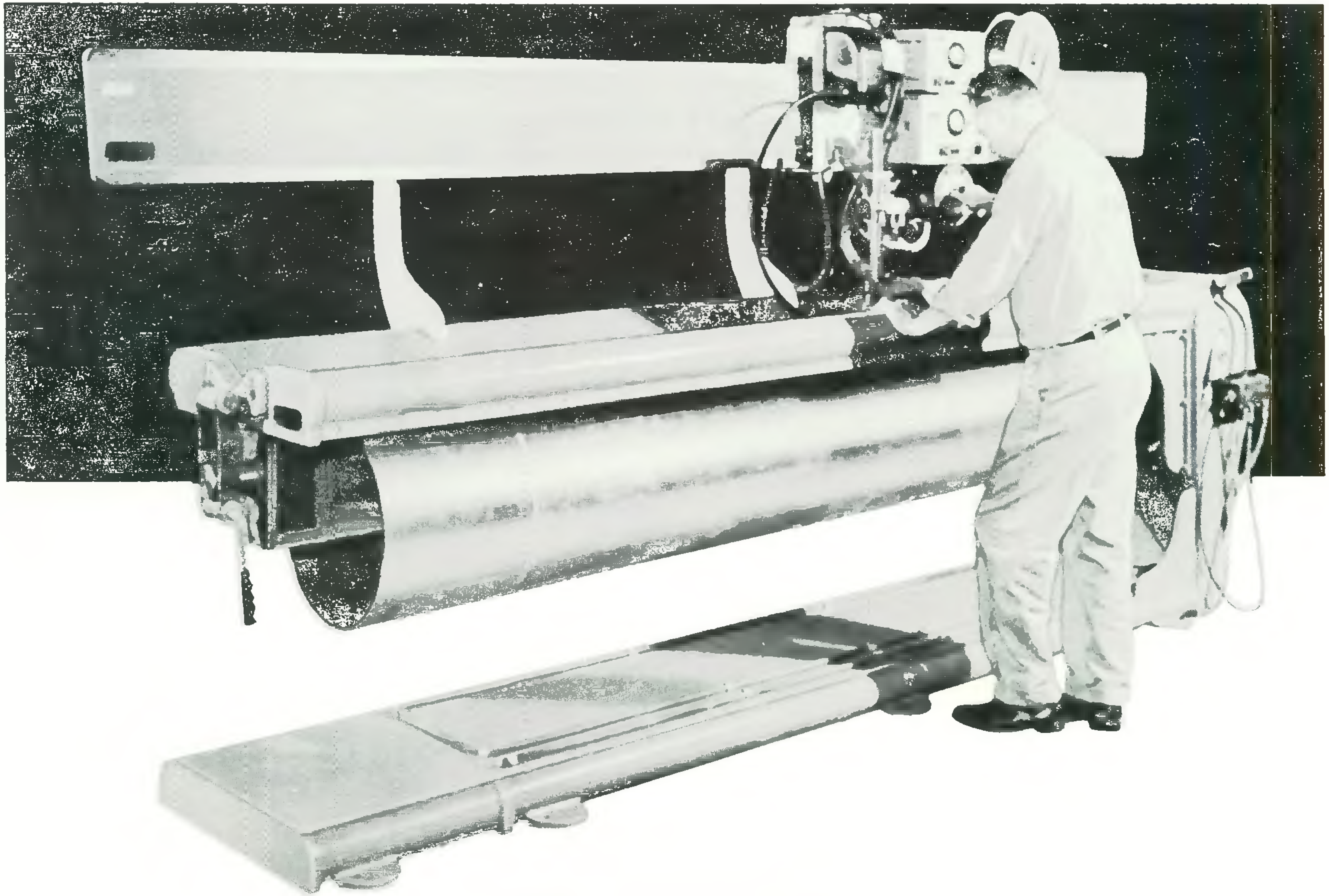


FIGURE 5. "STAKE" FIXTURE

Courtesy of Airline Welding and Engineering Company in proper position for welding and to conduct welding current to the parts. Sometimes tooling is also 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 precipitation-hardening stainless steels. Generally, this means that nonmetallic or nonmagnetic components should be used exclusively, and the tooling should not contaminate the base metal.

JOINING PROCESSES

The precipitation-hardening stainless steels can be divided into two groups on the basis of their weldability by fusion-welding processes. The martensitic and semiaustenitic steels make up the first group. These steels are normally weldable with filler metals which have compositions which are the same or similar to those of the base metal. In general, weldments in these types can be heat treated to high strength after welding.

The second group is made up of the austenitic steels. Except in thin gages, these are not weldable with filler metals of the same or similar composition. When fusion-welded, low-strength stainless steel filler metals are usually used. These filler metals avoid the weld cracking problems that occur when fillers of the same composition as the base plate are used. Even when specially formulated fillers are used, heat-affected zone cracking may still be a problem. Welds made with normal stainless steel fillers cannot be heat treated to increase strength. Consequently, either the strength of the joint must not be important in service or the joint has to be thickened to reduce the service stresses in the weld.

Widespread use has been made of the arc-fusion and resistance-welding processes for fabricating the precipitation-hardening stainless steels. Other processes have also been used. Wide use has been made of brazing and some use of solid-state welding has been reported. Table X shows the joining processes which have been used for fabricating the precipitation-hardening stainless steels. These processes are described briefly in Appendix A. Detailed descriptions of the processes and the equipment used can be found in References 19 and 26. Oxyacetylene and other oxy-fuel gas processes are not discussed here (except for upset-butt welding) since they are not generally used for fabricating aerospace components and structures.

FUSION WELDING

Fusion-welding processes are those in which substantial amounts of molten metal are produced during the joining operation. Fusion-welding processes frequently are thought of being only the arc-welding processes. However, there are other processes that rightfully belong in this category, particularly resistance welding. All of the fusion-welding processes that commonly have been used in the fabrication of precipitation-hardening stainless steel hardware are included in this section.

The arc-welding processes have had wide application in joining precipitation-hardening stainless steels. The most frequently used has been the gas tungsten-arc process (GTA). Shielded metal-arc and gas metal-arc (GMA) processes have been used to a lesser degree while the use of submerged-arc welding is quite limited. Electron-beam welding is finding ever widening acceptance, particularly in the joining of thin sheet. Plasma welding is only in the experimental stage, although the application of plasma for cutting is relatively common.

Resistance spot welding has been used extensively for fabricating a limited number of the precipitation-hardening stainless steels. Seam welding, projection welding, and flash welding also have been used for these alloys but to a lesser degree. The use of high-frequency resistance welding and stud welding has been limited.

TABLE X. PROCESS SELECTION CHART FOR THE PRECIPITATION-HARDENABLE STAINLESS STEELS (Ref. 14)

Steel	Process									
	Shielded Metal Arc	Submerged Arc	Gas Tungsten Arc	Gas Metal Arc	Plasma Arc	Electron Beam	Resistance Spot, Seam and Projection	Flash	Solid State Welding	Brazing
					Martensitic					
17-4 PH	X[1]	NR[2]	X	X	X	X	X	X	X	Copper base and Ni dispersion braze materials at solution treat temperature
15-5 PH	X	NR	X	X	X	X	X	X	X	Same as 17-4 PH
414 Ti	NR	NR	X	X	X	X	X	X	X	Silver brazing materials
ALMAR 362	NR	NR	X	X	X	X	X	X	X	--
					Semiaustenitic					
17-7 PH	NR	NR	X	X	X	X	X	NR	X	Silver base and nickel-manganese braze materials at conditioning temperature
PH 15-7 Mo	NR	NR	X	X	X	X	X	NR	X	Same as 17-7 PH
AM-350	X	X	X	X	X	X	X	X	X	Silver base or nickel base braze materials at either conditioning or solution treat temperature
AM-355	X	X	X	X	X	X	X	X	X	Same as AM-350

TABLE X. (Continued)

Steel	Process: Shielded Metal Arc	Submerged Arc	Gas Tungsten Arc	Gas Metal Arc	Plasma Arc	Electron Beam	Resistance Spot, Seam and Projection	Flash	Solid State Welding	Brazing
					Austenitic					
A-286	NR	NR	NR	NR	NR	NR	X[3]	X	X	Silver base alloys at aging temperature
17-10P	NR	NR	NR	NR	NR	NR	X[3]	X	X	Same as A-286
HNM	NR	NR	NR	NR	NR	NR	X[3]	X	X	Same as A-286

(1) Special electrodes must be used if weld is to be hardenable. All of the steels in this table can be welded with non-hardenable stainless steel electrodes, but a low-strength weld will be obtained.

(2) NR means not recommended for hardenable welds. Non-hardenable stainless steel materials can be used, but welds will be low strength.

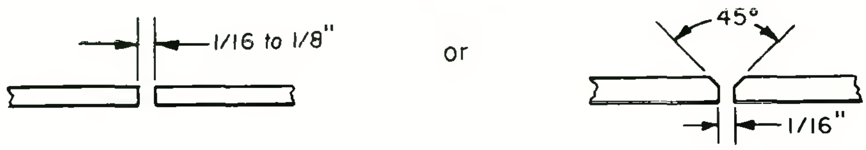
(3) Projection only.

Shielded Metal-Arc Welding. The shielded metal-arc process (also called metal-arc, stick, or covered-electrode welding) can be used for welding the precipitation-hardening stainless steels that do not contain aluminum (17-4 PH, AM 355, and AM 350). (This process cannot be used for welding the aluminum-containing steels due to the difficulty in recovering aluminum in the base metal.) Shielded metal-arc welding is a very versatile process that can be used for producing high-quality welds in all positions (flat, horizontal, or vertical). With care, steel as thin as 1/16 inch can be welded by this process.

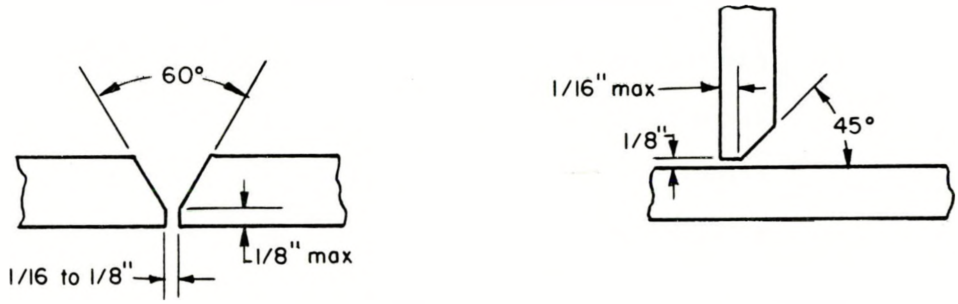
Electrodes are available commercially for welding 17-4 PH, AM 350, and AM 355. These electrodes have a titania covering that enables the electrodes to be used on either a-c or d-c. Normally, an electrode with the same composition as the base metal is used. If the welds will not be heat treated to achieve high strengths, standard austenitic stainless steel electrodes can be used, e.g., E308 or E316 (Ref. 27). 17-4 PH electrodes may be used to weld 17-7 precipitation-hardening steel (Ref. 7). Reasonable heat-treatment response can be obtained if high weld-metal dilution is obtained. This means the operator should "dig in" the electrode when welding to melt as much base metal as possible.

The covering on these electrodes has a tendency to pick up moisture from the air if the electrodes are not kept in a closed container. Moisture in the electrode coating may cause porosity in the weld metal. Thus, electrodes from freshly opened containers should always be used if possible. If electrodes must be used that have been out of the container for some time, they should be dried in an electrode drying oven. Usually, it is well to keep electrodes in a drying oven after the container has been opened. The temperature of the drying oven should follow the electrode manufacturer's recommendations.

Types of Weld Joints. Typical weld joints for use with the shielded metal-arc process in precipitation-hardening stainless steel are shown in Figures 6 and 7. The root gap and root face dimensions shown in these figures



a. 1/8 to 3/16-inch-thick base metal



b. 3/16 to 1/2-inch thick base metal

FIGURE 6. JOINT DESIGNS FOR SHIELDED-METAL-ARC WELDS IN PRECIPITATION-HARDENING STAINLESS STEEL, BASE METAL UNDER 1/2 INCH THICK

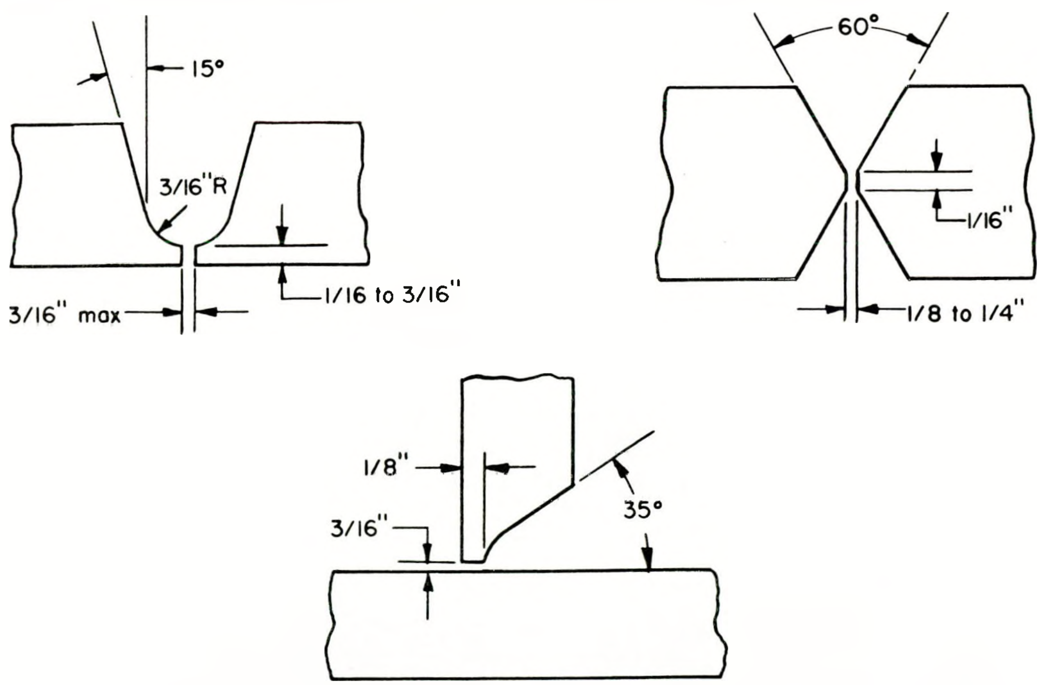


FIGURE 7. JOINT DESIGNS FOR SHIELDED-METAL-ARC WELDS IN PRECIPITATION-HARDENING STAINLESS STEEL, BASE METAL OVER 1/2 INCH THICK

are approximate and may vary according to the thickness of plate being joined, the welding position, and the diameter of the electrode.

For welding plate where thickness is 3/16 to 1/2 inch, the edges of the plate are beveled to produce a 60-degree V-joint (Figure 6). Welds in material 1/4 inch or more thick should be made with a minimum of two passes.

For welding plate which thickness exceeds 1/2 inch, a single- or double U-groove or a double V-groove should be used (Figure 7). A J-groove should be used for fillet and corner welds. Although the U- and J-grooves are more expensive to prepare, less filler metal is required to fill them. Cleaning between weld passes is required and the backside of the root pass should be ground to solid metal before welding from the backside of a double U- or double V-joint.

Welding Procedures. No unusual procedures are required for shielded metal-arc welding of precipitation-hardening stainless steels. Welders trained in the welding of conventional stainless steels have little difficulty in learning to make good welds in precipitation-hardening stainless steels. Recommended welding conditions are available from the electrode supplier, although these recommendations should serve as a guide only. The best conditions for any application will vary, depending on joint shape and alignment, metal thickness, proximity of chill bars, and the operator's preference. Typical conditions are given in Table XI.

Precautions. The heat-treatment response of welds in precipitation-hardening stainless steels will vary with the composition of the weld metal. The composition of AM 350 and AM 355 welds should match the composition of the base metal as closely as possible so that the weld-metal strength will be similar to the base-metal strength (Ref. 7). However, the weld-metal composition can be affected by the travel speed, arc length, and the operator's technique. For this reason, qualification of the welding operator is very important to ensure that

TABLE XI. SUGGESTED WELDING CONDITIONS FOR SHIELDED-METAL-ARC WELDING OF PRECIPITATION-HARDENING STEELS

Electrode Diamter, inch	Arc Voltage, volts	Current, amp	
		Flat	Vertical and Overhead
1/16	20-22	25-40	20-35
5/64	20-23	35-55	30-55
3/32	22-25	40-70	35-65
1/8	23-25	70-120	55-85
5/32	23-26	100-145	80-120
3/16	24-27	125-190	100-155

the operator is using procedures that will produce weld joints with the desired properties. In general, shielded metal-arc welding of precipitation-hardening stainless steels should be done with a short arc length. Long arcs cause a loss of chromium from the weld metal.

In multipass welding, each bead should be cleaned and wire brushed before the next bead is deposited to ensure that slag is not trapped in the weld. If welding is done from both sides, the underside of the root pass should be ground or chipped out to clean, solid weld metal before the back weld is made to eliminate slag entrappment and ensure full penetration.

It is important to always fill the crater before breaking the arc. A thin crater will be weak and may crack on cooling. Crater cracks are very difficult to remove when the subsequent pass is deposited. If they do occur, the crater should always be ground out before the next pass is deposited.

After the weld is completed, all welding slag should be removed from the surface of the weld joint. Particles of welding slag left on the surface can cause corrosive attack during subsequent service, particularly, if high-temperature service is anticipated.

Gas Tungsten-Arc Welding. The manual and automatic GTA welding processes are the most frequently used processes for joining precipitation-hardening stainless steels. High-quality weld joints can be produced in all types of precipitation-hardening stainless steels with thicknesses up to about 1/4 inch. GTA welding can also be used for welding material thicker than 1/4 inch, but welds can be made more economically and faster if the GMA process is used for these thicknesses. With GTA welding, the welding heat, the amount of penetration, and the bead shape can be very accurately controlled. Interpass or elaborate postweld cleaning operations are not required as there is very little spatter, there is no slag crust, and the bead surface is smooth and uniform. GTA welding operations can be manual, mechanized, or fully automatic.

2

Most precipitation-hardening stainless steel is GTA welded using direct current at straight polarity. Conventional d-c power supplies (the motor generator or rectifier) having a drooping volt ampere characteristic are used for GTA welding. These power supplies usually are equipped with high-frequency arc starting devices for initiating the welding arc. Alternating current power supplies sometimes are used for welding the precipitation-hardening stainless steels that contain aluminum. This is because the alternating welding current tends to eliminate the aluminum oxide scum which sometimes forms on the surface of the molten weld metal. Alternating current power supplies should be equipped with devices for superimposing a high-frequency current.

Electrodes for GTA welding precipitation-hardening stainless steels are made from either pure tungsten or tungsten alloy with 1% thorium with the thoriated tungsten electrodes being preferred. Compared to pure tungsten, the thoriated electrode lasts longer, makes arc starting easier, has a more stable arc especially at low currents, and has less tendency to spit off particles of tungsten into the weld metal. The size of the electrode to use is governed by the amount of welding current that is required to make the weld. The electrode sizes to be used for various current settings are given in Table XII. If the wrong size of electrode is used, the arc may be hard to control or tungsten may be deposited in the weld metal.

For welding precipitation-hardening stainless steel, the electrode is ground to a sharp point or to a point where there is a slightly rounded tip. During welding a small ball of molten tungsten will form at the end of the electrode. As long as this ball is small it will not interfere with good arc control. However, if the current is set too high for the size of the electrode being used, the molten ball will become larger and the arc will be harder to control. A danger also exists that a large molten ball on the end of the electrode may become

TABLE XII. RECOMMENDED CURRENT RANGES FOR TUNGSTEN AND THORIATED TUNGSTEN ELECTRODES (Ref. 26)

Electrode Diameter, inch	Current Range, amperes[a]				
	Direct Current Straight Polarity, Both Pure Tungsten and Thoriated Tungsten	Alternating Current, Unbalanced Wave Power Supply		Alternating Current, Balanced Wave Power Supply	
		Pure Tungsten	Thoriated Tungsten	Pure Tungsten	Thoriated Tungsten
0.040	15-80	10-60	15-80	20-30	20-60
1/16	70-150	50-100	70-150	30-80	60-120
3/32	150-250	100-160	140-235	60-130	100-180
1/8	250-400	150-210	225-325	100-180	160-250

(a) These current values are for argon shielding gas.

dislodged and drop into the molten weld puddle. The obvious solution to avoid such tungsten contamination is to use the next larger size tungsten electrode.

Care must be exercised to avoid contamination of the end of the electrode. Electrode contamination usually is caused by touching the end of the electrode to the molten weld metal. When the electrode is contaminated, a large molten ball of a mixture of tungsten and the base metal will form on the tip of the electrode. If this happens, the welding operation should be halted and the electrode reground to remove the contaminated portion.

Filler-wire feeders are used in mechanized and automatic GTA welding to add filler wire to the weld at a closely controlled speed and location. The wire is fed from a spool by motor-driven feed rolls whose speed can be regulated accurately over a wide range. An adjustable metal guide tube directs the wire into the weld puddle at the correct angle and direction. The guide tube usually is attached to the welding torch so that the correct alignment between the electrode and the filler wire can be maintained. In manual welding, a foot control usually is used to regulate the welding current. The operator can start the weld at a low current and then build up the current to the desired level during welding by operating the foot control. At the end of the weld, the current can be lowered to eliminate a crater which may otherwise form. Also, the current can be reduced when tying in with a weld already made.

Argon or helium or a mixture of the two gases are used to protect the end of the electrode, the arc, and the molten weld puddle from the atmosphere during welding.

Argon is used for manual GTA welding of precipiation-hardening stainless steel for several reasons. In argon, the arc is smooth and easy to start and control. Compared with helium, the arc in argon is cooler which means that the weld puddle will be smaller and the welding operator will have better control over penetration. Argon is more economical to use than helium because it is cheaper and because lower flow rates are used with argon. Since argon is heavier than air, while helium is lighter than air, the argon blankets the weld area better than helium. For helium to shield as well as argon, the flow rate must be two to three times that of argon. Argon also provides better shielding if there are any drafts or breezes that might disturb the gas shield.

Helium usually is used for automatic welding because, first, the arc is hotter, and second, the arc length can be controlled more accurately than with argon. The higher heat of helium-shielded arc permits high travel speeds to be used. The travel speed can be increased as much as 40% by using helium instead of argon. Automatic GTA welding is frequently used in high production applications, when high travel speeds are important. Occasionally, helium may be used for manual GTA welding very thick parts where a great many passes are required to fill the weld joint. By using helium instead of argon, heavier passes can be made and the joint can be completed quicker. In automatic welding, the arc length is controlled through measurement of changes in arc voltage. These changes can be measured more easily when the arc is shielded with helium. Thus, the arc length can be controlled more accurately in helium than in argon.

A mixture of argon and helium is sometimes used in automatic GTA welding. The mixture is usually used to obtain an arc that is less penetrating than the arc obtained with pure helium. A mixture of argon and helium might be used when welding very thin stainless steel to prevent burnthrough. The arc will become cooler as the amount of argon is increased. Usually, mixtures are 25 argon-75 helium, or 50 argon-50 helium. These, as well as other mixtures of argon and helium, can be obtained already mixed in tanks from gas suppliers. Special valves and controllers are also available that allow the user to mix the gases in any ratio desired from tanks of pure argon and helium.

Filler wire is used in GTA welding to fill up a joint that has a V- or U-shape or a joint that has poor fitup. Filler wire should be used when making butt welds in 1/16 inch or thicker material so that the weld will have a good bead reinforcement. Filler wire also should be used when making fillet welds. Lap and corner welds require filler wire when the base material is over about 1/8 inch thick.

The diameter of the filler wire that is used will depend upon the thickness of the material to be welded and the current settings. Filler wire that is too large will take too much of the welding heat to melt it and the weld may lack penetration. If the filler wire is too small, the welder may have difficulty feeding it into the weld pool fast enough to build up the weld bead properly.

Proper guiding of the filler wire into the weld puddle also is important. Weld-metal porosity has been caused by erratic guiding of the wire (Ref. 28). This porosity was eliminated by always guiding the wire into the puddle on the joint centerline and at the puddle leading edge.

Types of Weld Joints. Figure 8 shows recommended butt joints for GTA welding various thicknesses of precipiation-hardening stainless steels Although these joint designs are recommended for PH 15-7 Mo sheet, they could be used for the other precipitation stainless steels as well.

Welding Procedures. The GTA welding of precipiation-hardening stainless steels requires no unusual welding procedures. However, optimum quality welds require close control of the welding operation and the exercise of certain precautions.

Conditions used for welding the precipitation-hardening stainless steels are similar to those used to weld the austenitic stainless steels. Typical conditions are given in Table XIII. When welding the precipitation-hardening stainless steels that contain aluminum the scum that forms on top of the molten weld metal may become a problem to the operator. In this case, the operator may prefer to use alternating current instead of direct current straight polarity. This scum normally does not create any major problems, however, it is a nuisance, detracts from the appearance of the weld, and tends to hinder flow of the molten weld metal.

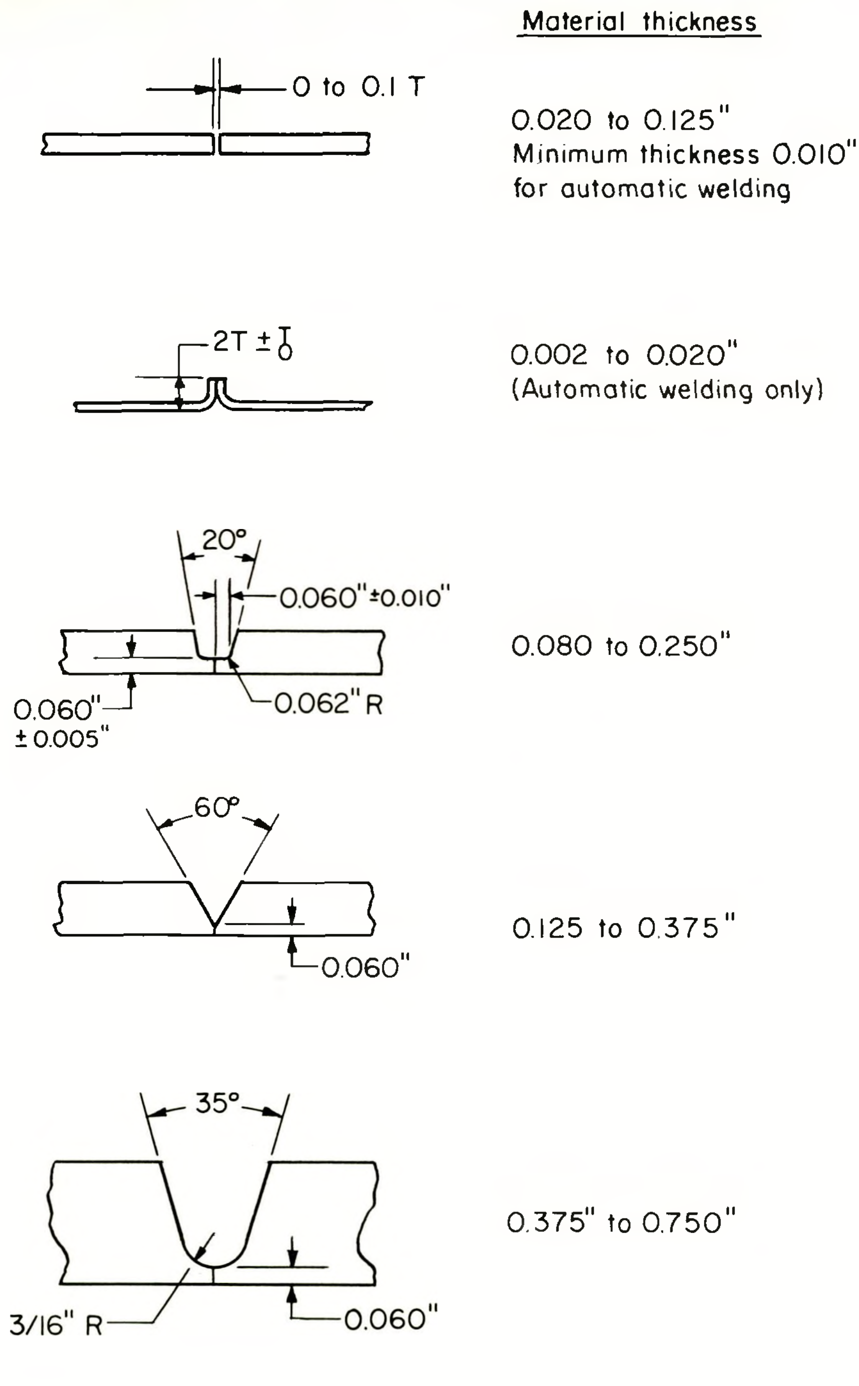


FIGURE 8. TYPICAL BUTT JOINTS FOR GTA WELDING PRECIPITATION-HARDENING STAINLESS STEEL

TABLE XIII. CONDITIONS FOR GAS TUNGSTEN-ARC WELDING PRECIPITATION-HARDENING STAINLESS STEELS

Material	Thickness, inch	Welding Current, amps	Voltage, volts	Travel Speed, ipm	Wire Feed Speed, ipm Wire Diameter 0.020	 0.030	 0.045	 0.062	Shielding Gas	Shielding Gas Flow, cfh	Reference
PH 15-7 Mo	0.063	59	12	10				10	A	Not given	83
		218	12	45				28.5	A	"	83
		280	12	60				37	A	"	83
	0.020	70	11.5	18	42	20			He	24	27
	0.040	125	11.5	15.5	55	23			He	28	27
	0.060	165	11.5	14		29			He	35	27
	0.080	195	11.5	12.5		37	17		He	43	27
	0.100	220	11.5	11.5		47	22		He	52	27
	0.120	240	11.5	10.5		62	27		He	60	27
AM 350	0.040	50	12	20			10		He	60	84
		50	12	10			5		He	20	84
		88	12	50		No Wire Added			He	50	84
	0.050	66	11	10			4		He	60	84
	0.090	115	12.5	10			8		He	60	84
AM 355	1/8, 3/16 (two passes)	130-170	14-17	2-1/2-4-1/2		Manual Feed of 3/32 inch wire			A	20	85

The film also tends to act as an insulating barrier to the weld metal which reduces the heat input into the weld, thus a somewhat higher welding current may be necessary to obtain complete penetration when using direct current. Some arc wander also may be induced by the scum.

Protection of the underside of the weld joint always is necessary to prevent oxidation of the backside of the weld and to insure smooth contour of the weld metal on the backside of the joint. The most common way of protecting the backside of the weld joint is to use a grooved copper bar. The pieces being selded are held tightly against the bar with clamps. By drawing heat away from the weld zone, the copper backup bar prevents burnthrough to the joint. If too much metal should be melted, the backup bar will support the molten metal and prevent it from dripping through the joint. If the backup bar is not used, the underside of the weld bead would be open to the atmosphere and could pick up contaminants from the air. For welding light gage precipitation-hardening stainless steel, better protection is obtained by reducing the size of the groove in the copper backup bar. For general welding of these thicknesses of material the groove should be about 3/32 inch wide and about 0.015 inch deep. With the bar in place only a small amount of air contained in the groove itself can contact the underside of the joint. Thus, much less contamination can occur. However, if it is desired to completely shield the underside from air, a gas-shielding backup bar can be used. This bar has provisions for flowing argon or helium into the groove and thus only an inert gas comes in contact with the underside of the bead. A typical backup bar of this type is shown in Figure 9.

For critical applications, the dimensions of the groove are very important. The chilling effect of the copper backup bar varies inversely with the width of the groove, i.e., the narrower the groove, the greater the amount of chilling. This, in turn, affects the width of the fusion and heat-affected zones of the weld joint. Ling-Temco-Vought has specified the dimensions of the groove for

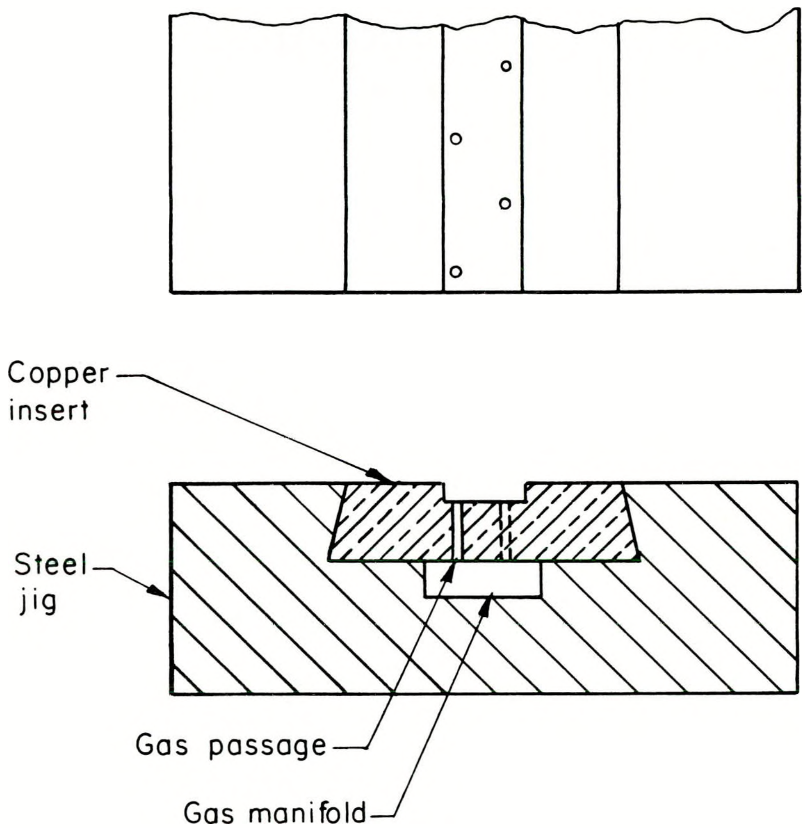


FIGURE 9. TYPICAL BACKUP BAR WITH GAS BACKING

various thicknesses of PH 15-7 Mo sheet so that uniform weld joint widths are ensured (Ref. 28). These dimensions are given in Table XIV.

Cooling of the weld joint also is affected by the spacing of the hold-down bars. Typical spacing as used by Ling-Temco-Vought for various thicknesses of PH 15-7 Mo sheet also is given in Table XIV. The copper hold-down bars were continuous for material thinner than 0.060 inch. When segment bars were used on thicker material, the spacing between segments was kept less than 0.010 inch. The hold-down bars should have some flexibility so that good metal-to-metal contact between the bar and the workpiece is ensured.

The dimensions of backup groove and the clamp spacing given in this table were developed for a specific application (XB-70 skin panels) and are not necessarily the best for all welding operations. The point that is being made is that for critical use where uniform weld joint dimensions and quality are required, these jigging parameters must be closely controlled so that uniform cooling is obtained. As a corollary, close control of the welding parameters also is required, otherwise precise jigging is meaningless.

For best results, the arc should be started on a tab of the same material as the base metal. The use of the starting tab permits the establishment of a steady arc before welding of the joint is begun. It also allows time to adjust welding conditions and to observe any irregularities in arc behavior. The arc should be initiated by high-frequency starting rather than by touching the electrode to the starting tab. Touching the electrode to initiate the arc can cause contamination of the electrode which in turn may result in an erratic arc. It is best to use a runoff tab at the end of the weld so that the weld can be ended outside of the weld joint. This avoids the formation of a crater within the weld joint. If it is impossible to use a runoff tab and the weld must be ended within the joint, then techniques should be used to fill in the crater before the arc is broken off. The presence of a crater in the weld joint can lead to the formation of cracks in the weld metal.

TABLE XIV. DIMENSIONS FOR TOOLING FOR GTA WELDING PH15-7Mo SHEET (Ref. 28)

Sheet thickness, inch	Backup groove width, inch	Backup groove depth, inch	Hold-down clamp spacing, inch
0.002-0.010	0.025±0.005	0.015±0.005	3/32±1/32
0.011-0.020	0.045±0.005	0.030±0.005	3/16±1/32
0.021-0.040	0.090±0.005	0.030±0.005	3/16±1/32
0.041-0.060	0.187±0.010	0.040±0.010	1/4 ±1/32
0.061-0.090	0.250±0.015	0.040±0.010	5/16±1/16
0.091-0.190	0.312±0.015	0.060±0.010	1/2 ±1/16
0.191-0.250	0.375±0.032	0.060±0.010	5/8 ±3/32
0.251-0.500	0.437±0.032	0.060±0.010	7/8 ±3/32

Precautions. During the course of making the weld, several difficulties may be encountered. The more common of these include arc wander, tungsten pickup, disruption of the gas shielding, and lack of penetration.

Arc wander is the name given when the arc moves from one side of the joint to the other instead of playing on its centerline. Arc wander in GTA welding of precipitation-hardening stainless steel can be caused by a contaminated electrode, a blunt electrode, a magnetic field, or air drafts. Arc wander due to a contaminated or blunt electrode usually is a rapid movement of the arc from one side of the joint to the other. If the arc moves back and forth slowly or stays on one side of the joint, magnetic fields or air drafts are probably the cause. Arc movement caused by a magnetic field usually can be solved, or at least minimized, by changing the position of the ground cable attachment. Sometimes steel jaws of hold-down clamps become magnetized and also can disrupt the arc.

Bits of tungsten can be picked up in the weld metal if the arc is struck on the workpiece or if the welding current is too high. Starting the arc by touching the electrode to the workpiece can cause the tip of the electrode to weld itself to the work just as the two touch. As the electrode is withdrawn to start the arc, a bit of electrode will break off and remain in the joint. This can be prevented by using the high-frequency starting or by starting the arc on a starting tab.

If the inert gas shield is not performing properly, air will come in contact with the molten weld metal and hot base plate and cause contamination. The gas shield can break down for several reasons: (1) the flow of shielding gas is too low and the weld metal is not completely protected, (2) the flow of shielding gas is too high and turbulence is created which sucks air into the shielding gas, (3) drafts can blow the shielding gas away, (4) the gas-supply hose fittings or gas passages in the torch are blocked or loose.

A weld joint that shows lack of penetration is not getting enough welding heat. This usually means that the current is too low or the travel speed is too high. In GTA welding this can also mean that the diameter of the filler wire is too big or that the filler wire is being dipped into the weld puddle too frequently. Too much of the welding heat then is being taken to melt the filler wire. To get proper penetration, the welding current, travel speed, filler wire size, and filler wire feeding rate must be carefully balanced.

Applications. GTA welding is the most frequently used process for welding the precipitation-hardening stainless steels. This is because this process produces high-quality welds, close control of the process parameters is provided, it is easy to use, and welds can be made both manually and automatically. Some typical applications follow.

GTA welding was used in one step of the fabrication of honeycomb panels for the wing surfaces of the XB-70 (Refs. 32 and 33). The cover sheets for these panels had stiffeners welded to the panels at periodic intervals. These stiffeners were attached by the GTA process using a melt-through technique. The panels were made from PH 15-7 Mo. Cover sheets and stiffeners were 0.042 to 0.072 inch thick. The stiffeners were about 1 inch high.

In the melt-through technique, the weld is made on the top side of the sheet without a joint or gap (Figure 10). Sufficient melting takes place so that the edge of the vertical stiffener is fused into the joint. Optimum weld shapes were obtained using relatively high welding currents and welding speeds slightly on the low side. PH 15-7 Mo filler wire 0.030 inch diameter was added. Tooling included inert-gas backup. The gas backup not only protected the underside of the weld joint from the air, but also acted as a support for the molten weld metal.

Jigging for these parts was specially designed although it followed conventional concepts. Hold-down fingers, actuated by fire hose, clamped the cover sheet to the copper backup bar (Figure 11). Fire hose is not shown in the figure.

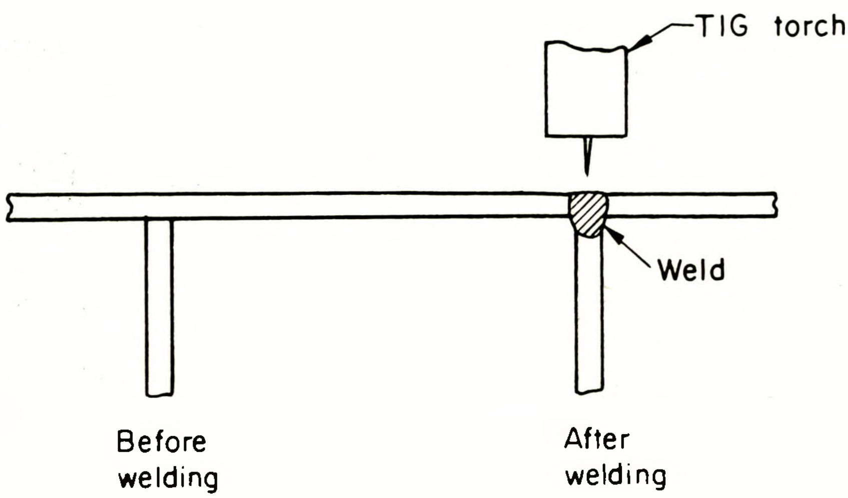
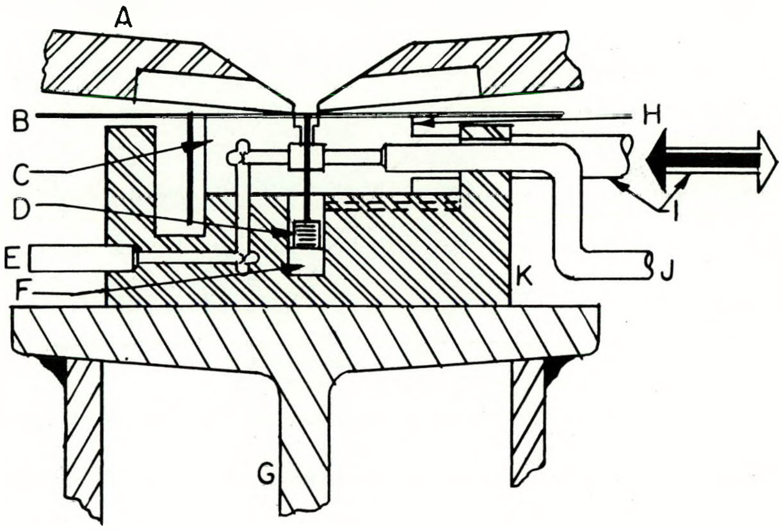


FIGURE 10. MELT-THROUGH WELDING

Jigs are necessary to obtain the joint configuration shown. A typical fixture with the needed backup bars is shown in Figure 11.



A. Copper-tipped hold-down fingers
B. Panel sheet
C.& H. Copper backup bars. ("C" is fixed, "H" is movable to clamp vertical stiffener)
D. Spacer to support vertical stiffener
E.& J. Inlets for inert backup gas
F. Rubber spacer
G. Structural support
I. Arm to move copper backup bar
K. Holder

FIGURE 11. FIXTURE USED TO HOLD PARTS FOR GTA MELT-THROUGH WELDING OF STIFFENED PANELS OF PH 15-7 Mo (Ref. 32)

The copper backup was split to hold the vertical stiffener. Gas passages were machined into the copper backup to provide for the inert-gas backing. After the parts were clamped in the fixture, the automatic GTA welder traversed the joint, riding on a horizontal rail also mounted adjacent to the fixture (Figures 12 and 13). Accurate tracking depended on precise location of the welding head rail and the positioner.

Ling-Temco-Vought developed conditions for automatically welding PH 15-7 Mo sheet and plate out-of-position (Ref. 34). This work was prompted by the fact that the parts being welded (aircraft and missile frames) had increased in size to the point where they could no longer be positioned for flat-position welding.

PH 15-7 Mo plate 0.56 inch thick was welded in the horizontal and overhead positions. Conventional automatic-welding procedures were used. The weld joint was a single vee. A joint included angle of 20 to 25 degrees was recommended. All welding was done from one side. However, "straightening" passes were used on the back side of the joint. After each welding pass, the joint was allowed to cool to room temperature. Then, a simple melt pass with no filler wire was made on the joint back side. The shrinkage of the melt pass counterbalanced the shrinkage of the weld pass and, thus, overall distortion of the joint was appreciably reduced.

PH 15-7 Mo sheet with thicknesses in the range of 0.031 to 0.125 inch were welded in the horizontal, vertical-up, and overhead positions. In the horizontal position, best results were obtained when the flow of shielding gas through the gas backup bar was kept low (5 cfh). This allowed a slight oxide film to form on the back surface of the weld bead. This oxide film increased the surface tension and retarded sagging of the molten weld metal. For overhead welding, relatively slow welding speeds permitted capillary action to draw the molten weld metal upward in the weld joint. This produced a good contour on the back side of the weld.

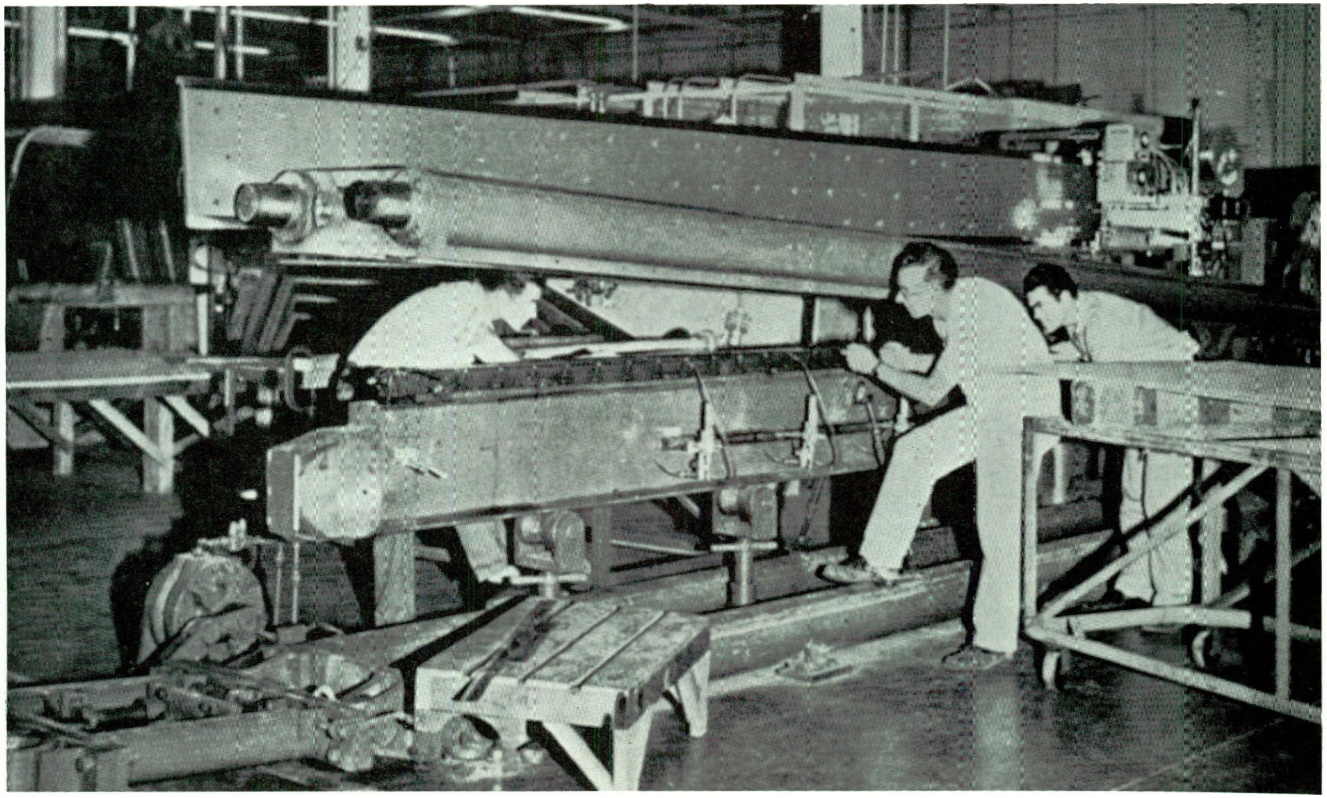


FIGURE 12. WELD POSITIONER USED IN FABRICATION OF STIFFENED PANELS OF PH 15-7 Mo (Ref. 32)

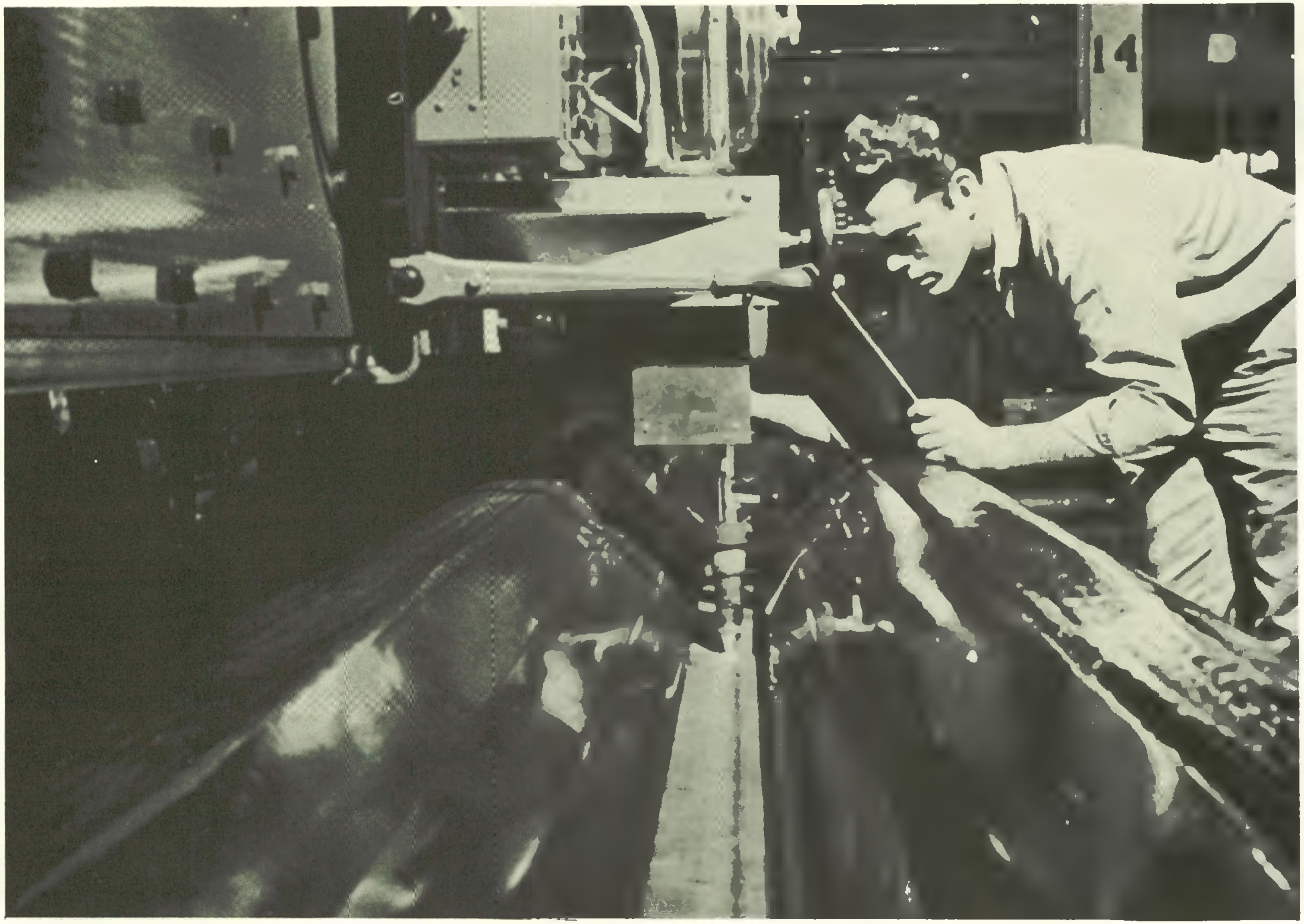


FIGURE 13. GTA MELT-THROUGH WELDING OF STIFFENED PANELS OF PH 17-7Mo (Ref. 33)

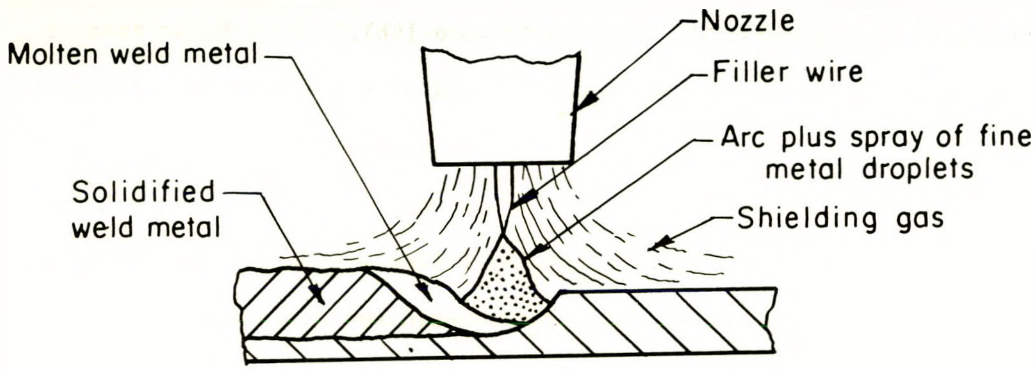
A combination of close control of welding parameters and tight fitting chill bars were required to produce good welds in the vertical-up position. Variations in parameters beyond rather close limits produced sagging of the weld bead and weld-metal porosity.

Lockheed Missile and Space Company has been using 0.040-inch-thick AM 350 sheet to fabricate toroidal tanks for thrust vector control of the Polaris A3 (Refs. 35, 36, and 37). To produce tanks that had optimum properties to ensure satisfactory performance, the effects of variations in welding procedures on the fracture toughness of the weld joints were determined. The results of Lockheed's work suggested that, where good fracture toughness of the weld joint is important, AM 350 filler wire should be used in preference to AM 355 filler wire. Repair welding should be done after the weldment is fully heat treated and the repair welds should be left in the as-welded condition. Heat treating after repair welding results in very erratic fracture-toughness properties in the repair weld.

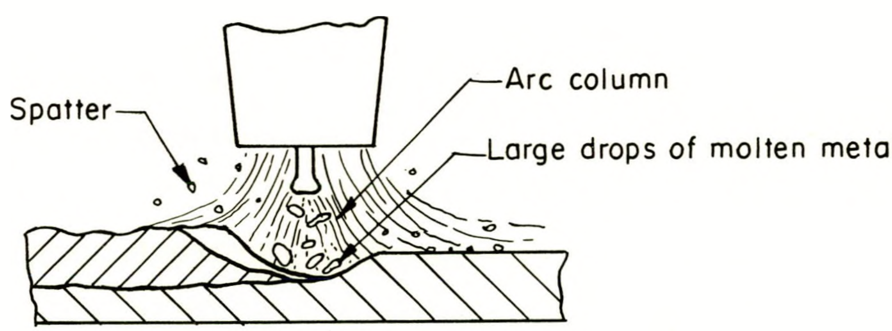
Gas Metal-Arc Welding. The gas metal-arc welding process has been used for welding precipitation-hardening stainless steels thicker than about 1/4 inch. GMA welding produces high-quality welds at higher welding speeds than does GTA welding. However, the higher heat input of GMA welding limits its use to the relatively thick parts. Since most precipitation-hardening stainless steels are used in the form of thin sheet material, the use of GMA welding is rather limited. The use of GMA welding is limited to the flat or horizontal position.

The metal that is melted off the end of the electrode filler wire transfers across the welding arc to the weld puddle as a spray of very fine metal droplets (Figure 14a). These droplets are too fine to be seen individually. The droplets are interspersed in the arc itself and the combined arc-metal spray has the shape of an inverted cone. The end of the electrode takes on a pointed shape as it melts.

Two electrical requirements must be met if spray transfer is to be achieved: (1) reverse-polarity direct-current must be used, and (2) the welding current must



a. Spray Transfer



b. Globular Transfer

FIGURE 14. GAS-SHIELDED METAL-ARC WELDING WITH SPRAY AND GLOBULAR TRANSFER

be above a certain critical level. Globular rather than spray transfer will occur if either of these requirements is neglected (Figure 14b). In globular transfer, large balls of molten metal will build up on the end of the electrode and drop into the weld puddle. When this occurs, the arc is hard to control, penetration and bead shape are poor, and there is a lot of spatter. The critical level of welding current depends on the size of electrode filler wire that is being used. Higher currents must be used for larger wire to obtain spray transfer.

A variation of gas-shielded metal-arc welding is called short-circuiting GMA welding. In this process the end of the electrode wire rapidly and repeatedly touches the molten weld puddle. Each time this occurs, the molten end of the electrode wire transfers to the molten weld puddle. Several years ago, short-circuiting GMA welding was investigated briefly as a method for welding 16-gage PH 15-7 Mo sheet (Ref. 38). Although results were satisfactory, this process has not been used for production welding of precipitation-hardening stainless steels, as far as is known.

Equipment. The equipment needed for gas metal-arc welding includes a power supply, a welding gun, a mechanism for feeding the filler wire, a set of controls, and a shielding gas.

Two types of power sources are used for spray-transfer GMA welding. These are the constant-current drooping-voltage type and the constant-voltage type, with the constant-voltage type finding the widest use. Motor generator or d-c rectifier power sources of either type may be used.

Both manual (usually called semiautomatic) and automatic welding guns are available. Both manual and automatic guns have a nozzle for directing the shielding gas around the arc and over the weld puddle. The wire passes through a copper contact tube, located in the nozzle, where it picks up the welding current.

Manual guns differ in design in the manner in which the electrode wire is fed. Some manual welding guns contain the wire-driving mechanism in the gun proper.

These are called "pull" guns because they pull the wire into the gun. The drive rolls may be powered by an electric motor contained in the gun or by a flexible shaft leading from a motor mounted in the control unit. Some of the guns that contain the wire-drive motor also hold a small spool of filler wire. While these guns are bulkier than the other types, the number of connections to the control unit are minimized. The wire-drive mechanism also may be mounted on the control unit with the wire being driven through a flexible conduit to the welding gun. This is called a "push" type of wire drive. The gun is less bulky than the pull type. Small-diameter wire may buckle when fed long distances by a push-type mechanism. Thus, the wire-drive mechanism must be placed relatively close to the welding station. The normal maximum distance that filler wire is fed is about 12 feet. One type of manual welding gun combines both a gun-located "pull" mechanism and a remote "push" mechanism for feeding the filler wire (called a "push-pull" wire feed). This equipment was especially designed for welding with very fine wires.

Automatic GMA welding guns are mounted directly to the wire-drive mechanism. The combined unit may be in a fixed location with provision for moving the workpiece underneath the nozzle or the work may be fixed and the gun-drive mechanism can be mounted on a movable head. The automatic gun contains the current pickup tube, a water-cooled jacket, and a nozzle for directing the flow of shielding gas. The automatic gun is built more ruggedly than the manual gun and is designed to operate at higher currents.

For GMA welding of precipitation-hardening stainless steels, argon, argon with a small addition of oxygen, or argon-helium mixtures may be used. Pure helium is not used since spray transfer is difficult to obtain, high gas flow rates are required, and the gas shield is easier to disrupt than with the heavier argon.

When pure argon is used, the weld metal does not wet the base metal uniformly and the arc tends to wander. This can result in a non-uniform weld bead that may have undercutting at the edges of the bead. By introducing a small amount of oxygen into the argon shielding gas, the weld deposit becomes very uniform and undercutting is eliminated. Normally, argon with 1-2 percent oxygen is used for welding precipitation-hardening stainless steels that do not contain aluminum. The presence of oxygen in the shielding gas will oxidize aluminum in the filler wire resulting in poor recovery of the aluminum in the weld metal. Such weld metals would have poor heat-treatment response.

Argon-helium mixtures are used where a hotter arc and increased penetration are desired. As the percentage of helium is increased, the amount of penetration also increases. Mixtures with as much as 75 percent helium have been used (Ref. 7). There is no hard and fast rule governing argon-helium mixtures--the amount of helium added depends on the application and the users preference. Spray transfer can be obtained as long as the percentage of helium is kept below about 80 percent.

Various sizes and shapes of gas nozzles are used with GMA welding equipment. Each of these nozzles has a range of shielding gas flow rates to achieve optimum shielding. For this reason, no recommendation can be made for shielding gas flow rates for the GMA welding of precipitation-hardening stainless steels. Instead, the operator should refer to the instruction book for the equipment that is being used.

Filler wires are available in 17-4 PH, 17-7 PH, PH 15-7 Mo, AM 350, and AM 355 compositions. As a general rule, the composition of the filler wire should be the same as that of the base metal. It has been reported that with PH 15-7 Mo filler wire, weld-metal flow is poor and instability of the arc occurs (Ref. 7). If this problem is encountered, AISI 308 stainless steel filler wire can be used for welding PH 15-7 Mo steel. As would be expected, though, the weld metal will not respond to heat treatment and the mechanical properties of the weld metal will be lower than those of the base metal.

The size (diameter) of the filler wire used for GMA welding depends on the size of the weld bead and the penetration that is desired. As the size of the filler wire increases, the weld bead that is deposited will become thicker. Also, a higher welding current will be required to achieve spray-transfer. The increase in welding current will increase penetration. The level of welding current required to achieve spray transfer is shown in Table XV.

The common sizes of filler wire used for GMA welding are 3/32-, 1/16-, 0.045-, and 0.035-inch diameter. The recommended sizes of filler wire for various base-metal thicknesses are shown in Table XVI. Although this table includes base-metal thicknesses down to 1/8 inch, GMA welding usually is restricted to material with a 1/4-inch minimum thickness. The most common filler wire sizes, therefore, are 1/16- and 3/32-inch diameter.

Joint Design. Joint designs used for gas-metal-arc welding are similar to those used for shielded metal-arc welding. The joints are modified slightly, however, to take advantage of the greater penetration obtainable with this process. These modifications are: narrower root openings, narrower groove angle, and thicker root faces. The use of the narrower groove angle has the added advantage of requiring less filler metal to fill up the groove. For example, when a 45-degree groove angle in 3/4-inch-thick plate is used instead of a 60-degree groove angle, 30 percent less weld metal is required. Typical joint designs are illustrated in Figure 15.

Welding Procedures. Weld joint penetration, weld-bead reinforcement, and bead shape can be altered by adjusting certain welding conditions. Penetration and bead width both increase as the welding current increases. A short arc will "dig in" and increase penetration. If less penetration is desired, a longer arc should be used. A higher welding current also will produce a heavier weld deposit. The amount of electrode "stick-out" will affect the rate of melting of

TABLE XV. WELDING CURRENT REQUIRED TO ACHIEVE SPRAY TRANSFER (Ref. 26)

Electrode wire diameter, inch	Minimum current required to achieve spray transfer, amps
0.030	150
0.035	170
0.062	275

(Additional data for other wire sizes being obtained)

TABLE XVI. ELECTRODE WIRE SIZE FOR GMA WELDING VARIOUS THICKNESSES OF PRECIPITATION-HARDENING STAINLESS STEEL

Base-metal Thickness, inch	Electrode Wire Diameter, inch
1/8	0.035 - 0.045
1/4	0.045 - 1/16
3/8	1/16 - 3/32
1/2 and thicker	3/32

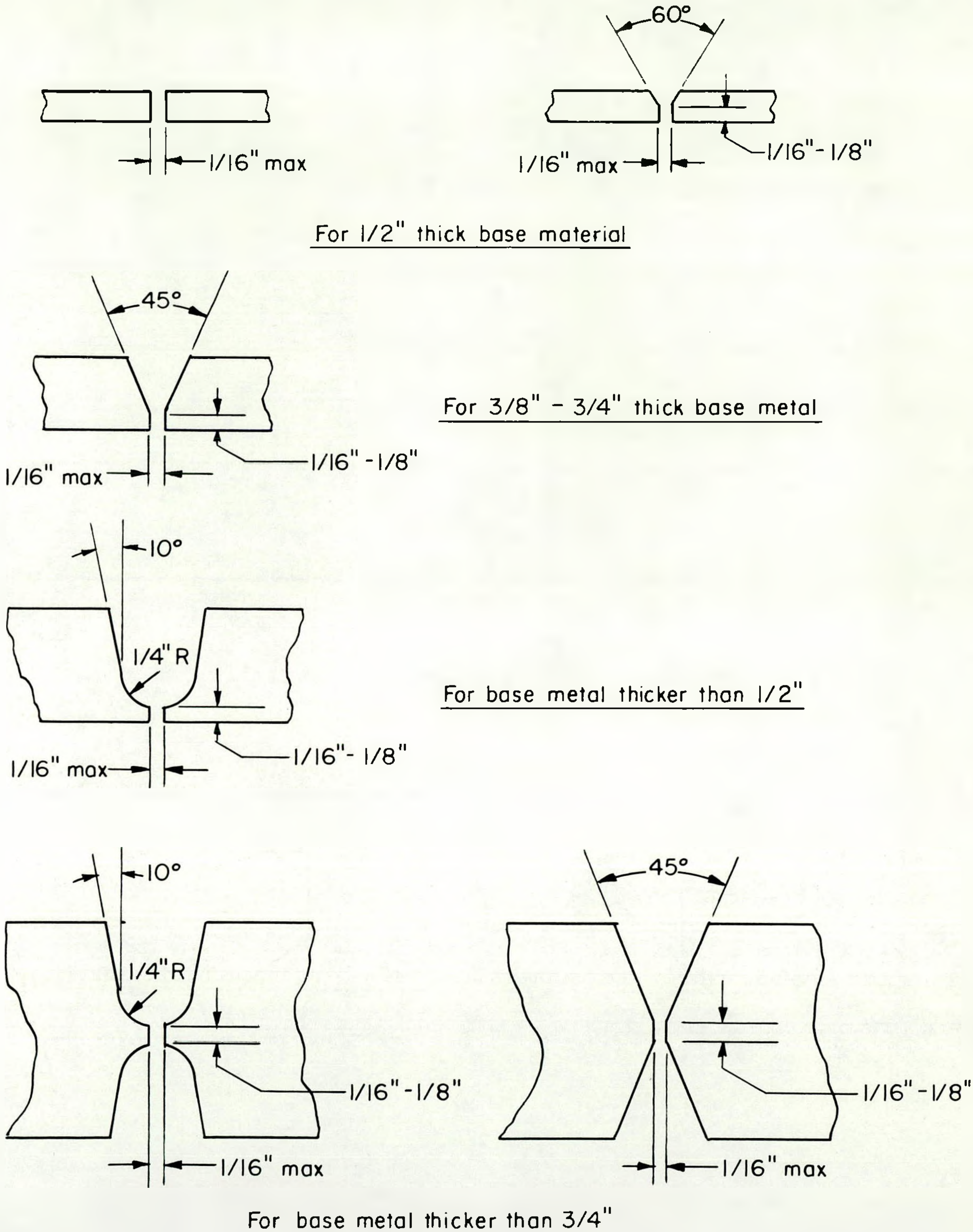
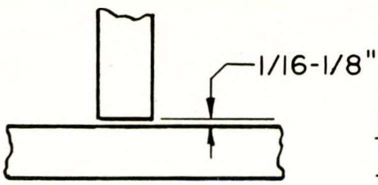
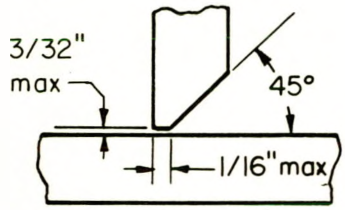


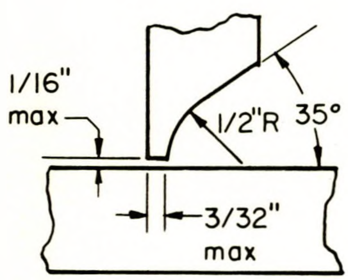
FIGURE 15. TYPICAL JOINT DESIGNS FOR GAS-SHIELDED METAL-ARC WELDING

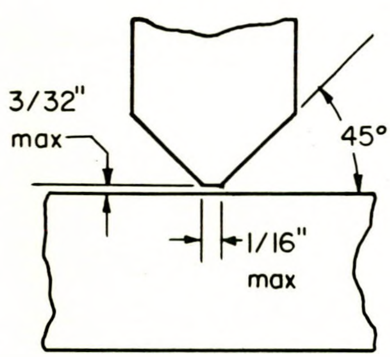


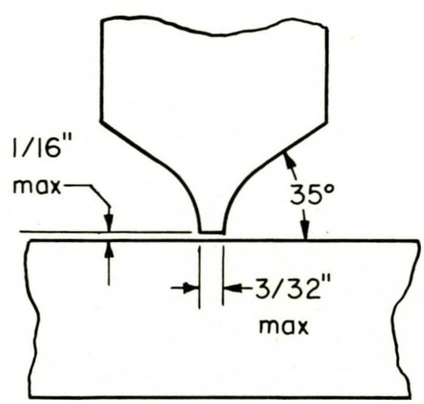
For 1/4" thick base material welded from both sides



For 1/4"- 3/4" thick base material







For 3/4" and thicker base material

FIGURE 15. (Continued)

the wire. (Stick-out is the distance from the end of the contact tube to the end of the electrode wire.) The greater the stick-out, the higher will be the melting rate. By changing the amount of stick-out, the amount of filler wire that is melted and the size of the weld bead can be altered without changing the welding current.

Changing the angle of the welding gun will change the shape of the weld bead. Tilting the gun in the direction of welding (backhand technique) decreases penetration, increases bead width, and improves the smoothness and contour of the bead surface. Cap passes on multipass welds may be made with the backhand technique. With the gun tilted back away from the direction of welding (forehand technique), penetration, though greater than with the backhand technique, still is not as much as when the gun is perpendicular to the bead surface. Automatic welds normally are made with the gun perpendicular or with a small amount of backhand tilt.

Increasing the welding speed will decrease both penetration and bead width. If the speed becomes too fast, undercut will occur along the edges of the bead and there may be areas of lack of fusion. Higher travel speeds can be used when the weld is being deposited in narrow grooves in thin material than when welding wide joints in thick plate.

In manual GMA welding, the operator holds and manipulates the welding gun. The important thing for the operator to remember is that the motion of the gun along the joint must be uniform and the position of the gun with respect to the joint must be held constant.

In shielded metal-arc welding, penetration is relatively shallow and variations in the movement of the electrode along the joint do not affect penetration very much. In GMA welding, penetration is much greater and changes in travel speed can have a greater effect on penetration. This can lead to burnthrough of the joint or lack of penetration if the operator moves the torch erratically along the joint. Motion must be as uniform as possible.

The distance between the end of the torch and the joint is very important also. In shielded metal-arc welding, changing the distance between the torch and joint, changes the arc length and arc voltage. In GMA welding, the equipment automatically maintains a constant arc length through variations in wire feed speed or welding current. Thus, changing the gun-to-work distance will not alter the arc length. It will change the amount of stick-out, though. As the stick-out changes, the melting rate or welding current (depending on the type of equipment) also will change. This means that the bead size or penetration also will change. If the operator cannot keep the gun-to-work distance constant, the bead size or penetration will not be uniform.

Changes in the angle between the gun and joint will change the bead shape and penetration. The effect of using forehand or backhand techniques is the same for manual as it is for automatic GMA welding. Most manual GMA welding is done using the backhand technique. This technique allows the operator to see the weld crater better and produce welds of more consistent quality.

The same precautions should be exercised in protecting the underside of the weld joint in GMA welding as in GTA welding. Grooved copper backup strips and inert-gas backing may also be used with GMA welding. In making multipass welds, maximum quality is obtained by grinding out the underside of the root pass and rewelding from that side. Root passes are subject to various defects such as incomplete penetration and lack of fusion. By grinding out the root pass to sound metal and rewelding, these defects can be eliminated from the finished joint.

Precautions. The precautions to be observed in GMA welding of precipitation-hardening stainless steels are concerned with both the equipment and the welding procedure.

Equipment Precautions. Successful GMA welding depends on feeding the electrode wire through the gun at a precise and uniform speed. This means that the equipment must be kept in good operating condition. Most problems with

GMA welding equipment may be traced to a wire-feeding system that has not been kept clean and in good condition. A well kept schedule of preventive maintenance of this system plays a major role in successful GMA welding. Important points to check in such a schedule are:

(1) Adjustment of wire-straightening rolls (if so equipped). Improper adjustment can cause the wire to bend as it exits from the contact tube and the arc will not be properly positioned in the weld joint.

(2) Alignment of the wire with the groove in the feed rolls. Misalignment will cause bending of the wire. The wire also may climb out of the groove with resulting erratic wire feeding.

(3) Feed roll clamping pressure. If the pressure is too light, slippage and erratic feeding will result. If the pressure is too heavy, the wire may be deformed to the point where it will not pass freely through the contact tube.

(4) The wire-feed cable between the wire reel and the feed rolls should be clean and free of kinks. Dirt in the cable can be transferred to the wire and ultimately to the weld metal. A buildup of dirt in the cable and kinks in the cable can restrict free movement of the wire through the cable. As a result, wire feed may become erratic.

(5) The sizes of the wire feed cable, feed rolls, and contact tube should match the size of the electrode wire being used. If any of these parts are of the improper size, the wire will not feed smoothly. If the contact tube is too large, poor pickup of the current will occur. The equipment manufacturers suggestions should be followed regarding proper sizes of these parts.

(6) Distance between wire feed rolls and contact tube or wire feed cable. This distance should be as short as possible. In this area, the wire is unsupported and if this distance is large, the wire may buckle.

(7) Winding of the electrode wire on the spool or coil. If the wire becomes loose on the spool or coil as it feeds, loops of wire may become entangled stopping feeding of the wire. Most mounting spindles for wire spools or coils are equipped with friction devices that apply a small amount of tension to the wire as it feeds. This prevents loosening of the wire. Care should be taken when mounting the wire spool or coil that entanglement of the wire does not occur.

The operator should check the gas passages and gas-shielding nozzle periodically to be sure that the flow of shielding gas is not being disrupted. Spatter tends to build up on the inside of the nozzle. If this buildup becomes too great, proper shielding cannot be obtained. Thus, the inside of the nozzle should be cleaned periodically.

Contact tubes may be another source of trouble. Contact tubes are made from copper or copper alloy and being softer than the welding wire, tend to wear from the passage of the wire through the tube. This enlarges the base of the tube, which, in turn, can cause erratic current pickup. Contact tubes should be replaced periodically to maintain good current before wear becomes so great that problems occur.

Procedure Precautions. The quality of the weld joint also depends on the welding procedures that are used. Slight variations in procedure can have major effects on the quality of GMA joints in precipitation-hardening stainless steels. The most frequently encountered defects and their causes are discussed in the following paragraphs.

Burnthrough and excessive penetration can be caused by putting too much welding heat into the joint. The welding current should be decreased or the travel speed increased. Penetration will be decreased by tilting the gun toward the direction of welding (forehand technique). This defect also may be caused by excessive root opening or too small a root face. If the joint dimensions cannot be changed, the use of a copper backup bar or a weaving technique can help to prevent burnthrough.

Lack of penetration is caused by the opposite conditions to those that cause excessive penetration. The welding current may be too low or the travel speed too high. The gun may be at too large an angle with the weld joint (either backhand or forehand). Straightening up the gun angle will increase penetration. Increased root opening may be needed. The position of the arc in the weld puddle also will affect penetration. The closer the arc is to the front of the puddle, the greater will be the amount of penetration.

Overlap occurs when the weld metal does not fuse to the base metal at the edges of the top surface of the joint. Usually, it is caused by carrying a weld puddle that is too large. Reducing the wire-feed speed or increasing the travel speed will help to correct this problem. Another solution is to use a slight weave so that the arc will cover all areas of the weld joint where fusion is desired. Keeping the arc at the front of the puddle will improve fusion and reduce overlap.

An unfilled groove along the edge of the weld bead is called undercut. Decreasing the travel speed will help to fill up these grooves. The use of an argon-oxygen shielding-gas mixture will reduce undercut. However, oxygen should not be used in the shielding gas for welding precipitation-hardening stainless steels that contain aluminum.

"Wagon tracks" may occur in multipass welding. It is the name given to a line of voids that are trapped at the edges of the underlying bead when the subsequent bead is deposited. This defect only shows up on an X-ray photograph of the joint when the line of voids has the appearance of wagon tracks on a dirt road. Wagon tracks can occur if the lower weld bead is too high crowned. The use of argon-oxygen shielding gas will improve the shape of the weld bead surface. Bead shape also can be altered by adjusting the arc voltage and travel speed. Care should be used when depositing the second pass to be sure that the arc melts the entire surface of the underlying bead.

Applications. Procedures have been developed for GMA welding of PH 15-7 Mo at Ling-Temco-Vought (Ref. 28) for possible application in hydrofoil or ground-handling equipment fabrication. Sheet 0.160 and 0.210 inch thick was welded using a square-butt joint. Suggested welding conditions were:

	0.160-inch-thick sheet	0.210-inch-thick sheet
Voltage, volts	34	34
Current, amps	370	370
Travel speed, ipm	41	30
Torch gas flow, cfh	60 (argon + 1 percent oxygen)	
Backup gas flow, cfh	25 (argon)	

PH 15-7 Mo filler wire 1/16 inch diameter was used. PH 13-7 Mo filler wire also could be used and in certain cases, might prove better than PH 15-7 Mo because a better metallographic structure would result.

Submerged-Arc Welding. Submerged-arc welds with properties comparable to those of the base metal can be produced only in AM-350 and AM-355. Low-strength nonheat-treatable welds can be made in the aluminum-bearing alloys. The minimum thickness of steel that is welded without providing some method of backing-up the weld is about 1/2 inch. There is no limit on the maximum thickness. Plate several inches thick is commonly welded by submerged ar.

Submerged-arc welding can be used only in the flat or horizontal positions. Recent developments indicate that submerged-arc welding of vertical joints is feasible. However, no work has been done on the vertical submerged-arc welding of precipitation-hardening stainless steels. The deep penetration inherent with submerged-arc welding can cause difficulties when welding metal less than about 1/2 inch thick. The joint must be backed up with a copper bar or a pad of flux to prevent melting through the joint. It is difficult to track the joint when welding manually since the arc and electrode end are buried under the flux blanket. In multipass welding, the slag from the previous pass must be carefully and completely removed to prevent slag inclusions or entrapment in subsequent passes.

Equipment. The choice of power supply depends largely on the work to be welded. D-C permits fast arc starting, gives good control over the weld bead shape, and provides quick current buildup at the start of the weld which is advantageous when making short welds. Best control of the bead shape and deepest penetration are obtained with d-c reverse polarity (electrode positive), while the highest welding speeds and shallowest penetration are obtained with d-c straight polarity (electrode negative). The use of a-c current provides a degree of penetration in between that of d-c straight and d-c reverse polarity. A-C current also cuts down on arc blow (the swerving of the arc from its normal path due to magnetic forces) which can become a severe problem when very high welding currents are used.

Filler wires and a flux have been developed for welding AM-350 and AM-355 (Ref. 7,26). The filler wires are standard AM-350 and AM-355 wires used for GMA welding. The flux has been specially formulated, but it is available commercially. The use of this special flux and the standard wires produces weld deposits that match the base metal composition very closely. Conventional stainless steel fluxes should not be used for welding AM-350 or AM-355 because the composition of the weld metal will be altered to the point where proper heat treatment response cannot be obtained.

Fluxes for welding the aluminum-bearing precipitation-hardening stainless steels are not available. However, submerged-arc welds can be made in these steels, provided high-strength weld joints are not required (Ref. 14). For such applications, ER308, ER310, or ER316 austenitic stainless steel filler wire can be used with the appropriate stainless steel flux. The resulting weld deposit will not be heat treatable and will not have strength as high as the base metal.

Typical designs for butt and fillet joints are shown in Figure 16. Greater penetration is obtained with submerged arc welding than other arc-welding processes. Care must be taken not to melt through the joint when depositing the root pass. Frequently, the root pass is deposited by shielded-metal-arc welding and the joint then is filled by submerged arc welding.

Welding Procedures. Welding conditions for welding AM-350 and AM-355 must be very carefully controlled (Ref. 7, 27). This is because slight variations in arc voltage, current, or travel speed can cause changes in the chemical composition of the weld metal. When such variations occur, the amount of flux being melted will change and the amount of alloying elements picked up from the flux by the weld metal will be altered. Since correct heat treatment response of these steels depends on close control of the weld metal composition, close control of the welding conditions is required. However, these conditions will change with the application, joint design, material thickness, etc. This means that the procedure should be qualified for the particular application and that the conditions

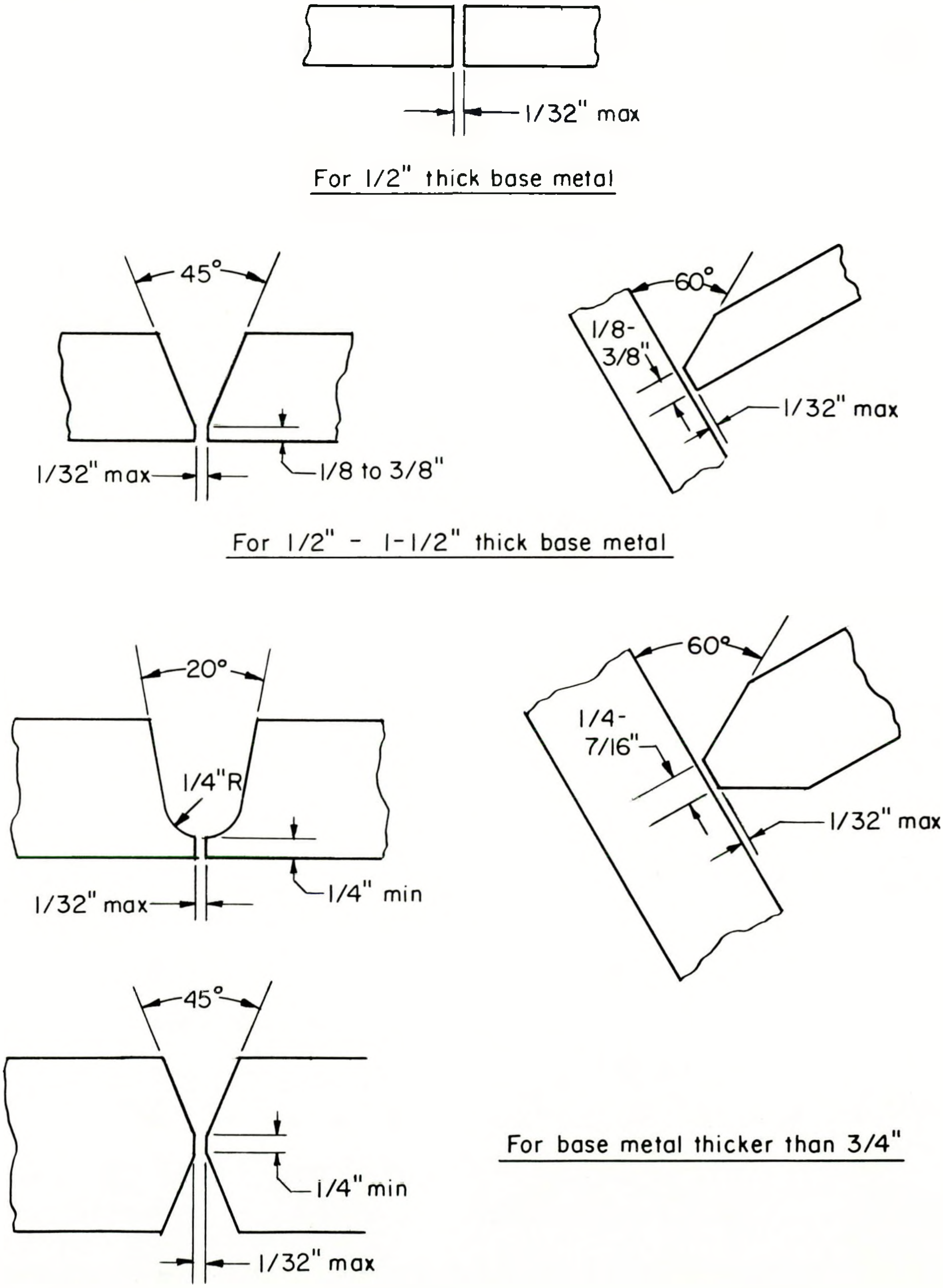


FIGURE 16. JOINT DESIGNS FOR SUBMERGED-ARC WELDING

must be closely monitored during welding. The wire and flux supplier should be consulted for suggested welding conditions.

Plasma Arc Welding. The plasma arc is one of the newly developed methods of arc welding. While the plasma arc closely resembles the gas-tungsten arc, there are important differences that affect arc behavior and properties. The gas-tungsten arc is an unconfined arc. In contrast, the arc column of the plasma arc is constricted as it passes through the nozzle orifice; its diameter is decreased, the current density is increased, and the arc temperature is increased. Plasma-arc equipment has been developed specifically for welding. The most recent innovation is the "needle arc", a small diameter-plasma arc that can be used to weld foil gage materials.

Because of the arc constriction and the relative stiffness of the arc column, the plasma arc is concentrated on a small area on the workpiece. As a result, the following characteristics are associated with plasma-arc welding:

(1) For a given current more heat is transferred to the workpiece with the plasma arc than with the more diffused gas-tungsten arc.

(2) Welding can be conducted at higher rates with the plasma arc. The weld bead and associated heat-affected zone are narrow.

(3) The plasma arc is relatively insensitive to minor variations in the process variables.

(4) Piercing or "keyholing" of the workpiece occurs during welding. The occurrence of piercing is a positive indication of full penetration.

(5) Welds can be made without backup fixturing.

For welding the plasma arc is established between the electrode and the workpiece to obtain maximum heat transfer.

Applications. At the time of this report, there was no information on the use of plasma-arc welding for joining the precipitation-hardening stainless steels. However, they can probably be welded in accordance with the conditions established for welding the 300 series of stainless steels (Refs. 18, 39). The following data may be used as a guide:

TABLE XVII. PLASMA-ARC WELDING CONDITIONS FOR SQUARE BUTT JOINTS IN TYPE 304 STAINLESS STEEL (REF. 40)

Thickness, inch	Welding Speed, ipm	Straight Polarity, Direct Current, amperes	Arc Voltage, volts	Shielding Gas Flow,(1) cfh
3/32	38	160	31	35
1/8	24	145	32	35
3/16	16	165	36	45
1/4	14	240	38	50

(1) Shielding gas composition: Argon + 7.5% Hydrogen.

Electron-Beam Welding. Electron-beam welding can be an attractive process for welding precipitation-hardening stainless steel parts. The process can be used for welding material with thicknesses ranging from the foil gages to over 2 inches in a single pass. In addition to being very versatile regarding material thickness that can be welded, electron-beam welding has two other major advantages: (1) welding is done in a vacuum and (2) very narrow welds are produced. By welding in a vacuum, contamination from gaseous impurities is virtually nonexistent. The vacuum atmosphere is even purer than the inert-gas atmosphere of GTA or GMA welding. The very narrow welds that are produced are subject to very little distortion or warpage.

The requirement for welding in a vacuum is also one of the chief disadvantages of electron-beam welding. All the parts being welded must be placed in a vacuum chamber. The chamber size thus limits the size and shape of the parts being welded. Movement of the parts during welding and observation of the welding operation also are hindered by the vacuum chamber. Loading and unloading parts from the chamber and pumping the vacuum on the chamber after each loading operation is time consuming. As a result, production rates for electron-beam welding are quite low. Sliding vacuum chambers have been developed to alleviate this problem and work currently is under way to develop "out-of-vacuum" electron-beam welding.

The other major disadvantage of electron-beam welding is the cost of the equipment. Electron-beam welding equipment is expensive. Unless the special characteristics of electron-beam welding are required, it is cheaper and usually quicker and easier to use one of the more conventional welding processes.

Electron-beam welding equipment is classed as either high-power density or low-power density. Only the high-power-density equipment is capable of producing deep narrow welds. Low-power-density equipment was produced in the early days of electron-beam welding development but, as far as is known, no low-power-density equipment is being produced currently. However, such equipment still exists and may be used occasionally by some fabricators.

High-power-density equipment may be further subdivided into low-voltage and high-voltage classes. In low-voltage equipment, the high welding power is achieved by using a "low" accelerating voltage and high beam currents. Maximum voltage obtainable on such equipment normally is around 30 kv although some 60 kv equipment is now being produced. The 60 kv equipment really should be classed as medium-voltage equipment. The high-voltage equipment uses accelerating voltages as high as 150 kv in conjunction with low-beam currents.

There are advantages and disadvantages to both high- and low-voltage electron-beam welding. The process that is used depends on the needs of the particular fabricator. An almost equal number of high- and low-voltage welders have been produced and are in use in the United States (Ref. 41).

In general, higher power can be achieved with the low- and medium-voltage equipment. Most equipment of these classes have power ratings in the range of 9 to 15 kw. (Ref. 42). The high-voltage welders usually have power ratings in the 3 to 6 kw range. The results obtainable with both the high- and low-voltage high-power-density welders are comparable. Weld joint shape produced by both classes is comparable. The low-voltage welders have slightly greater penetrating ability due to their generally higher power ratings. The 60 kw welder is claimed to be capable of penetrating 9-inch aluminum plate in a single pass. The high-voltage welders generally are better suited for welding thin material and small parts. This is because the beam can be accurately focused to a smaller diameter than the low-voltage beam. High-voltage welders are equipped with optical viewing devices that enable the operator to observe the welding operation. The high-voltage electron beam has a greater depth-of-focus than a low-voltage beam. This means that the part can be located further from the gun, up to 24 inches away. In low-voltage welding, the part must be about 3 to 6 inches from the gun. However, recent advances in equipment design permit parts to be welded at greater distances from the gun. Changes in shape of the part do not affect the welding operation in high-voltage welding while the beam must be refocused when welding variable shape parts in low-voltage welding.

Welding Procedures. Welding procedures used in electron-beam welding are dependent on material thickness and the type of electron gun being used. For a given thickness of material, various combinations of accelerating voltage, beam current, and travel speed are satisfactory. In electron-beam welding,the 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 on a given piece of equipment with only a very few trials.

In very thick material, the first pass made to completely penetrate the joint sometimes is undercut along both edges of the weld metal. This undercutting can be

TABLE XVIII. TYPICAL CONDITIONS FOR ELECTRON-BEAM WELDING PRECIPITATION-HARDENING STAINLESS STEELS (Ref. 41)

Material	Thickness, inch	Voltage, kv	Beam Current, ma	Travel Speed, ipm	Remarks
17-4 PH	0.032	90	2.5	30	
	0.046	120	3	58.5	
	0.100	100	10	30	
	0.125	125	5	30	
	0.625	140	8	25.4	
17-7 PH	0.050	120	4	70	
	0.250	145	15	46	
	0.500	150	18.5	14	Bead-on-plate weld
	0.750	150	20	20	
	1.000	150	40	28	
PH 15-7 Mo	0.150	150	5.5	27	0.060-inch longitudinal beam oscillation
AM-355	0.004	50	0.3	30	Lap joint
	0.250	145	11	28	0.010-inch circular beam oscillation
	0.645	150	17.5	10	

eliminated by a second weld pass made at somewhat lower energy levels with a slightly defocused beam. However, undercutting frequently can be reduced by making minor adjustments in travel rate. 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 usually is used in electron-beam welding. The welding positions that can be used are limited by the versatility of the available welding equipment. Table XVIII shows some of the welding conditions that have been used in the electron-beam welding of precipitation-hardening stainless steels.

Applications. Electron-beam welding has been investigated extensively for joining PH 15-7Mo parts for the XB-70 (Ref. 43). Sine-wave parts were welded to brazed honeycomb panels (Figure 17) and then these panels were welded together (Figure 18).

In welding the spar to the panels, the part was placed so that the spar was in a horizontal position. In this position, the electron beam, being in the vertical plane, did not "see" a sine-wave joint but a straight T-joint that varied up and down in the vertical plane. The beam was focused at about the midpoint of the sine-wave height and then traversed the joint. A high-voltage beam with a broad depth-of-focus was used so that no further adjustment of the focus was required as the weld was made. In welding the panels together, the beam was directed at the top joint of the upper honeycomb panel. The beam penetrated the top and bottom face sheets of the top panel and the top and bottom sheets of the lower panel. Thus, all four joints were made simultaneously.

Techniques and equipment were developed for making the final close-out weld on the wing to fuselage joint on the XB-70. This joint is shown in Figure 19. The bottom face sheet of the brazed PH 15-7Mo honeycomb panel was GTA welded. The GTA torch was positioned through a gap in the upper face sheet. After GTA welding,

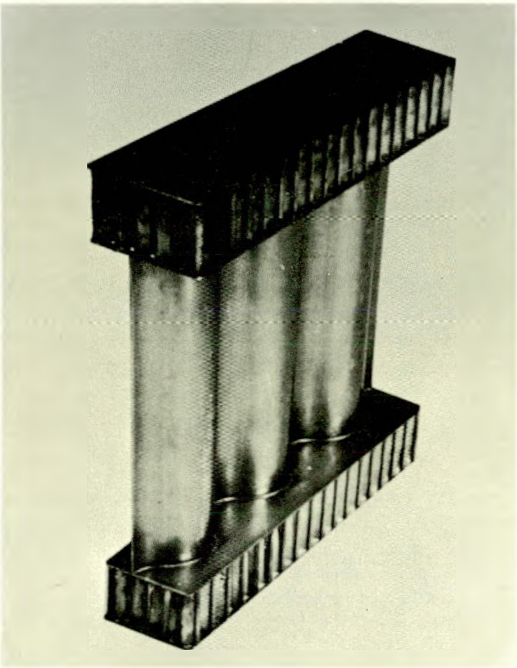


FIGURE 17. SINE WAVE SPECIMEN IN PH 15-7 Mo STAINLESS STEEL (Ref. 43)

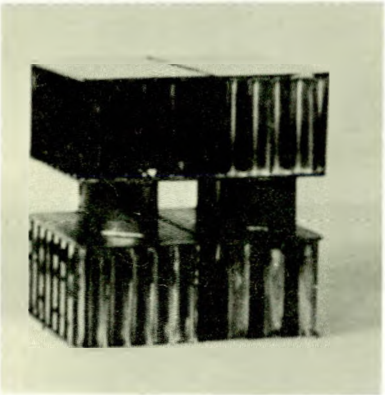


FIGURE 18. SIMULTANEOUS FOUR WELD SPECIMEN IN PH 15-7 Mo STAINLESS STEEL (Ref. 43)

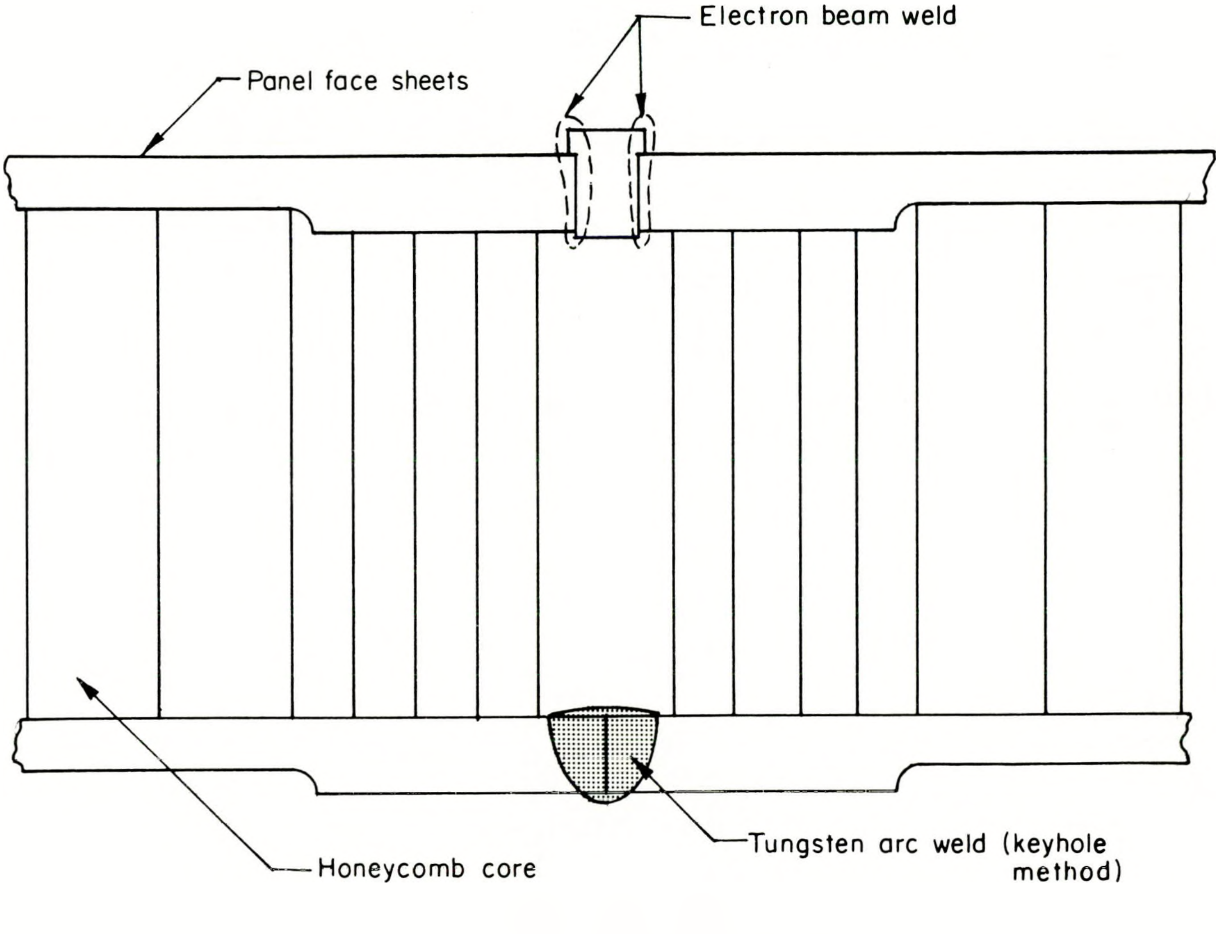


FIGURE 19. WING-TO-FUSELAGE JOINT IN XB-70 (Ref. 43)

this gap was filled with a T-shaped filler strip. A portable electron-beam welder was clamped over the joint area on the upper sheet and an electron-beam weld was made along each side of the filler strip (Figure 20).

The portable welder that was developed consists of a small half-shell-type vacuum chamber that clamps on the part to be welded. The part being welded (which must be large and flat) forms the bottom half of the chamber. The electron gun is mounted on a lid that slides along the top of the chamber (Figure 21). The equipment can be used for overhead welding of large parts also (Figure 22).

Other precipitation-hardening stainless steel parts that have been fabricated by electron-beam welding include a 17-7 PH pressure vessel and an A-286 turbine wheel. The pressure vessel (Figure 23) (Ref. 24) was 8-inch diameter with 0.140-inch wall thickness. This part illustrates an excellent application for electron-beam welding. Jigging of the pressure vessel is simple and there is no requirement for internal backing strip or clamps. Thus, the problem of removing internal parts does not present itself and a large exit hole is not required. The turbine wheel consisted of an A-286 turbine disc and a ring of Udimet 500 blades. Electron-beam welding has proven to be an excellent method of joining certain dissimilar metals or alloys and this is a typical example of such an application.

Resistance Spot Welding. In resistance spot welding, all the heat required to accomplish 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, then solidifies to form the weld.

Resistance spot welding has been applied to a limited number of the precipitation-hardening stainless steels such as 17-7 PH, A-286, PH 15-7 Mo, PH 14-8 Mo, AM-350, and AM-355. but information on applications, welding conditions and techniques, and properties is limited. Alloys such as 17-4 PH, 17-10P, HNM, and AFC-77 are not widely used for applications requiring spot welding. When spot welding the

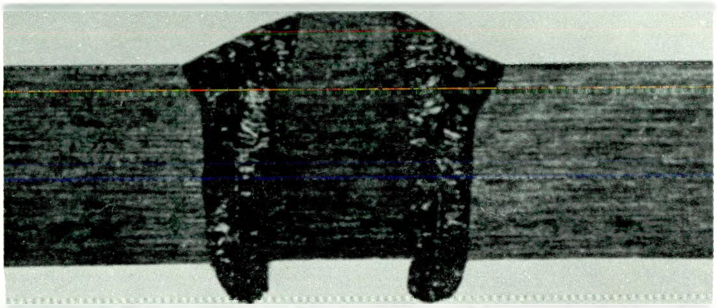


FIGURE 20. PHOTOMACROGRAPH OF SIMULATED WING-TO-FUSELAGE WELD (Ref. 43)

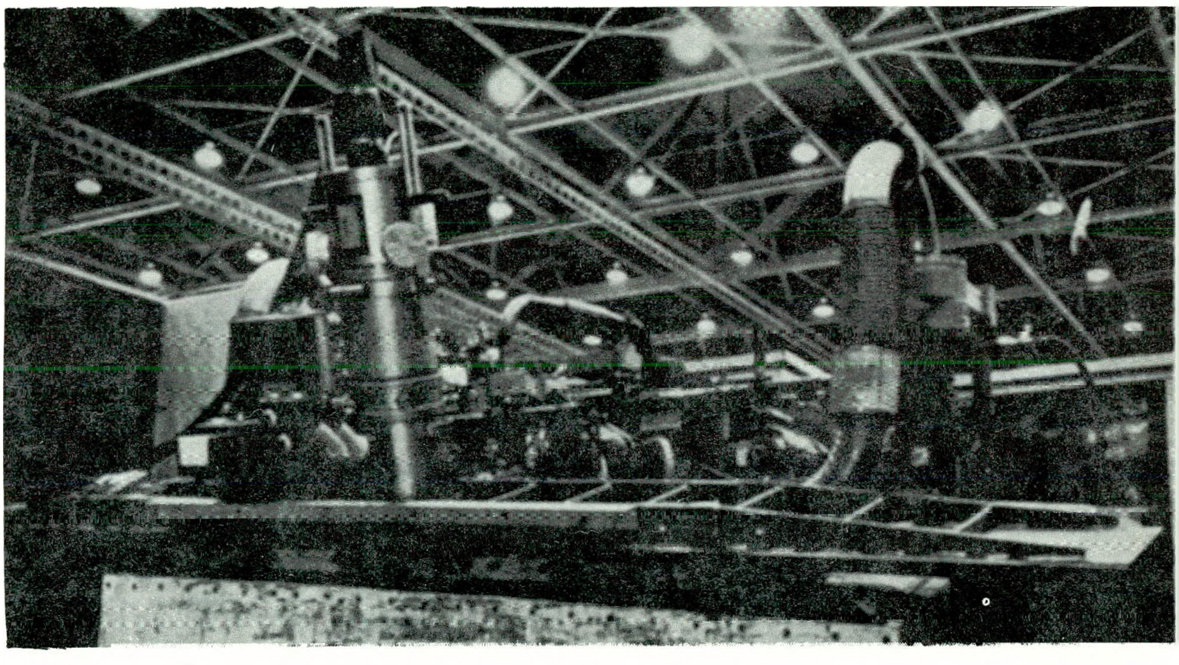


FIGURE 21. PORTABLE ELECTRON-BEAM WELDER (Ref. 44)

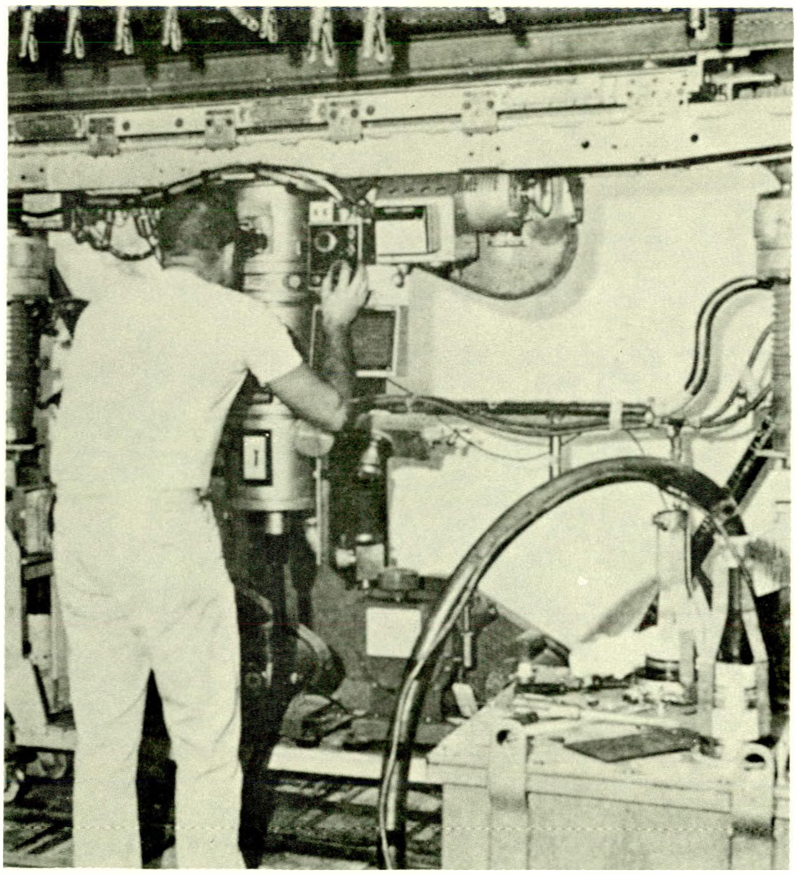


FIGURE 22. PORTABLE ELECTRON-BEAM WELDER SET UP FOR OVERHEAD WELDING OF LARGE PARTS (Ref. 44)

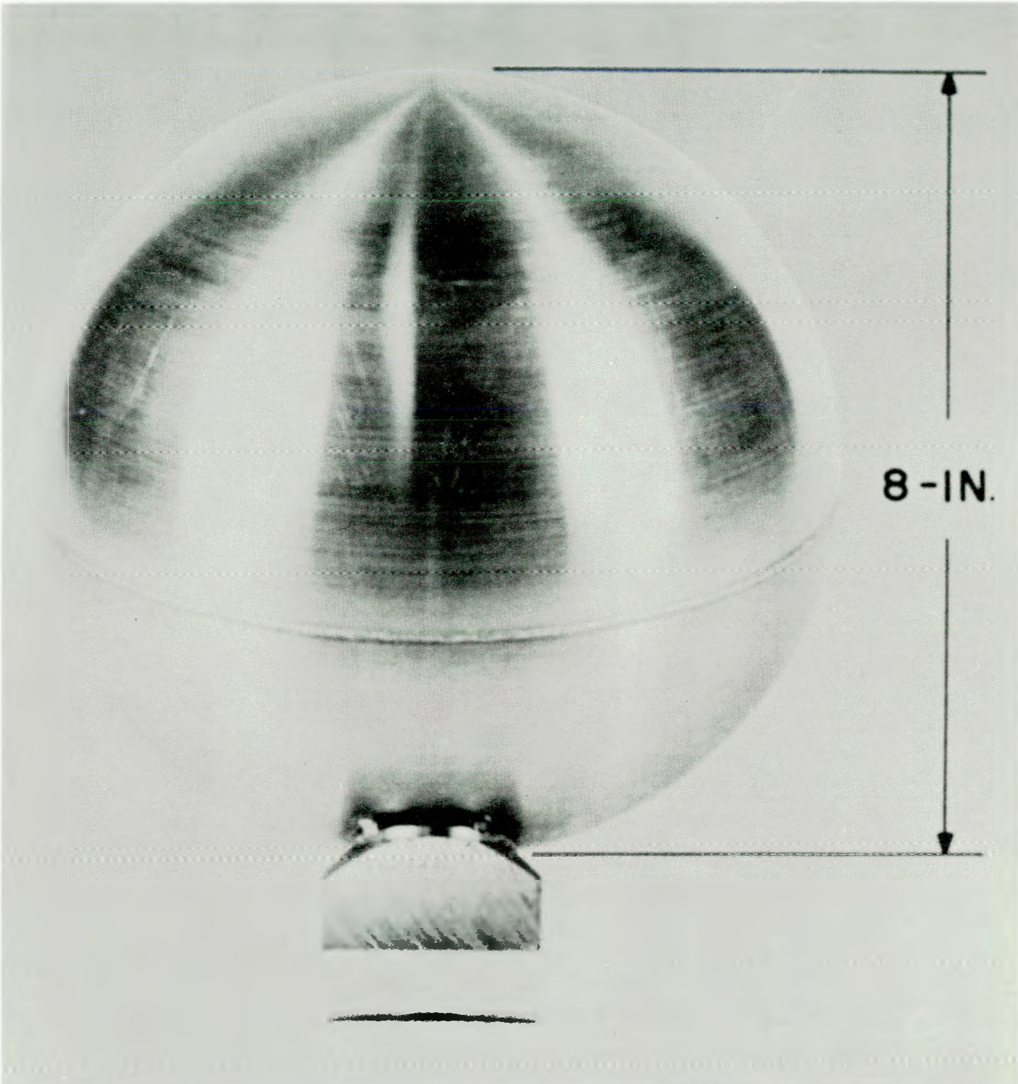


FIGURE 23. ELECTRON-BEAM WELDED PRESSURE VESSEL
(17-7 PH STAINLESS STEEL,
0.140-INCH WALL THICKNESS)
(Ref. 24)

precipitation-hardening stainless steels, welding conditions are based on those used for the austenitic stainless steels. For best welding results with alloys like 17-7 PH and PH 15-7 Mo, welding just before or just after the final hardening treatment is usually recommended. This procedure leaves the spot weld nugget in a softer, tougher condition than the base metal.

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 during resistance spot welding. The thermal and electrical conductivities, and mechanical properties of the precipitation-hardening stainless steels vary, depending on the alloy and its condition. Conditions for spot welding, therefore, are adjusted to account for the material properties as with other materials. Usually, several combinations of welding variables can produce similar and acceptable results.

Equipment. Precipitation-hardening stainless steels have been welded successfully using conventional resistance spot-welding equipment (Ref. 45). 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, however, desirable to have enough control over the parameters to obtain reproducible results, once the optimum settings are obtained for a given application. Because of the higher currents and electrode forces required for thicker sheet and for the harder alloys, the larger press-type machines are more suitable. 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, but there may be a preference by some fabricators for three-phase equipment.

RWMA Group A Class 3 electrode alloy generally is used for spot welding precipitation-hardening stainless steels. In conventional practice, internally cooled electrodes are recommended to improve tip life. For small parts, the electrodes often are not water cooled. Both flat face and spherical radius tip geometries are used.

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

(1) Joint Overlap - A sufficient amount of overlap should be provided to contain the weld.

(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 to some current through previously made welds.

Welding Conditions. Resistance spot-welding conditions are primarily controlled 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 precipitation-hardening stainless steels generally 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. Current is set at a value that is somewhat above the value that produces a week or just "stuck" weld, but below values that produce expulsion.

Properties. The quality of spot welds is determined 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-6858 (Ref. 46), place certain restrictions on weld penetration, sheet separation, electrode indentation, and weld diameter.

Many properties and characteristics of resistance spot welds in precipitation-hardening stainless steels have been determined. 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 extensively for fabricating some of the precipitation-hardening stainless steels, and considerable information has been developed on spot welding these alloys. Some of the precipitation-hardening stainless steels have not been so widely used in sheet form, so the information available on spot welding them is quite limited.

AM-350, AM-355, AM-362, and AM-363 alloys are spot welded using conditions similar to those used for austenitic stainless steels (Ref. 47). These alloys can be spot welded before or after the final hardening treatment. However, spot welding AM-350 before the transformation treatment can result in low strength and brittle failures (Ref. 48). To obtain tension-to-shear ratios greater than 0.25, it is recommended that the aging treatment precede the welding operation. Strengths of spot-welded AM-350 and AM-355 are shown in Table XIX. The effects of various heat-treating cycles on the tension-to-shear ratio of spot-welded AM-350 are shown in Table XX. The tensile-shear strengths at elevated temperatures of various thicknesses of spot-welded AM-350 are shown in Figure 24. An AM-350 spot-welded strap hinge is shown in Figure 25. Spot welds also have been made to join AM-350 to 17-7 PH. The tensile-shear strengths of these welds were very similar to those in AM-350.

TABLE XIX. TENSION-SHEAR STRENGTHS OF SPOT-WELDED AM-350 AND AM-355 STAINLESS STEELS (Ref. 47)

Heat Treatment Condition[a]	Electrode Diameter, inch	Electrode Force, pounds	Weld Time, cycles	Welding Current, amperes	Tension-Shear Strength, pounds
		0.024-Inch-Thick AM-350			
A + welded	5/32	1200	12	8,500	1090
	1/4	1200	24	10,500	1275
C + welded	5/32	1200	12	7,500	1020
	1/4	1200	12	9,500	1440
C + welded	5/32	1200	12	7,500	1030
	1/4	1200	12	9,500	1260
		0.037-Inch-Thick AM-355			
A + welded	1/4	900	10	9,500	1810
			14	9,500	1900
B + welded	1/4	900	10	9,500	1850
			14	9,500	2500
C + welded	1/4	900	10	9,500	1410
			14	9,500	1940
Welded + D	1/4	900	10	9,500	1840
			14	9,500	2140
Welded + E	1/4	900	10	9,500	2480
			14	9,500	2080
Welded + F	1/4	900	10	9,500	1780
			14	9,500	2240

(a) Code — Heat Treatment
- A — Mill annealed at 1750 F
- B — Mill annealed; -100 F for 2 hours; 850 F for 2 hours
- C — Mill annealed; 1375 F for 1 hour; air cool; 850 F for 1 hour
- D — -100 F for 2 hours; 850 F for 2 hours
- E — 1710 for 15 minutes; air cool; -100 F for 2 hours; 850 F for 2 hours
- F — 1375 for 1 hour; air cool; 850 F for 1 hour.

TABLE XX. EFFECT OF HEAT TREATMENT ON TENSION-TO-SHEAR RATIOS OF SPOT-WELDED 0.080-INCH-THICK AM-350 STAINLESS STEEL (Ref. 47)

Preweld Heat Treatment	Postweld Heat Treatment	Strength, pounds: Tensile-Shear Test	Strength, pounds: Cross-Tension Test	Tension-to-Shear Ratio
Anneal (1720 F)	None	7475	2575	0.34
Anneal (1720 F)	SCT	8725	2100	0.24
SCT	None	7450	3060	0.41
SCT	SCT	8710	2550	0.25

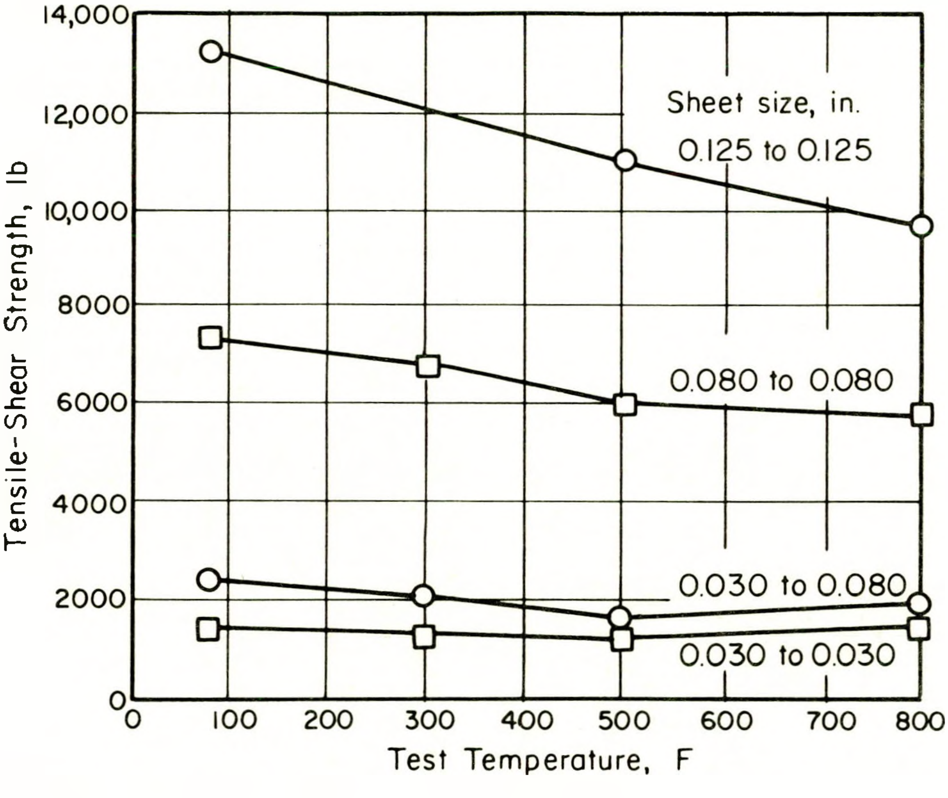


FIGURE 24. TENSILE-SHEAR STRENGTH AT ELEVATED TEMPERATURES FOR SPOT-WELDED AM-350 STAINLESS STEEL (Ref. 47)

Material in SCT heat-treated condition prior to welding. No postweld heat treatments given.

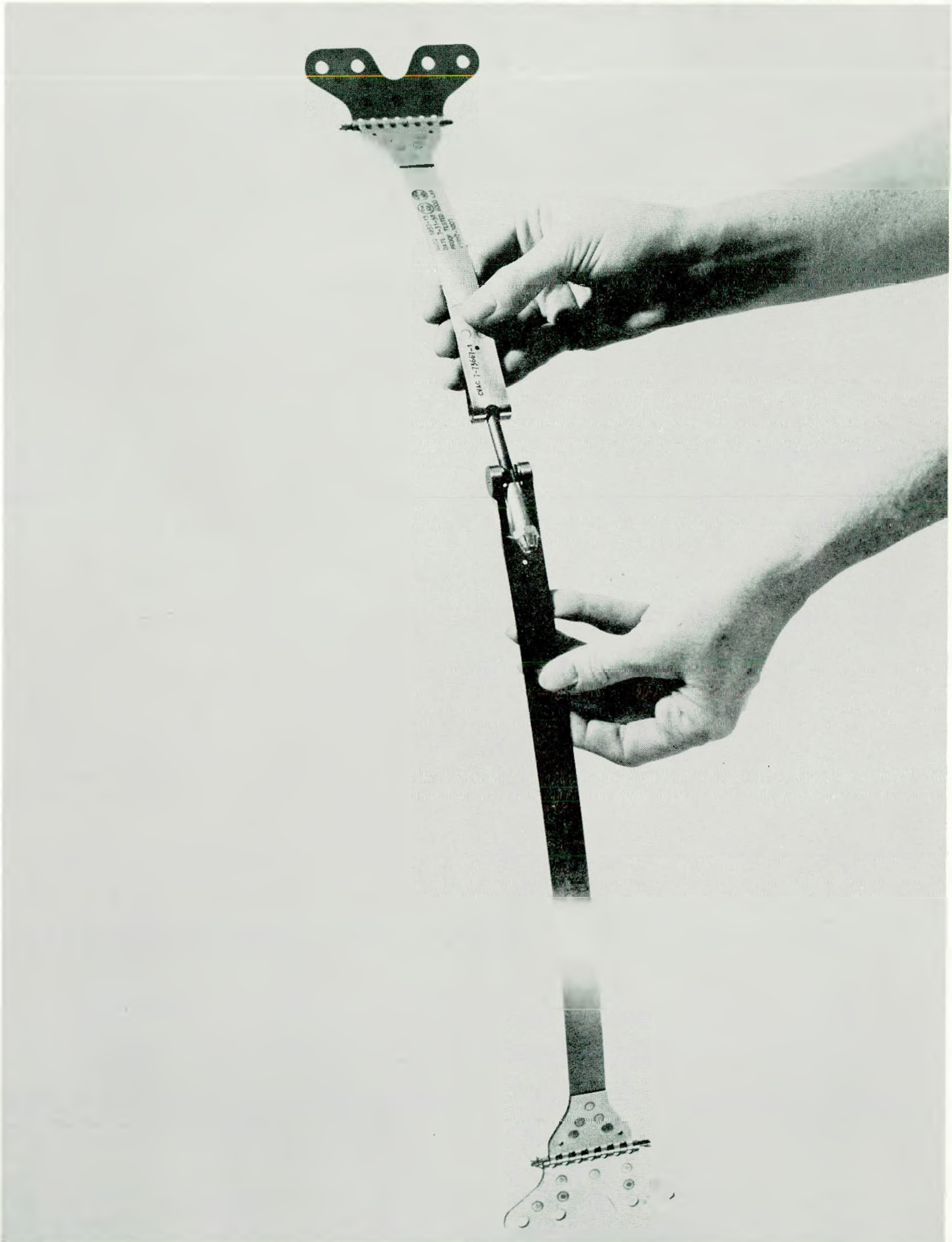


FIGURE 25. STRAP-HINGE OF AM-350 USED TO FASTEN CANISTERS OF DELICATE INSTRUMENTS IN THE ATLAS MISSILE (Ref. 49)

Spot welding was used to fabricate light weight AM-355 rocket chambers strong enough to withstand 305,000 psi wall stress (Ref. 50). These chambers, shown in Figure 26 and 27, were fabricated by "strip winding" and spot welding multiple layers. This method of fabrication was used as a replacement method for brazing and resin bonding. Brazing introduced extra weight and the high brazing temperatures weakened the parent metal. Resin-bonded layers separated when subjected to aerodynamic heating.

Slightly higher spot welding currents are required for Almar 363 than for the austenitic stainless steels because the material is magnetic (Ref. 51). The spot welded strengths increase with the weld diameter in the same manner as the austenitic stainless steels. Figure 28 illustrates the weld strengths which are well above the AWS minimum values of 2400 pounds. The transportation industry uses spot welding extensively to fabricate Almar 363. Its high strength makes it attractive for the structural framework in applications such as shipping containers, railroad cards, and trailer truck bodies. Figure 29 shows the joining of AISI 201 truck panels to "hat" shaped structural framework which is made of Almar 363 steel.

Armco 17-7 PH, PH 14-8 Mo, and the PH 15-7 Mo alloys also have been fabricated into useful products by spot welding. Typical recent applications of spot welding include rocket chambers and a variety of assembly operations on the XB-70 and other type aircraft. Welding conditions for these alloys also are similar to those used for the austenitic stainless steels. For best spot welding results, it is recommended that spot welding be performed just before or after the final hardening treatment. This procedure produces a spot weld nugget that is in a tough austenitic condition (Ref. 52. These alloys can be spot welded readily to satisfy the requirements of MIL-W-6858 (Ref. 52, 53, 54).

Typical welding conditions and properties of spot welds in 17-7 PH are given in Table XXI. These data show that acceptable spot welds can be produced

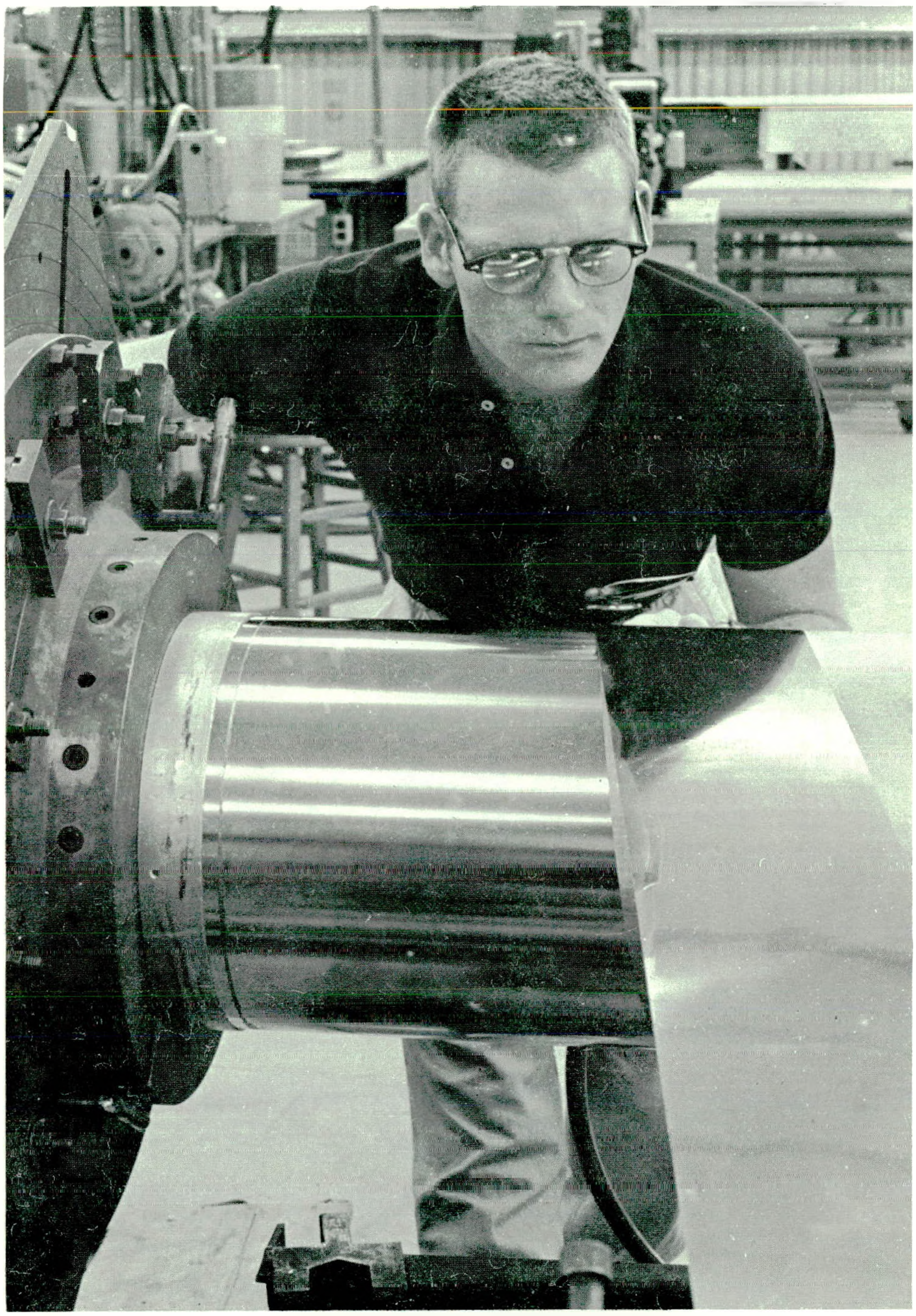


FIGURE 26. WRAPPING AM-355 FOIL ONTO A MANDREL WHERE IT IS TACK WELDED INTO POSITION PRIOR TO SPOT WELDING (Ref. 50)

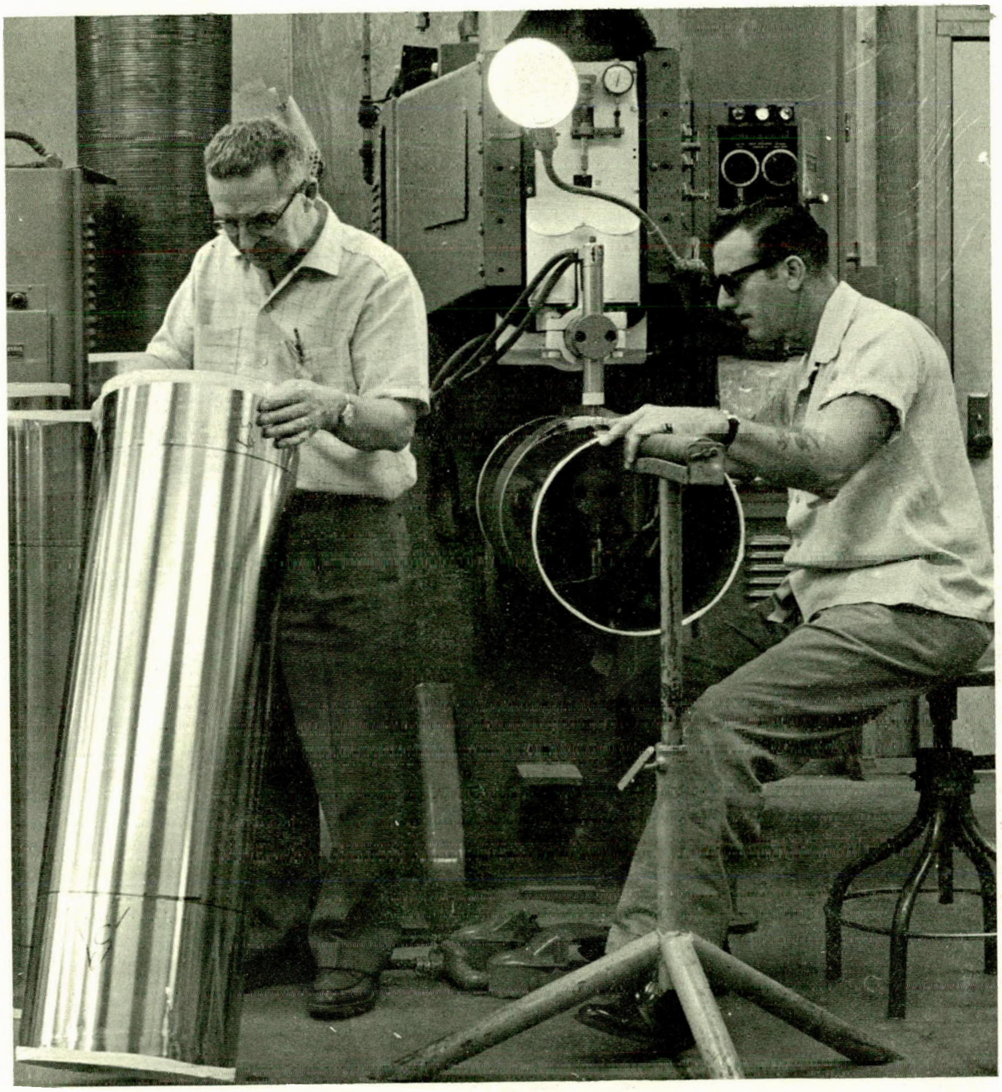


FIGURE 27. RESISTANCE SPOT WELDING A NEW AM-355 CASE (Ref. 50)

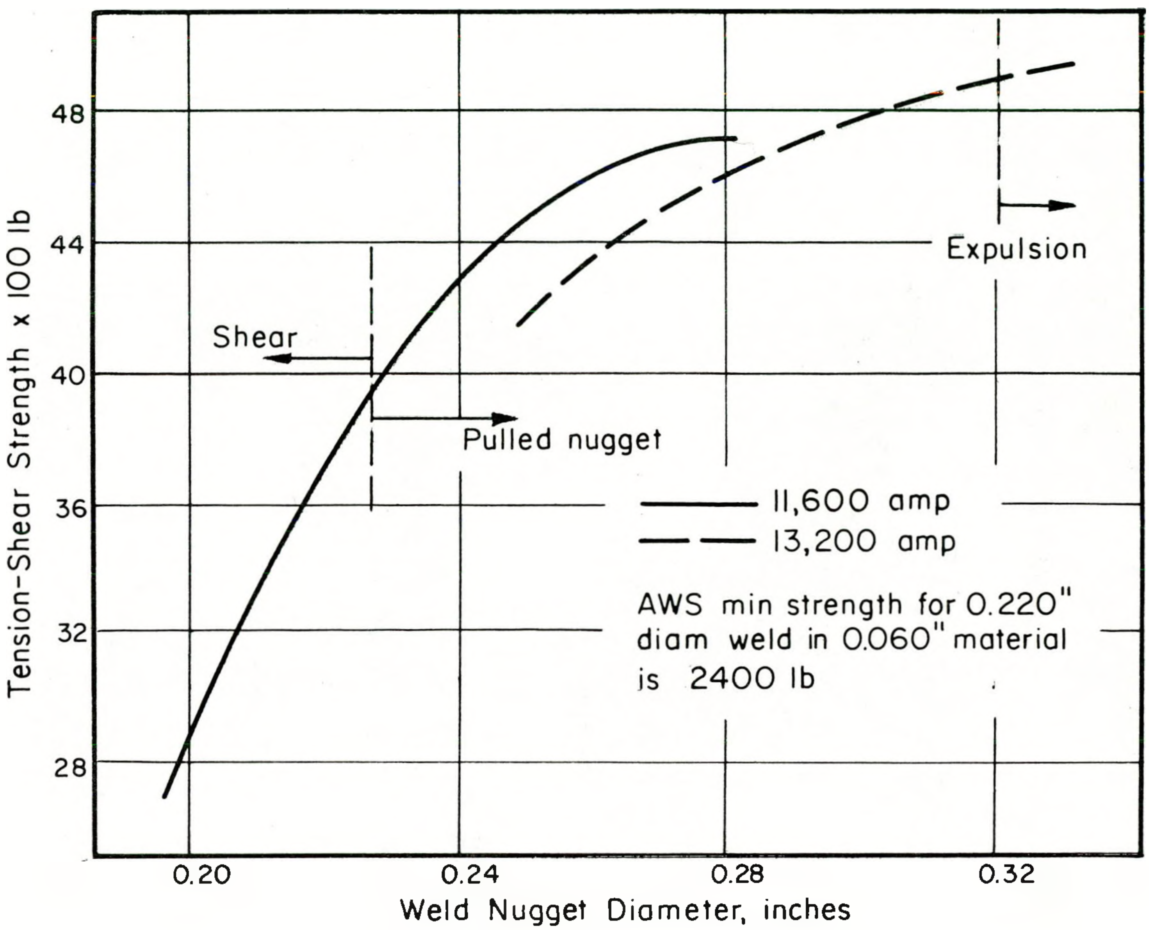


FIGURE 28. TENSION-SHEAR STRENGTH FOR SPOT WELDS IN 0.060-INCH-THICK ALMAR 363 (Ref. 51)

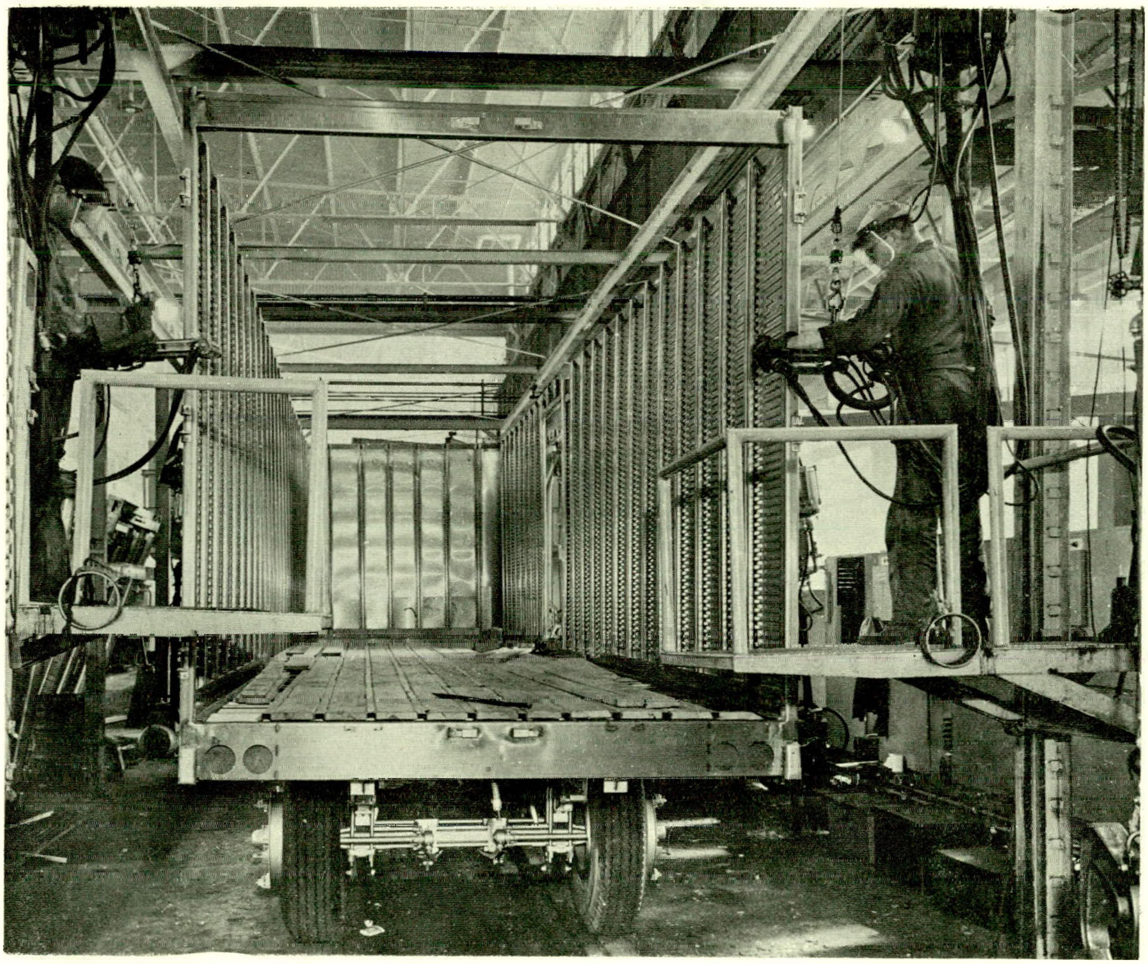


FIGURE 29. ALMAR 363 STRUCTURAL MEMBERS BEING SPOT WELDED TO TYPE 201 STAINLESS STEEL PANELS (Ref. 51)

TABLE XXI. RESISTANCE-SPOT WELDING CONDITIONS AND PROPERTIES FOR SPOT WELDS IN 17-7 PH PRECIPITATION-HARDENING STAINLESS STEEL (Ref. 52)

Thickness, inch	Condition In Which Welded	Condition In Which Tested	Force, lb	Time, cycles	Current, amperes	Average Tension-Shear Strength, lb
0.050/0.050	A	RH950	1200	10	7500	2556
0.050/0.050	R-100	RH950	1200	10	7500	2882
0.050/0.050	RH950	RH950	1200	10	7500	26660
0.050/0.050	A	TH1050	1200	8	8700	2990
0.050/0.050	A	TH1050	1200	10	8700	2790
0.050/0.050	A	TH1050	1200	12	8700	2680
0.050/0.050	A	TH1050	1400	10	8700	2870
0.050/0.050	A	TH1050	1600	10	8700	2730
0.050/0.050	A	TH1050	1800	12	8700	2900
0.050/0.050	T	TH1050	1200	10	7500	2970
0.050/0.050	T	TH1050	1200	12	7500	3250
0.050/0.050	T	TH1050	1400	10	7500	2790
0.050/0.050	T	TH1050	1600	10	7500	2710
0.050/0.050	T	TH1050	1800	12	7500	2980
0.050/0.050	TH1050	TH1050	1200	10	7500	2610
0.050/0.050	TH1050	TH1050	1200	12	7500	2747
0.050/0.050	TH1050	TH1050	1400	10	7500	2620
0.050/0.050	TH1050	TH1050	1600	10	7500	2550
0.050/0.050	TH1050	TH1050	1800	12	7500	2700

in 17-7 PH with a variety of material and welding conditions. Spot welding of a typical 17-7 PH aircraft component is shown in Figure 30 (Ref. 55).

The PH 14-8 Mo alloy also can be spot welded (Ref. 14). Welding schedules developed for PH 14-8 Mo, a candidate skin material for supersonic transport aircraft, are recorded in Table XXII (Ref. 56). The alloy was spot welded in the annealed condition and in the heat-treated condition. Specimens made from heat-treated material were tested in the as-welded condition, and specimens made from annealed material were heat treated after welding. The postheat treatment was as follows: Trigger annealed at 1700 F for 1 hour and air cooled, then sub-zero cooled at -110 F for 8 hours, and then aged at 1050 F for 1 hour.

The PH 15-7 Mo alloy also can be spot welded readily (Ref. 53). Properties obtained for spot welds prepared in intermediate stages during heat treatment to the standard conditions TH 1050, RH 950, and CH 900, are shown in Table XXIII. As part of the B-70 program, PH 15-7 Mo stainless steel was spot welded using existing certified welding schedules for 17-7 PH (Ref. 57). Material thickness combinations were 0.025/0.025, 0.025/0.040, and 0.040/0.040 inch.

A-286 alloy also is readily resistance welded. Several aircraft companies have experienced no problems with cracking or other defects related to spot welding this alloy (Ref. 47). Other investigators, however, have encountered cracking and recommend the use of increased force or downsloped welding current as possible remedies (Ref. 45). Another fabricator (Refs. 54, 58) concluded that the range of spot welding machine settings was found to be narrower than for stainless steels of the 18-8 variety. Within the welding range, the alloy was weldable without flood cooling and with less discoloration than Type 321 stainless. There were indications that it would be difficult to avoid cracking in or adjacent to the weld nugget, especially if welded under restraint. Some typical properties for A-286 spot welds are given in Table XXIV.

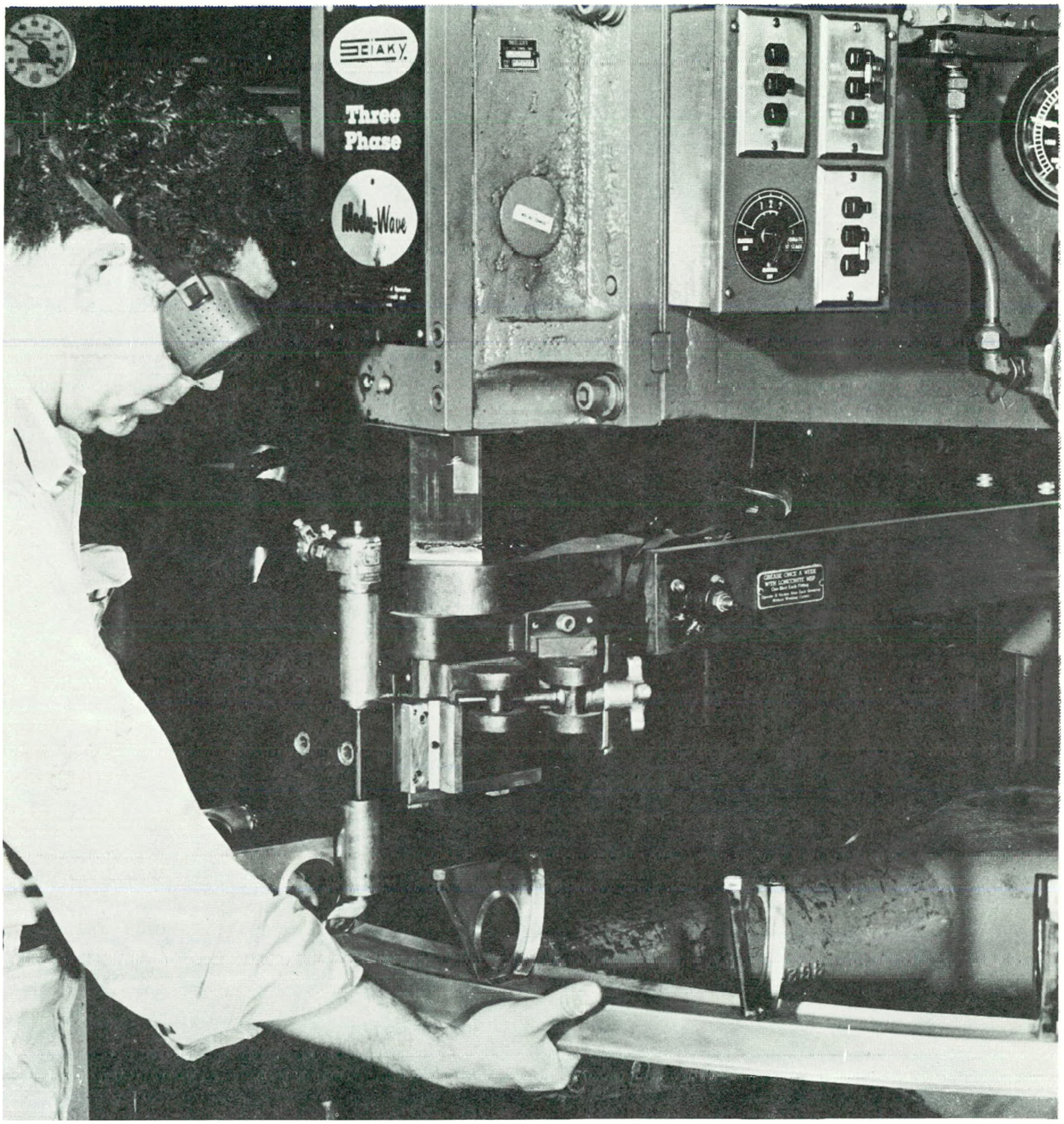


FIGURE 30. SPOT WELDING ECONOMICALLY FABRICATES A LIGHTWEIGHT HIGH-STRENGTH AIRCRAFT PART MADE OF 17-7 PH PRECIPITATION-HARDENING STAINLESS STEEL (Ref. 55)

TABLE XXII. SPOT-WELDING SCHEDULE FOR 0.025/0.025-INCH PH 14-8 Mo STAINLESS STEEL (Ref. 56)

	Condition Prior to Welding	
	Heat Treated	Annealed (as received)
Weld phase shift, percent	50	36
Heat cycles	2	3
Cool cycles	1.5	1.5
Impulses	1	2
Transformer	Series	Series
Weld force, lb	1,250	800
Electrodes	Copper	Copper
Class	III	II
Diameter, inch	5/8	5/8
Radius, inch	3	3
Nugget diameter, inch	0.115	0.115
Penetration, percent	50	30
Average tension shear strength, lb	850	765
Average cross tension strength, lb	417	448

TABLE XXIII. PROPERTIES OF SPOT WELDS IN PH 15-7 Mo (Ref. 53)[a]

Thick-ness, inch	Condition in Which Welded	Condition in Which Tested	Average Tension Shear Strength			Tension Breaking Load --- lb		
			low	low 3	Avg. of 20	low	low 3	Avg. of 20
0.049	A	TH 1050	2830	2840	3103	370	400	580
	T	TH 1050	3075	3208	3438	1360	1392	1648
	TH 1050	TH 1050	2530	2623	2896	1500	1652	2015
	MIL-W-6858	Minimums	2125	2470	2620	--	--	--
0.049	A	RH 950	2500	2550	2853	370	393	520
	A 1750	RH 950	3115	3248	3426	--	--	--
	R-100	RH 950	2945	3105	3335	1040	1050	1232
	RH 950	RH 950	2480	2533	2630	1890	1977	2170
	MIL-W-6858	Minimums	2125	2470	2620	--	--	--
0.040	C	CH 900	2545	2625	2648	740	767	854
	CH 900	CH 900	2115	2222	2422	1040	1113	1264
	MIL-W-6858	Minimums	1460	1700	1800	--	--	--

(a) Welding conditions:

Electrode force 1200 pounds
Dome radius of electrode: 3 inches
Current: 7500 amperes
Time: 10 cycles
No postheat or forge cycle.
Vapor blasting used to remove heat treat scale before welding.

TABLE XXIV. RESISTANCE-SPOT-WELDING CONDITIONS AND PROPERTIES FOR SPOT WELDS IN A-286 PRECIPITATION-HARDENING STAINLESS STEELS

Thickness, inch	Preweld Treatment	Postweld Treatment	Tip Face Diameter, inch	Electrode Force, lb	Weld Time,* cycles	Welding Current, amperes	Nugget Diameter, inch	Average Shear Strength, lb	Tension/ Shear Ratio, per cent	Reference
0.036/0.036	Fully soft	None	3/16	950	15	4800	0.128	1090	61.2	45
	Fully soft	None		800	10	5200	0.145	1200	69.3	45
	Fully soft	None		1000	7.5	6100	0.100	920	44.3	45
0.050/0.050	1800 F, 1 hr, oil quench	None	--	--	--	--	--	2035	90	47
	Ditto	1325 F, 16 hr	--	--	--	--	--	2845	49	47
	1800 F, 1 hr, oil quench 1325 F,16 hr.	None	--	--	--	--	--	2665	66	47
0.064/0.064	Fully soft	None	1/4	1500	30	6900	0.255	2770	78.8	45
	Fully soft	None		1700	20	7500	0.245	2580	76.0	45
	Fully soft	None		1700	15	7900	0.245	2640	76.7	45

* 50 cycle per second power supply.

Resistance Seam Welding. Seam welding is similar to spot welding. The principal advantage of seam welding 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. Experience in seam welding the precipitation-hardening stainless appears to be limited to 17-7 PH.

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 seam welding, the wheels usually can be rotated continually or intermittently. The use of continuous seam welding imposes additional limitations on 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. When the completed weldment is intended for applications requiring leaktight seams, suitable pressure or leak tests are used. In addition, many of the tests applicable to spot welds also are applicable to seam welds.

Applications. Seam welding is used for welding sheet metals usually for applications requiring gastight or leaktight seams. The precipitation-hardening stainless steels have been resistance seam welded but, unfortunately, only limited information is available in the published literature. The available information is further restricted to the 17-7 PH alloys. Seam welding conditions and properties for this alloy are given in Table XXV. When developing these conditions, the best combination of surface condition and weld spacing was produced using a seam welding speed of 25 inches per minute, 5 cycles heat time, and 4 cycles cool time. The seam welds were very nearly free of defects except for some expulsion and porosity near the beginning of each weld.

TABLE XXV. WELDING CONDITIONS AND PROPERTIES FOR RESISTANCE SEAM WELDS IN 17-7 PH PRECIPITATION-HARDENING STAINLESS STEEL (Ref. 59)

Thickness, inch	Condition Prior to Welding	Condition for Testing	Wheel[a] Face Width, inch	Wheel[a] Radius, inch	Electrode Force, lb	Timing, cycles On	Timing, cycles Off	Weld Spacing, Welds per in.	Wheel Speed, in./min	Weld Current, amperes	Width of Fused Zone, inch	Average Tension Shear Strength, lb
0.090/0.100	A	TH 1050	9/16	3	--	5	4	--	25	--	>0.240	5,520
	T	TH 1050	"	"	--	"	"	--	"	--	"	10,840
	C	As welded	"	"	--	"	"	--	"	--	"	10,430

(a) RWMA Class II alloy.

Seam welding also has been utilized for close-out joints in 2- and 3-ply pileups of 17-7 PH with access from one side only. Satisfactory welds were prepared using a series-resistance welding arrangement (Ref. 60). The electrode arrangement is shown in Figure 31. Electrode force required with the series arrangement was twice that required for normal seam welding.

Flash Welding. Flash welding is used extensively for joining a limited number of precipitation-hardening stainless steels. Typical products include jet engine rings, aircraft parts, band saws, knives, and pressure tanks (Ref. 61).

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 preferentially corroded are not present. Second, the hot metal in the joint is upset, and this upsetting operation may improve the ductility of the heat-affected zone.

Flash welding has several important advantages. Weight saving can be realized because there is no need for overlapping bolting, riveting, or welding flanges. 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. For welding, the parts are held firmly in two copper-alloy dies. One or both of these dies are movable. Current from a welding transformer passes through the dies and into the work. The parts initially may or may not be separated but are advanced toward each other. At the first contact of the parts, the current causes melting of the metal and violent expulsion. This behavior 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.

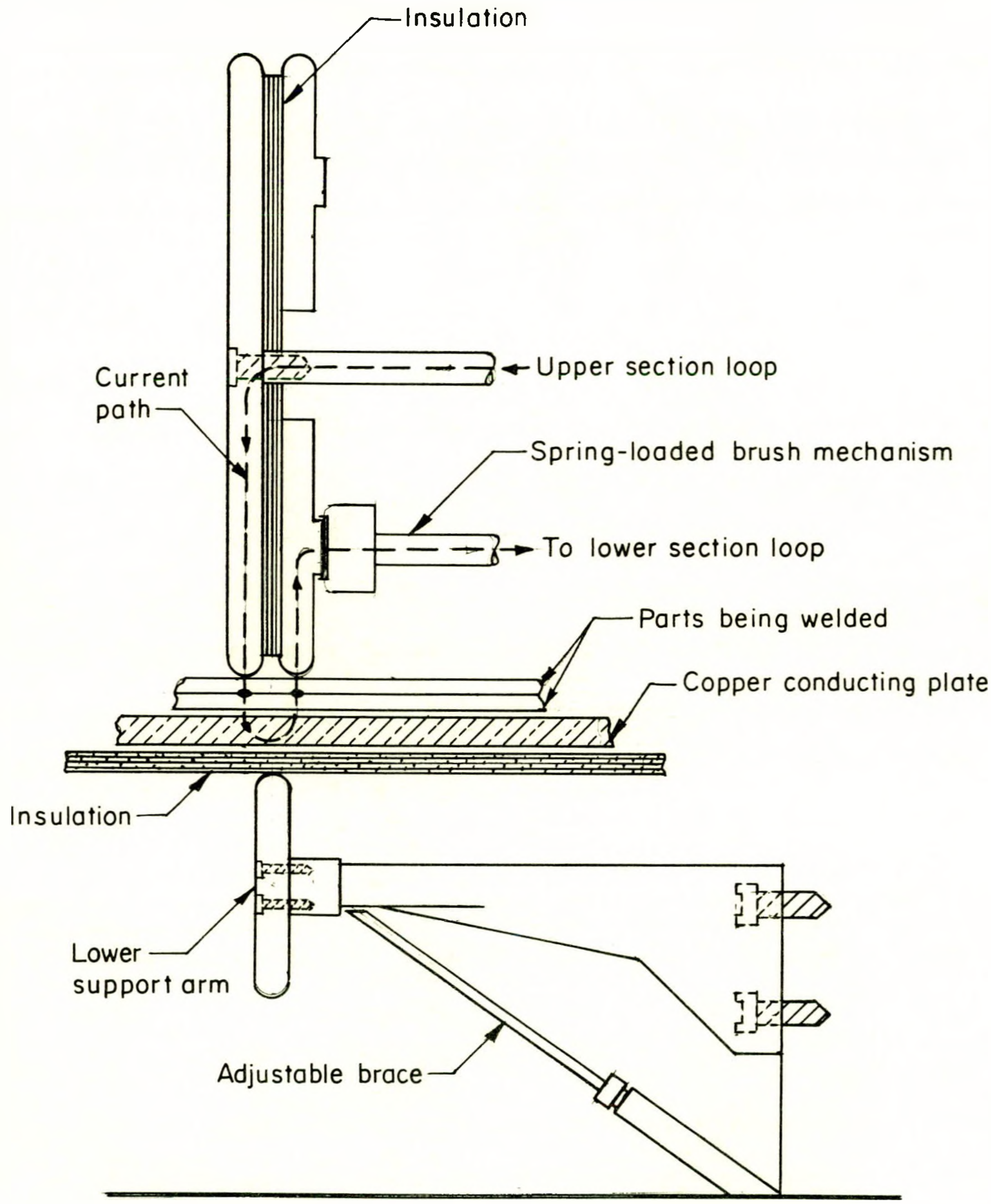


FIGURE 31. MACHINE ARRANGEMENT FOR SERIES SEAM WELDING (Ref. 60)

3

The machine capacity required to weld precipitation-hardening stainless steels 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 precipitation-hardening stainless steels is higher than that required for steel. Figures 32 and 33 show the transformer and upset capacity required for welds of different cross-sectional areas in stainless steels (Ref. 62). Also of importance is the fact that 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 flash welding precipitation-hardening stainless steels also 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 over-all 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 34 shows the metal allowances used in making flash welds in several materials including stainless steels. 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.

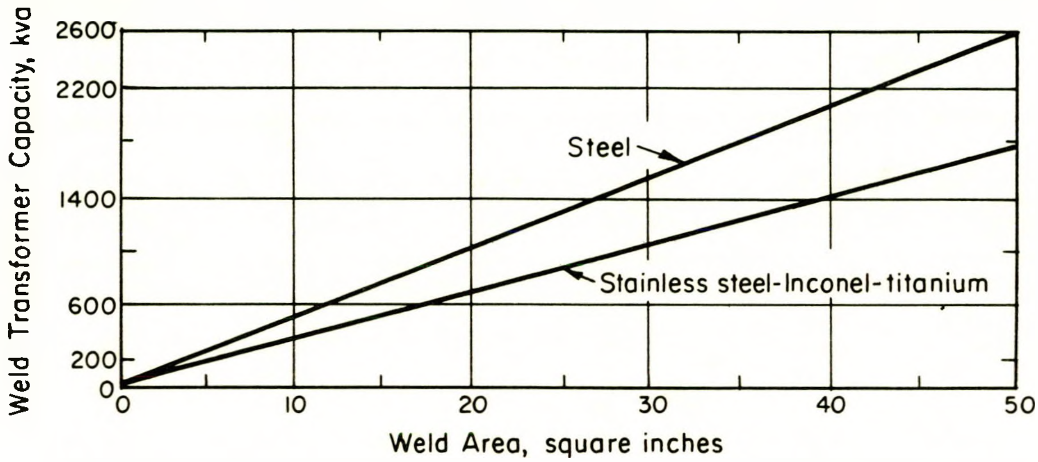


FIGURE ·32. TRANSFORMER CAPACITY VERSUS WELD AREA FOR FLASH WELDING (Ref. 62 as corrected)

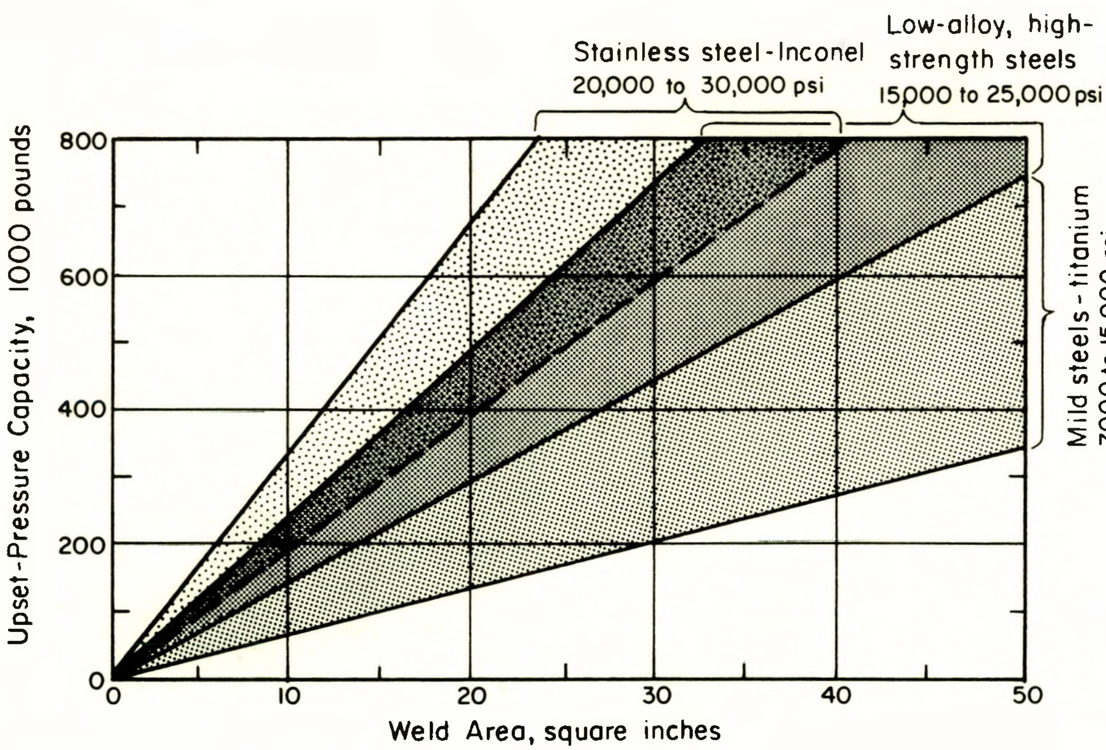


FIGURE 33. MAXIMUM MACHINE UPSET-PRESSURE REQUIREMENTS VERSUS WELD AREA FOR FLASH WELDING (Ref. 62)

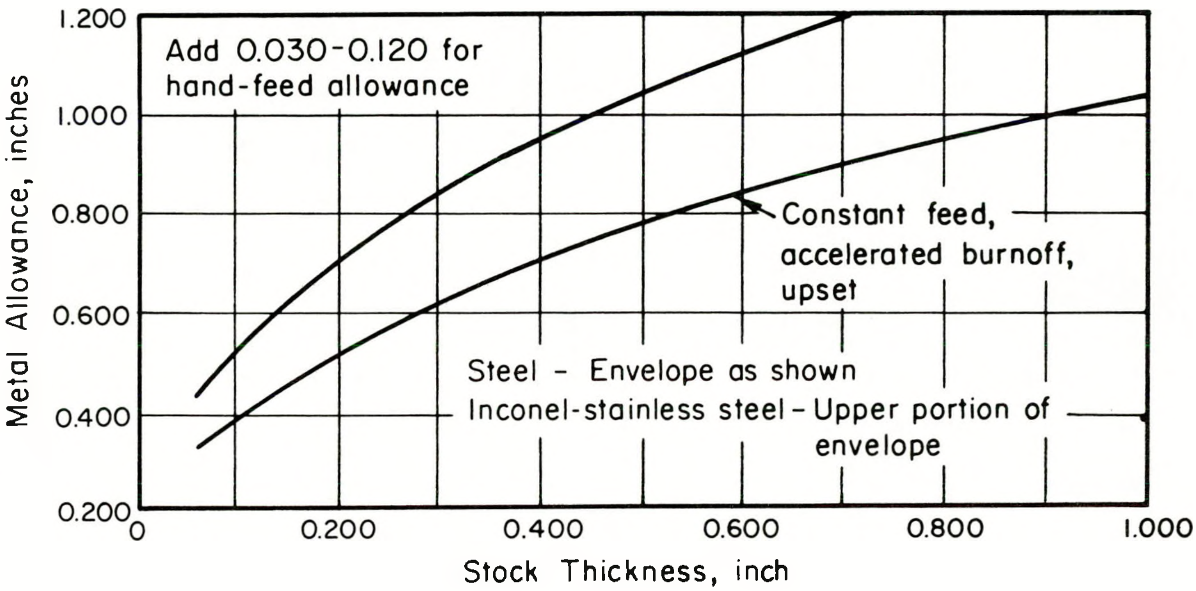


FIGURE 34. TOTAL METAL ALLOWANCE VERSUS STOCK THICKNESS FOR FLASH WELDING (Ref. 62)

Flash-welding variables vary from machine to machine and application to application. Welding current and arc voltage depend on the transformer tap that is used.

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 per cent or better are common for flash welds. The static-tension-test properties of flash-welded joints in 17-7 PH and A-286 are summarized in Table XXVI.

Applications. Flash welding has been used for joining precipitation-hardening stainless steels in a variety of forms and shapes. It is used for butt welding bar, rod, and extruded sections. The process also is used for joining rings such as jet-engine rings. A typical jet-engine ring fabricated by flash welding is illustrated in Figure 35. These rings are fabricated by ring rolling of extruded sections and flash welding. Some of the processing steps used by one ring manufacturer for fabricating flash-welded rings are illustrated in Figure 36 (Ref. 63).

Other Resistance Welding Processes. The precipitation-hardening stainless steels have been welded by other resistance welding processes but, unfortunately, information on welding conditions and properties is very limited. Stud welding has been tried, and conventional methods and fluxing procedures for stainless steels in general appear promising (Ref. 64).

Projection welding also has been used for cross wire welding the 17-4 PH alloy. Information available on this application is presented in Table XXVII (Ref. 16). Cross-wire weldment strengths can exceed the strengths for similar welds in Type 301 stainless steels, when the 17-4 PH weldment is properly heat treated subsequent to welding. The cross wire welds described in Table XXVII were made using a 75 kva a-c-type spot-welding machine and tested in simple tension using a special testing fixture.

TABLE XXVI. PROPERTIES OF FLASH WELDS IN PRECIPITATION-HARDENING STAINLESS STEELS

Material	Condition Prior to Testing	Ultimate Tensile Strength, ksi	0.2 Percent Yield Strength, ksi	Elongation, % in 2 in.	Reduction of Area, percent	Location of Failure	Reference
17-7 PH	Welded & solution treated[(a)] +900F-1hr-air cool	203.0	184	8.0	37	Weld	16
17-7 PH	Welded +900F-1hr-air cool	175.0	--	17.0	--	Base Metal	16
17-7 PH	Welded & solution treated[(a)] +900F-1hr-air cool	187.0	--	9.6	38.4	--	16
A-286	As welded	104.0	84.0	7.0	67.0	Weld	43
A-286	950 F, 16 hr	109.0	86.0	8.0	48.0	Weld	43
A-286	1325 F, 16 hr	147.0	99.0	22.0	41.0	Base Metal	43

(a) Solution treatments were 1900 F, 1/2 hr - air cool to 60 F for 1 hr.

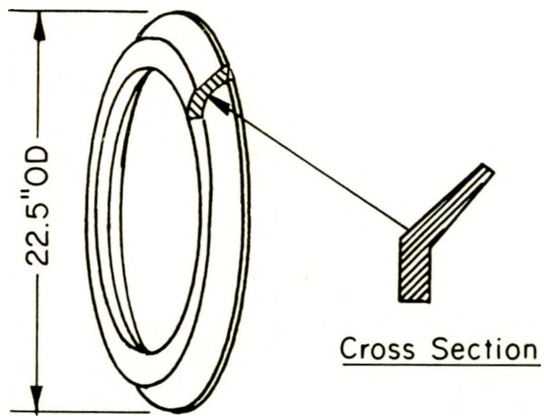
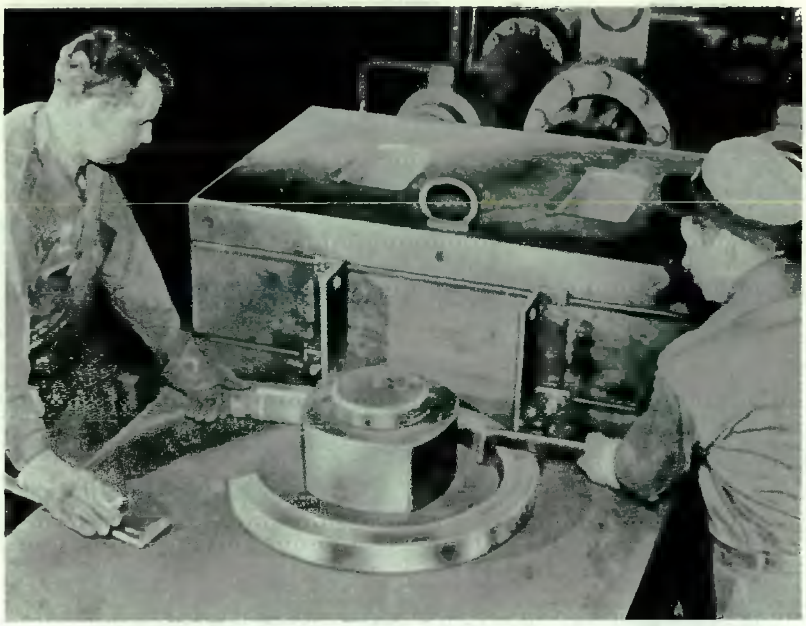
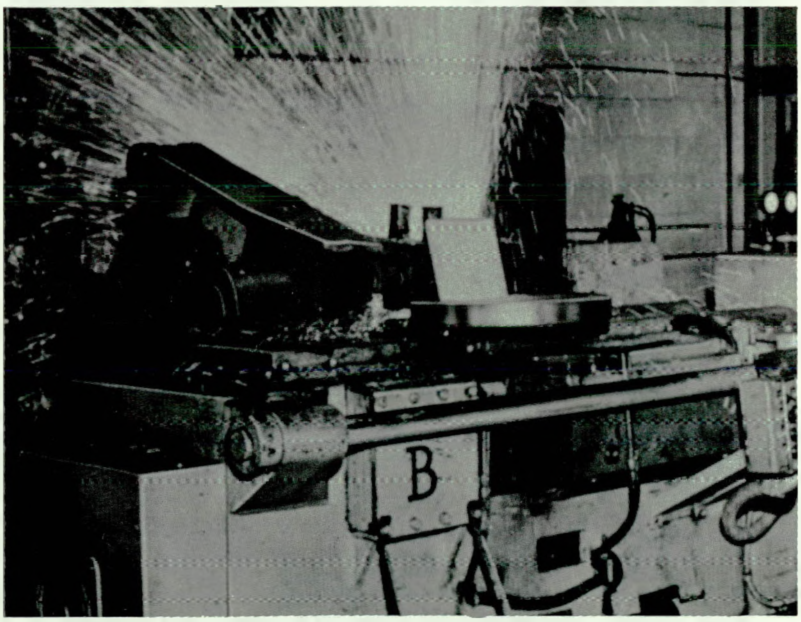


FIGURE 35. ILLUSTRATION OF A FLASH-WELDED JET-ENGINE RING (Ref. 56)



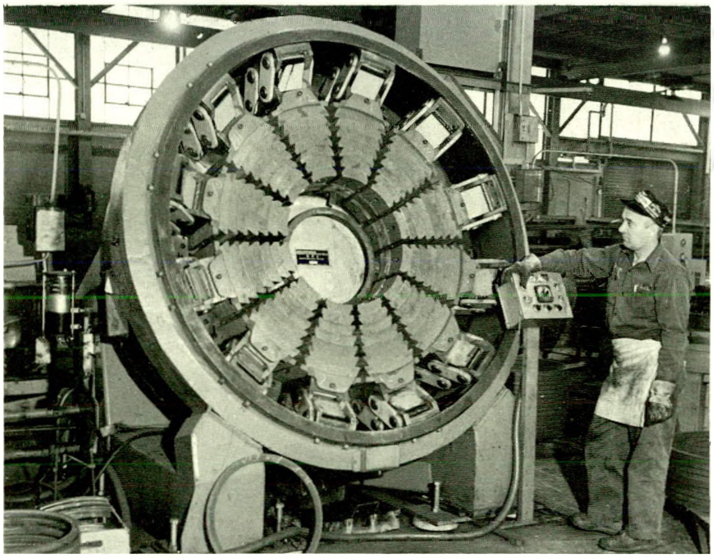
(a) Bending



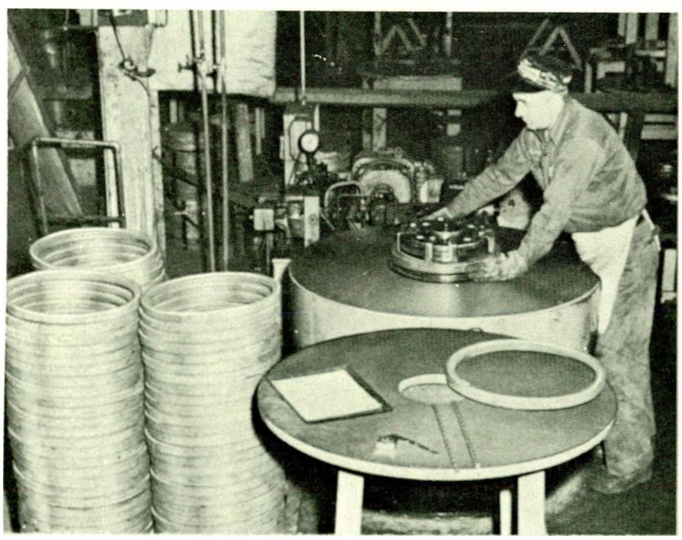
(b) Flash welding

FIGURE 36. PROCESSING STEPS FOR FABRICATING FLASH-WELDED JET ENGINE RINGS

(Courtesy King Fifth Wheel Co.)



(c) Shrinking



(d) Expanding

FIGURE 36. (Continued)

TABLE XXVII. TENSILE STRENGTH OF RESISTANCE PROJECTION WELDED CROSS-WIRE JOINTS (Ref. 16)

Alloy Name	Diameter, inch	Final Condition Prior to Testing	Breaking Load in Tension, lb[a]
17-4 PH	1/4	Welded + 900 F - 1 hr - air cool	2,864[b]
		H900 + Welded + 900 F - 1 hr - air cool	3,307[b]
		Weld + Solution Treated + 900 F - 1 hr - air cool	3,988[b]
		H900 + Welded	4,876[b]
302	1/4	Cold Drawn (UTS 160,000 psi) + welded	3,295[b]
17-4 PH	5/32	A + Weld + 975 F - 1 hr - air cool	1,670[c]
		A + 975 F + Weld - 1 hr - air cool	3,090[c]

(a) Values are averages of five tests.
(b) The mutual indentation of round wire sections at the cross wire joint was approximately 10 to 12%.
(c) The mutual indentation of round wire sections at the cross wire joint was 24%.

High-frequency resistance welding also has been used for welding 17-7 PH experimentally (Ref. 65).

SOLID-STATE WELDING

In solid-state welding, two or more solid phases are metallurgically joined without the creation of any liquid. Welding occurs by the action of atomic forces and is not the result of only mechanical interlocking. For engineering purposes, solid-state welding is conveniently divided into two categories, diffusion welding and deformation welding. In diffusion welding, deformation is restricted to that amount necessary to bring the surfaces to be joined into intimate contact and diffusion is the primary mechanism of weld formation. In deformation welding, diffusion plays a less important role and deformation is the primary factor in creation of the weld. Both deformation and diffusion occur in these two solid-state welding processes.

These processes are described in more detail below and experience in the application of these methods to precipitation-hardening stainless steels is presented. The fundamentals of solid-state welding have been extensively discussed in a previous report of the Redstone Scientific Information Center. (Ref. 66).

Diffusion Welding. Solid-state diffusion welding is a joining method in which metals are joined with the application of pressure and heat. Pressure is limited to the 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 permit melting of the surfaces to be joined. Once the surfaces are in intimate contact, the joint is formed by diffusion of atomic species 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 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 alloy or strengthening elements is eliminated.

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 than the base metal 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) Retention of the welding pressure and temperature for the desired welding time.

(5) Removal of the welded parts from the welding equipment for inspection, testing, or placement in service.

The preparation steps involved in diffusion welding 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 "intermediate" material by plating or vapor deposition to provide surfaces that will weld more readily. Preplaced, dissimilar-metal foils can also be used for intermediates. Coatings such as ceramics are sometimes applied to prevent welding in certain areas of the interface. Methods used to apply pressure include simple presses containing a fixed and movable die, evacuation of sealed assemblies so that the pressure differential applies a load, andplacing the assembly in autoclaves so that high gas pressures can be applied. A variety of heating methods also can be used for diffusion welding.

Diffusion welding conditions that have been reported in the literature for precipitation-hardening stainless steels are given in Table XXVIII.

The usefulness of diffusion welding for the joining of precipitation-hardening stainless steels is probably much greater than is indicated by the limited experience shown in Table XXVIII. For example, joining could be performed simultaneously with the age-hardening treatments used with these steels. The feasibility of such an approach has been indicated by a study of diffusion welding Type 347 stainless steel that is not age hardenable (Ref. 66). Using a gold-copper-gold intermediate system, this alloy was successfully joined at 700 F in 15 minutes under 25,000 psi pressure. The welds were leak tight and had tensile strengths of 24,500 psi.

In another solid-state-welding study, measurements were made of adhesion in ultra-high vacuum between pieces of A-286 steel and also pieces of 17-4 PH steel (Ref. 67). Several dissimilar metal combinations that were examined were:

(1) 304 stainless steel to A-286

(2) Rene 41 to A-286

(3) 2014-T6 aluminum to A-286.

Studies of ultrasonic welding of PH 15-7 Mo have also been conducted (Ref. 68).

TABLE XXVIII. SUMMARY OF DIFFUSION-WELDING PROCESSES FOR PRECIPITATION-HARDENING STAINLESS STEELS

			Welding Parameters					
Alloy	Surface Preparation	Intermediate	Time, min.	Temperature, F	Pressure, psi	Atmosphere	Remarks	Reference
PH 15-7Mo	None given	None	10-30	2050	500	Vacuum	Satisfactory Welds	69
PH 15-7Mo	None given	Ni,Pd,HS-25	--	--	--	Vacuum	Welding Feasible	69
AM-350	None given	None	10	2050	500	Vacuum	Satisfactory Welds	69
AM-355	None given	None	10	2050	500	Vacuum	Satisfactory Welds	69
A-286	None given	None	10	2200	500	Vacuum	Satisfactory Welds	69
17-7 PH	400 grit polish and degrease	Ni-1.5Be or Ni-3Be; 4-mil foil	1	2100	<1	7×10^{-5} torr vacuum	Excellent Welds	70

Deformation Welding. Deformation welding differs from diffusion welding primarily because a large amount of deformation takes place in the parts being joined. The deformation makes it possible to produce a weld in such shorter times and frequently at lower temperatures than are possible with diffusion welding. When joining assemblies 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 per cent may be used. The steps involved in deformation welding are very similar to those used in diffusion welding.

Roll Welding. Roll welding is a solid-state-deformation-welding process that has been used for the fabrication of structural shapes and sandwich panels (Refs. 66, 71, 72, 73, 74). The roll-welding process utilizes conventional techniques and equipment and is fabricated in a standard hot rolling mill. An especially important attribute of roll welding is that neither new machines nor unusual techniques are required. Forming is accomplished on hydropresses, brakes, and by other standard airframe manufacturing techniques.

Roll welding usually includes the following processing steps:

(1) Prepare the core, by corrugating or shaping to the desired configuration.

(2) Fill the spaces between corrugations or ribs, using filler bars of mild steel or other appropriate metal.

(3) Position the face sheets on the core-and-filler-bar section.

(4) Place the sandwich in an appropriate yoke.

(5) Weld covers to the yoke to form an airtight pack.

(6) Evacuate the pack, to protect against oxidation.

(7) Hot roll thepack, in the same manner as a single metal plate, to the desired reduction in thickness; welding is accomplished in the same operation.

(8) Contour the pack, if contouring is required, by appropriate hot or cold rolling or other forming process.

(9) Remove the covers, mechanically.

(10) Remove the filler bars chemically, leaching with dilute nitric or other appropriate acid.

Primary advantages of roll-welded sandwich structures include: (1) the fabrication of complex contoured surfaces are possible; (2) a reliable diffusion bond between core and faces, with the properties and strength of the base metal can be achieved; (3) low cost compared to conventional sandwich structures. These advantages make it a suitable method for fabricating fuel tanks, solid propellant engine cases, pressure vessels and space vehicle structures of many kinds.

In a current program, metallurgical practices are being developed for composite rolling metal panels of five specific alloys, one of which is PH 14-8 Mo (Ref. 74). The investigation entails assembling a pack consisting of an expendable container for enclosing the skin sheets and rib members of the structural material. Expendable filler bars are included to separate the ribs and to maintain the desired geometry during rolling. A pack design is shown in Figure 37. Prior to assembly, the PH 14-8 Mo is cleaned by pickling in a solution of 8 parts water, 2.5 parts nitric acid, and 0.5 part hydrofluoric acid at 125 F for about 6 minutes. Following pickling, the steel is:

(1) Rinsed in water

(2) Dipped in weak aqueous solution of ammonia

(3) Rinsed again in water

(4) Washed with acetone

(5) Dried with a clean towel.

Roll welding at 2200 F and a pack reduction of 60 per cent has produced an excellent weld showing complete elimination of the original joint interface.

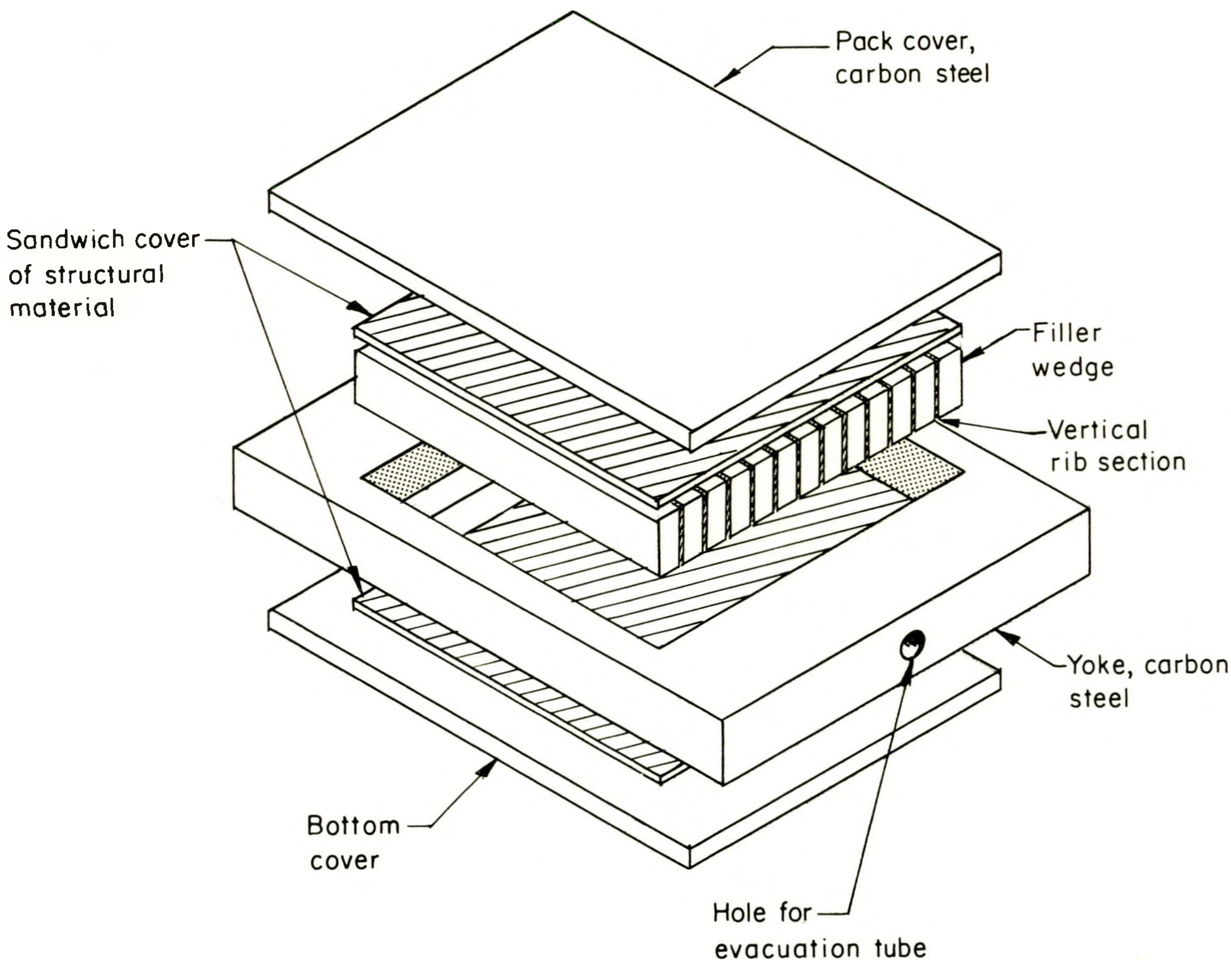


FIGURE 37. EXPLODED VIEW OF PACK ASSEMBLY FOR PRODUCING ROLL-WELDED VERTICAL-RIB SANDWICH PANELS FROM PH 14-8 Mo (Ref. 74)

Pressure-Gas Welding. Pressure-gas welding is a deformation-welding process that uses induction or gas-flame heating and high pressure to butt weld metal pieces without an intermediate material (Refs. 26, 75). Pressure-gas welding may or may not be a solid-state-welding process, depending on the actual welding procedure used. The two modifications of the process 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 until a predetermined upsetting of the joint occurs. In the open-joint method the faces to be joined are individually heated to the melting temperature and then brought into contact for upsetting. This latter process is not a solid-state-welding method but more nearly resembles flash welding in which molten metal is expelled from the joint as upsetting occurs. The upsetting force during welding, which varies depending upon the material and weld area, is usually applied by a hydraulic system. Commercial installations are almost always partially or fully mechanized.

Although this process is adaptable to the joining of nearly all metals and has been applied to the welding of plain-carbon steels, low- and high-alloy steels, nickel-base alloys, titanium alloys, and several other nonferrous metals and alloys; the use of pressure-gas welding for joining precipitation-hardening stainless steels has not been reported. Should it become desirable to pressure-gas weld the precipitation-hardening stainless steels, welding conditions will have to be determined experimentally using conditions for other materials as a guide.

BRAZING

Success in the fabrication of brazed assemblies from the precipitation-hardening stainless steels is dependent on a knowledge of the characteristics of the particular alloy being brazed. Rigid adherence to certain items of process control dictated by these characteristics is a necessity. Heat treatments vary widely for the precipitation-hardening stainless steels; consequently specific brazing procedures are required for each of them. Brazing filler metals must be chosen for compatibility with the desired heat treatments in addition to the end use proposed for the brazement.

There are a large variety of brazing filler metals which can be used to braze the precipitation-hardening alloys. Selection of the proper filler metal for a particular base metal and application can be a most critical operation. In most cases the base metal alloy is chosen for its mechanical properties, resistance to oxidation or corrosion, and to utilize the high strength-to-weight structures possible with these alloys. Consequently, a brazing filler metal must meet the requirements imposed by the designer, be usable at temperatures amenable with the thermal treatments necessary for the base metal and must not adversely affect the base metal. The list of brazing filler metals which can be used on the stainless steels is almost unlimited. Commercial filler metals are available which contain copper, gold, silver, palladium, nickel, manganese, iron, and many other elements either as the base or as additional elements. Usually they are grouped according to their useful temperature and oxidation resistance. General purpose silver-base brazing alloys are suitable for service up to about 800 F, and the copper-manganese-nickel alloys can be used to around 1000 F. For temperatures above 1000 F the nickel-base brazing alloys are most commonly used but the alloys based on either gold or palladium are also widely used. Some typical brazing filler metal alloys for the precipitation-hardening stainless steels are listed in Tables XXIX and XXX.

Cleanliness of all parts to be brazed and of the filler metal is extremely important to successful brazing. Any surface contaminant will inhibit wetting by the molten brazing filler metal and should be removed prior to assembly. In the case of most precipitation-hardening stainless steels the presence of aluminum/ and/or titanium also can inhibit brazing alloy flow. These elements form refractory oxides on the surface unless procedures are used which prevent their formation. These procedures may be copper or nickel plating the surface, or reducing the oxides to metal, or depletion of the titanium and aluminum from the surfaces, or brazing in a controlled atmosphere after very careful cleaning followed by minimum times before brazing.

TABLE XXIX. COMMONLY USED NOBLE METAL BRAZING ALLOYS FOR PRECIPITATION-HARDENING STAINLESS STEELS

Composition, weight per cent								Flow Temperature, F	AMS Number
Ag	Au	Pd	Cu	Li	Zn	Cd	Other		
45	--	--	15	--	16	24	--	1145	4769
50	--	--	15.5	--	16.5	18	--	1175	4770B
56	--	--	22	--	17	--	5 Sn	1205	--
50	--	--	15.5	--	15.5	16	3 Ni	1270	--
35	--	--	26	--	21	18	--	1295	4768
61.5	--	--	24	--	--	--	14.5 In	1305	--
60	--	--	30	--	--	--	10 Sn	1325	--
45	--	--	30	--	25	--	--	1370	--
72	--	--	27.8	0.20	--	--	--	1400	--
50	--	--	34	--	16	--	--	1425	--
40	--	--	30	--	28	--	2 Ni	1435	--
72	--	--	28	--	--	--	--	1435	--
54	--	--	40	--	5	--	1 Ni	1575	4772A
92.5	--	--	7.3	0.20	--	--	--	1635	--
54	--	25	21	--	--	--	--	1742	--
63	--	--	27	--	--	--	10 In	1346	--
75	--	20	--	--	--	--	0.5 Mn	2050	--
--	37.5	--	62.5	--	--	--	--	1841	--
--	82	--	--	--	--	--	18 Ni	1742	--
--	80	--	20	--	--	--	--	1666	--
--	35	--	62	--	--	--	3 Ni	1877	--
--	50	25	--	--	--	--	25 Ni	2050	--
--	70	8	--	--	--	--	22 Ni	1899	--
--	35	--	62	--	--	--	3 Ni	1886	--
--	81.5	--	16.5	--	--	--	2 Ni	1697	--

TABLE XXIX. (Continued)

Composition, weight per cent								Flow Temperature, F	AMS Number
Ag	Au	Pd	Cu	Li	Zn	Cd	Other		
5	75	--	20	--	--	--	--	1643	--
--	60	--	37	--	--	--	3 In	1652	--
--	--	60	--	--	--	--	40 Ni	2260	--
27.5	--	50	23.5	--	--	--	--	1515	--
54	--	25	21	--	--	--	--	1728	--

TABLE XXX. COMMONLY USED NICKEL-BASE BRAZING ALLOYS FOR PRECIPITATION-HARDENING STAINLESS STEELS

Composition, weight per cent						Brazing Temperature Range, F	AMS Number
Cr	Si	B	Fe	Ni	Other		
13.0-20.0	3.0-5.0	2.75-4.75	3.0-5.0	Balance	1.0Co max, 0.6 C.max	1975-2200	4776
6.0-8.0	3.0-5.0	2.5 -3.5	2.0-4.0	Balance	1.0Co max, 0.5 C max	1850-2150	4777
--	3.0-5.0	1.8- 3.5	--	Balance	1.0Co max, 0.5 C max	1850-2150	4778
--	--	--	--	Balance	11 P, 0.1C	1700-1850	--
19	10	--	--	Balance	0.1 C	2100-2200	--
13	--	--	--	Balance	10 P, 0.1C	1700-1950	--
--	8	--	--	Balance	17Mn, 0.1C	1900-2100	--
--	3.5	1.8	--	Balance	0.06 C	1950-2150	4779
7	4.5	3.2	3.0	Balance	6W, 0.1C	1950-2150	--
4	--	0.9	--	Balance	45Mn, 0.1C	2000-2150	--
3.5	2.5	0.9	1.0	Balance	35Mn, 0.1C	1950-2050	--
--	4.5	3.3	--	Balance	20Co	1950	--
--	11.0	--	30.0	Balance	3.5 P, 5.4Mo	--	--
33	4	--	--	Balance	25 Pd	2150-2175	--

Most brazing methods such as torch, induction or furnace, can be used on precipitation-hardening stainless steels. Methods which do notprotect the assembly during brazing require fluxes and pose subsequent flux removal problems. They may also produce weakened joints due to entrapment of flux residues. Consequently, almost all brazing operations on these alloys are carried out in a protective atmosphere. Dry, oxygen-free atmospheres that are used include inert gases, hydrogen, and vacuum. Atmospheres having dew points of -70 F or lower are necessary to prevent oxidation of the base metal during heating. Carbonaceous material should not be permitted in the brazing atmosphere or in the furnace. Carbon in contact with the brazement and carbonaceous atmospheres will carburize the stainless steel. Carburization decreases the strength developed by later hardening treatments (Ref. 14). When brazing in inert atmospheres or vacuum the brazement should be isolated from carbonaceous materials by the use of a thin stainless steel "slip sheet". Slip sheets should be discarded after each use. Dissociated ammonia atmospheres should never be used with the precipitation-hardening stainless steels. Nitriding which results from the use of dissociated ammonia will lower the mechanical properties of these steels.

Additional details of brazing procedures are determined by the particular base metal alloy, the brazing filler metal, and the intended service. Producers of the materials being used and the published literature should be consulted for details that may be applicable to specific applications. Joint property data are not included here. The published literature, standard handbooks and manuals can be consulted for this data.

Applications. The manufacture of honeycomb structural panels and hydraulic systems for supersonic aircraft are significant applications of brazing to the precipitation-hardening stainless steels.

Portions of these aircraft including parts of the wings and engine nacelles are made from honeycomb structures to obtain maximum strength and minimum weight.

One of the base metals used for these applications is 17-7 PH; another is PH 15-7 Mo. Brazing of these structures is accomplished in a controlled atmosphere of argon with the brazing filler metal and brazing cycle chosen to accomplish heat treatment as part of the brazing cycle. The technique as applied to 17-7 PH is thoroughly covered in the Brazing Manual (Ref. 76). A satisfactory combination of brazing and heat treating cycle is outlined below:

(1) Braze 1625-1750 F for 10 minutes using sterling silver plus lithium brazing filler metal (93 per cent Ag-7 per cent Cu plus Li)

(2) Cool to 1000 F within 30 minutes

(3) Cool to -100 F and hold 8 hours

(4) Harden to specified condition (TH1050 or RH950) (Ref. 14).

A section of a retort and tooling used to produce stainless steel honeycomb structures is shown in Figure 38 (Ref. 77).

The production of honeycomb structures from PH 15-7 Mo to give minimum mechanical properties of (UTS-225 ksi, 0.2 per cent YS-200 ksi and 4 per cent elongation) can be accomplished with the following brazing cycle for base materials having a nominal thickness of 0.020 inch.

(1) Braze at 1640-1690 F for 10 minutes

(2) Cool to 1000 F in 75 minutes

(3) Transform at -100 F for 8 hours

(4) Harden at 900 F for 8 hours (Ref. 14).

Other brazing cycles can also be used to meet mechanical property requirements. Brazing filler metals can also be altered to meet particular requirements. For example, during the fabrication of contoured sandwiches for the XB70 aircraft, indium was added to the basic silver-copper brazing alloy to reduce the thermal conductivity, palladium to control the melting temperature, lithium to act as a flux and promote wetting, and nickel powder to control flow in contoured areas (Ref. 78). Figure 39 shows the lay-up operation for XB70 structures and Figure 40 indicates the size and configuration of some of the panels.

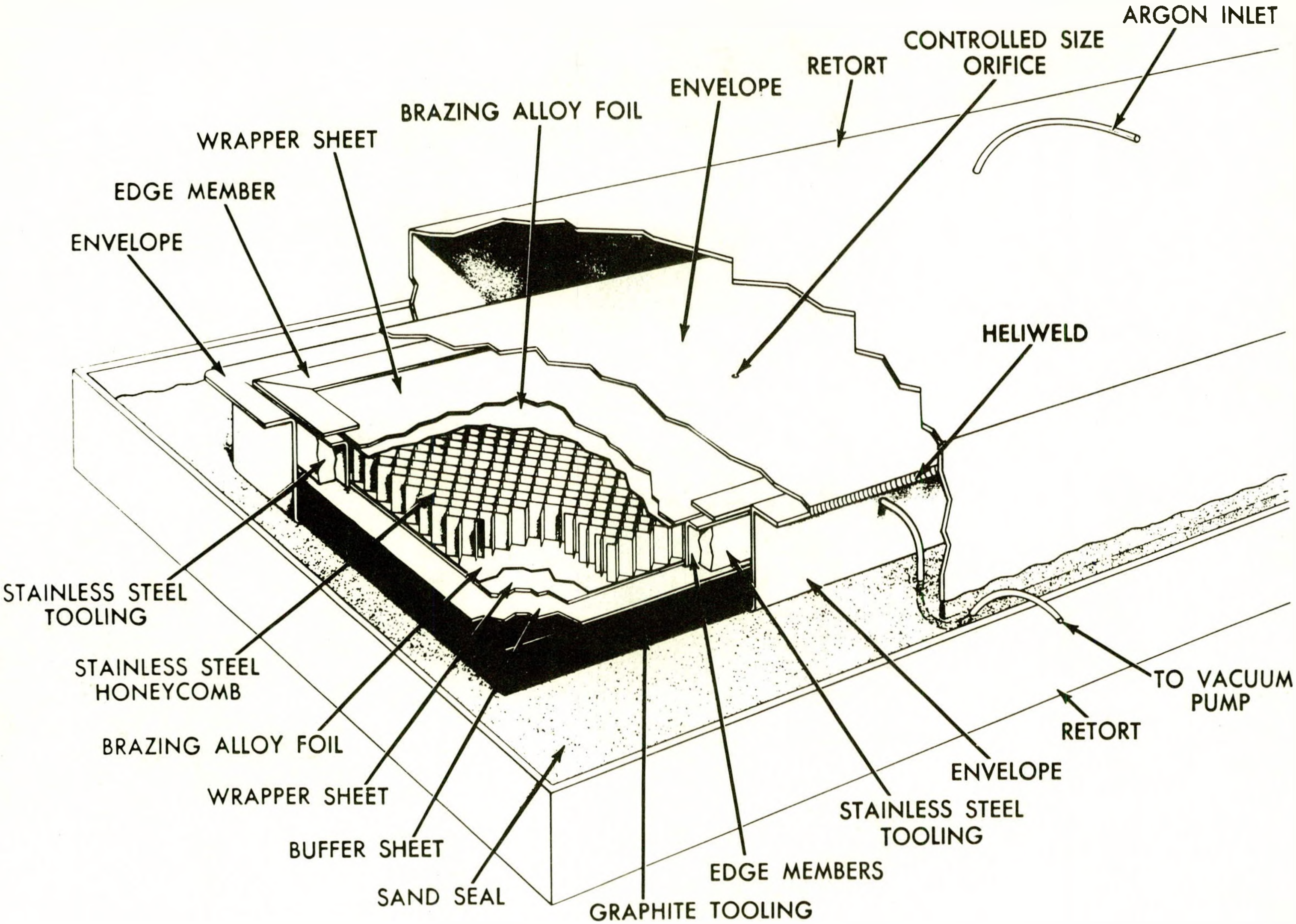


FIGURE 38. RETORT AND TOOLING FOR BRAZING 17-7 PH PRECIPITATION-HARDENING STAINLESS STEEL HONEYCOMB

This is a partial section through a retort and envelope showing the various elements. An assembly such as this, after flushing, is ready for placement in the furnace. Blanket brazing retors contain the same basic components. (Ref. 77)

FIGURE 39. ASSEMBLY OF PANEL FOR THE XB-70 PRIOR TO BRAZING INCLUDES SILVER BRAZING ALLOY (RIGHT), HONEYCOMB CORE OF PH 15-7 Mo PRECIPITATION-HARDENING STAINLESS STEEL, FACING SHEETS AND EDGE MEMBERS (Ref. 78)

FIGURE 40. SIZE AND CONTOUR OF VARIOUS HONEYCOMB SANDWICH PARTS MADE FOR XB-70 ARE ILLUSTRATED BY THESE CERAMIC FACES FOR ELECTRIC BLANKET BRAZING (Ref. 78)

Hydraulic systems for operation at 4000 psi and 450 F are fabricated from AM-350 tubing and AM-355 fittings which are brazed. The brazing alloy is the eutectic silver-copper alloy plus lithium (71.8Ag-28Cu-0.2Li) which melts at about 1500 F where it is not necessary to heat treat for maximum properties (Ref. 79). A similar silver-base brazing filler metal which melts at 1710 F is used when heat treatment is required. A valve with fittings which are to be brazed later to AM-350 tubing is shown in Figure 41. The brazing filler metal is preplaced. Joints in the tubing are made by placing a portable induction-heating tool around the joint and fitting. Typical joint designs are shown in Figure 42 (Ref. 80). Inspection holes on the chamfered portion of the fittings permit examination of brazing filler metal flow. The joint is protected by an inert atmosphere during brazing. This is shown schematically in Figure 43.

The nickel brazing filler metals which contain boron are widely used for joining precipitation-hardening stainless steels. As is the case when using these filler metals on other base metals caution must be exercised to assure their proper use. They have a tendency to dissolve the base metal and penetrate due to diffusion. This is most important when brazing thin sections. Properly made joints will be as strong as the parts joined and highly oxidation and corrosion resistant. Some examples of assemblies made from 17-7 PH with a brazing filler metal having the nominal composition 82Ni-4.5Si-2.9B-7.0Cr-3Fe are shown in Figures 44 and 45 (Ref. 81).

JOINT QUALITY

Precipitation-hardening stainless steel weldments may contain undesirable features that will interfere with proper operation in service. Inspection techniques that will detect such undesirable features must be used. For many applications it is desirable to determine the causes of the undesirable features so proper remedial and repair procedures can be initiated.

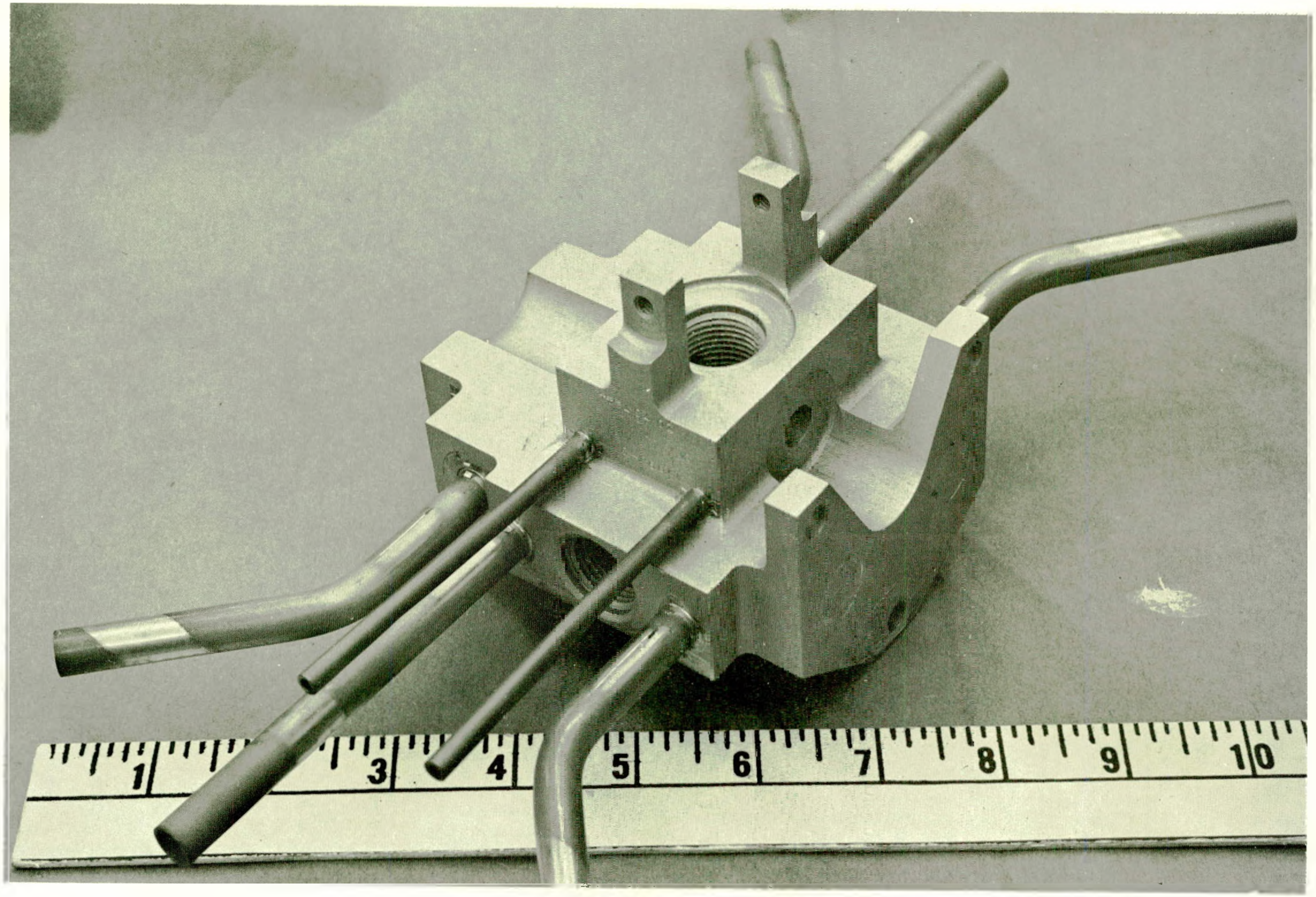


FIGURE 41. HYDRAULIC VALVE FABRICATED BY BRAZING AM-355 PRECIPITATION-HARDENING STAINLESS STEEL BODY TO TUBING SEGMENTS OF AM-350 STEEL (Ref. 78)

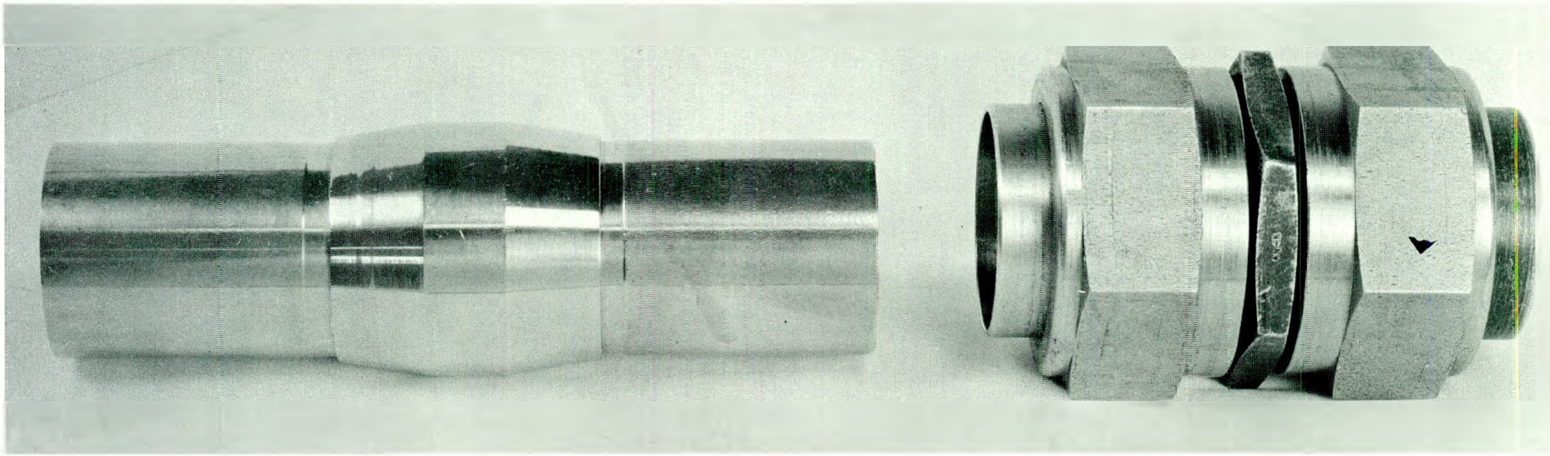


FIGURE 42. BRAZED JOINTS FOR AIRCRAFT HYDRAULIC SYSTEMS

(Courtesy of North American Aviation, Los Angeles)

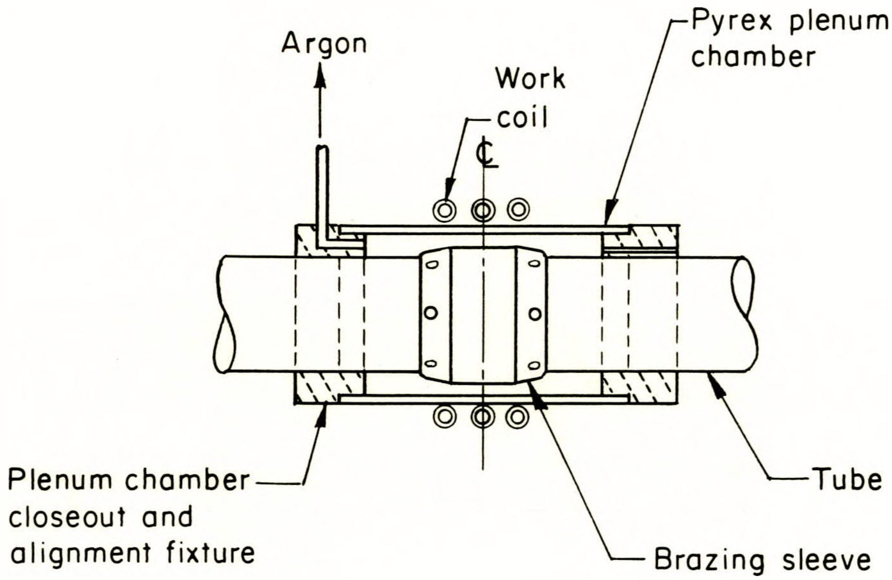


FIGURE 43. BRAZED JOINT FOR B-70 HYDRAULIC SYSTEM, ILLUSTRATING TOOLING USED DURING BRAZING (Ref. 78)

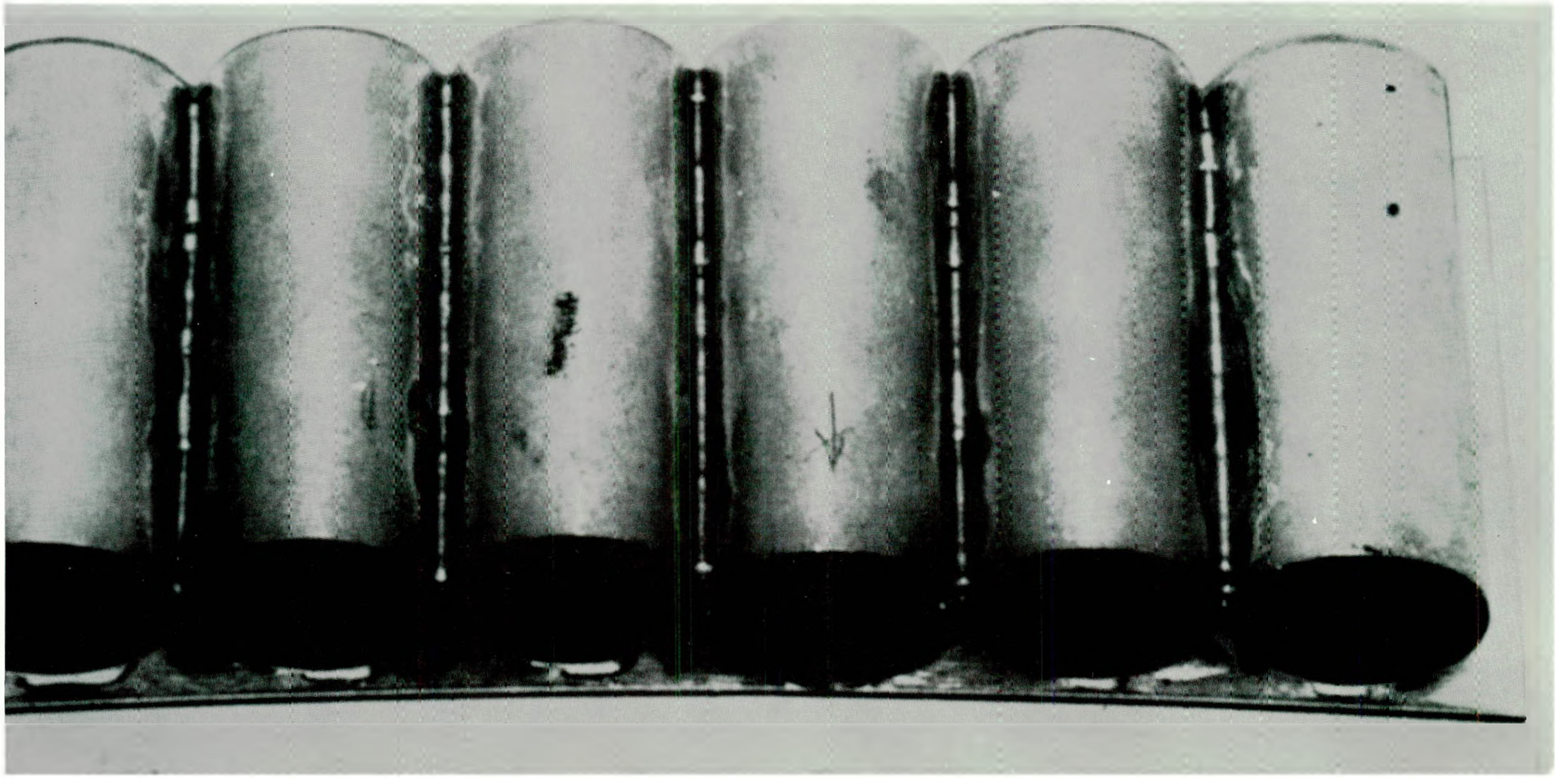


FIGURE 44. MISSILE ASSEMBLY USED WITH RED FUMING NITRIC ACID

It is made of 17-7 PH, brazed at 1950 F, a nickel-base filler metal, and heat treated. Full joint was required which was obtained by applying braze in local 1-inch patches which were allowed to flow and fill the balance of the joint. (Ref. 81)

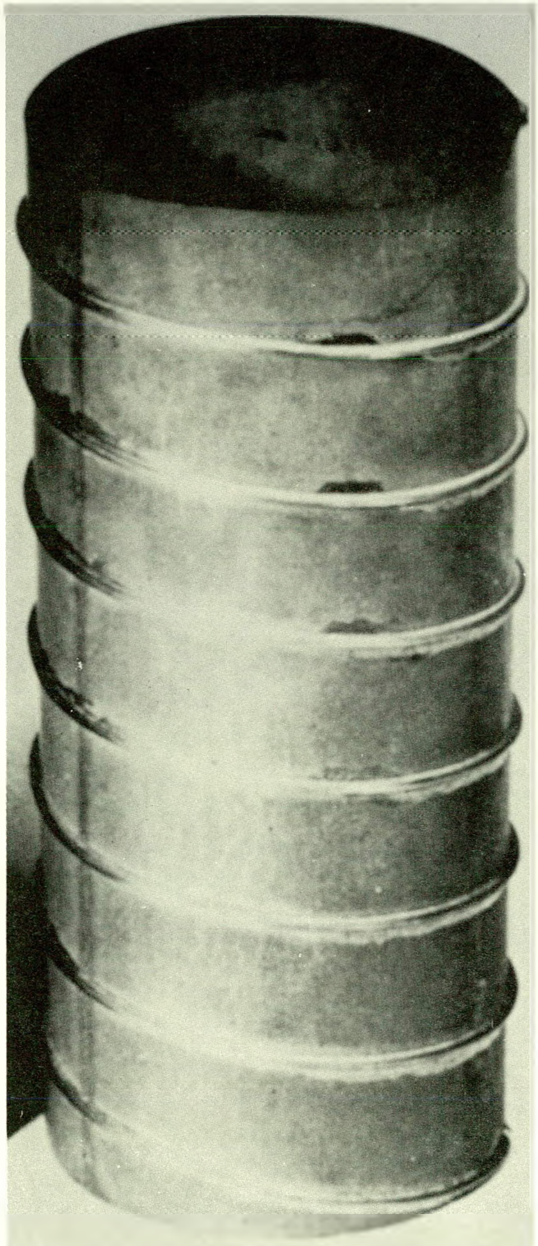


FIGURE 45. THESE TUBES ARE ABOUT 20 INCHES LONG AND 8 INCHES IN DIAMETER WITH A WIRE HELIX EXTENDING THE LENGTH OF THE TUBE.

Both tube and wire are made of 17-7 PH, brazed with a nickel-base filler metal. Part was hardened after brazing and there was no evidence of cracking or embrittlement. (Ref. 81)

INSPECTION

Precipitation-hardening stainless steel weldments are inspected using methods similar to those used for conventional stainless steel weldments. Nondestructive inspections are almost always performed but destructive inspection generally is performed only occasionally 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 techniques. Various types of leak tests are also 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 potentially might have been 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 and used.

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 defectlike weld features have no effect on the static-tension properties of the weld. However, these same features may be found to 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 46.

Porosity. Data on porosity in precipitation-hardening stainless steels is lacking. However, measures to control cleanliness and employment of good welding techniques can reduce the occurrence of porosity. Some factors known to cause porosity in welds include:

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

DEFECTS IN RESISTANCE WELDS

Characteristics described as defects in resistance welds are difficult to assess. Defects in resistance welds are generally subdivided into external and internal defects. With the exception of cracks that are exposed to the exterior of the sheets and that are obviously undesirable, the remaining external defects are

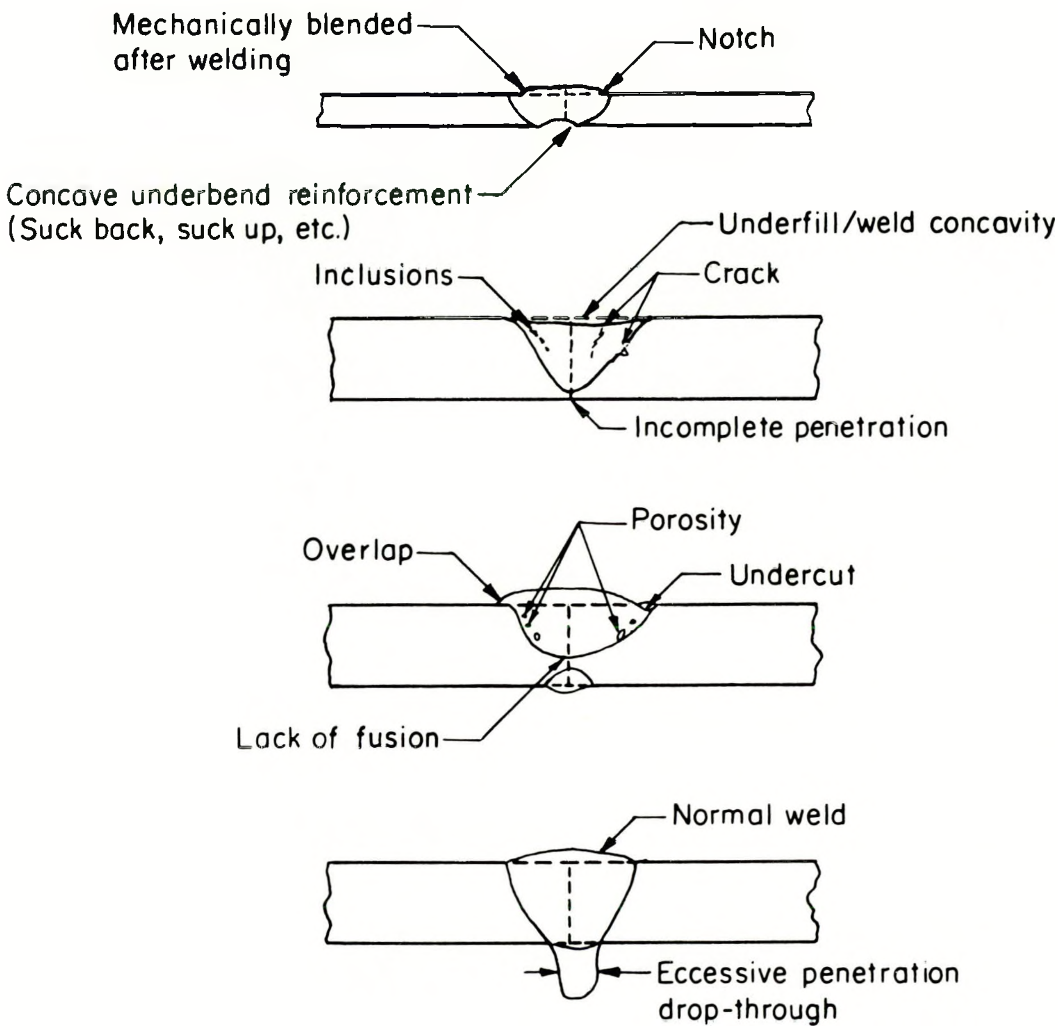


FIGURE 46. ARC-WELD DEFECTS

probably considered as such because they are indicative that the welding conditions may not have been exactly right. External defects in this category are sheet separation, surface pits, metal expulsion, tip pickup, and excessive indentation. With internal 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 47 (Ref. 82).

Another feature that has been experienced with A-286 alloy is a phenomenon known as "coring" or "incipient melting". This type of feature, shown in Figure 48, may resemble small cracks in the plane of the sheet extending from the edge of the weld nugget toward the unaffected base metal. These features are reported to be regions along grain boundaries into which metal melted during welding had flowed and subsequently solidified (Ref. 45). Central cracking in an A-286 spot weld also is shown in Figure 48. Increases in electrode force and in weld time reduce the likelihood of internal cracking (Ref. 83).

Work carried out on seam welding (Ref. 83) has shown that:

(1) One of the most common causes of internal cracks and porosity is incorrect weld spacing. Where successive weld nuggets are too close, cracks are often formed where they overlap.

(2) Slower welding speeds on longer weld and cool times can be used to reduce cracking.

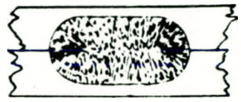
(3) Continuous-current seam welding eliminates cracking.

DISSIMILAR METALS

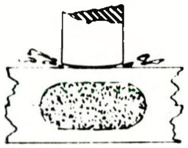
At times it becomes necessary to join the precipitation-hardening stainless steels to alloys of similar metallurgical characteristics but different compositions. It can also be desirable to joining these steels to other metals or alloys which are entirely different in all respects. Welding and brazing are preferred methods for making such dissimilar metal joints.

TYPICAL DEFECTS FOUND IN SEAM WELDING AUSTENITIC STAINLESS STEELS AND PREVALENT CAUSES FOR THEIR OCCURRENCE IN ORDER OF THEIR IMPORTANCE

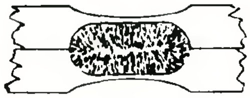
A—MATERIALS OF EQUAL THICKNESS

IDEAL  NUGGET

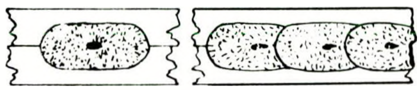
I. Excessive expulsion at interface.
1. Insufficient electrode force.
2. Excessive current or "on" time.
3. Electrode dressing too sharp.
4. Foreign matter at interface.



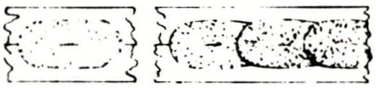
II. Surface expulsion.
1. Electrode dressing too sharp.
2. Excessive current for electrode force.
3. Foreign matter on surface.
4. Insufficient coolant on electrodes.



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.



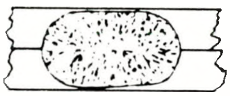
V. Cracks in nugget.
A. Horizontal cracks in center.
1. Insufficient electrode force.
2. Insufficient "off" time.
3. Electrode dressing too flat.
4. Excessive current.
5. Excessive roll speed.

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.

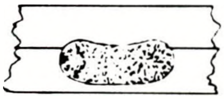
V. Cracks in nugget.
C. In crack sensitive metal.
1. Insufficient electrode force.
2. Electrode dressing too flat.
3. Insufficient "on" time.
4. Excessive current.
5. Insufficient "off" time.
6. Excessive roll speed.

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.

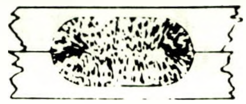
X. Unbalanced nugget.
1. Misalignment of electrodes.
2. Off center dressing of electrodes.

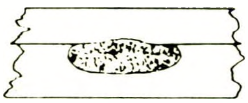
XI. Concave sides of nugget.
1. Insufficient "on" time.
2. Insufficient current.
3. Insufficient width of electrodes.

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).

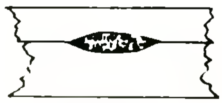
XIII. Lack of tangency or overlap.
1. Insufficient current.
2. Excessive "off" time or roll speed.
3. Insufficient "on" time.

B—MATERIALS OF UNEQUAL THICKNESS

IDEAL  NUGGET



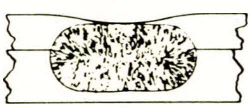
I. Lack of penetration in thin sheet.
1. Electrode dressing too flat on thin sheet.
2. Excessive electrode force.
3. Excessive electrical or thermal conductivity of electrode on thin sheet.
4. Insufficient electrical or thermal conductivity of electrode on heavy sheet.



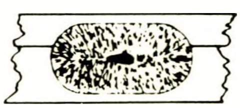
II. Lack of penetration in both sheets.
1. Electrode dressing too flat.
2. Excessive electrode force.
3. Insufficient current.
4. Insufficient "on" time.

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.

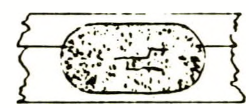


V. Excessive penetration.
1. Electrode dressing too sharp on thin sheet.
2. Insufficient electrode force.
3. Excessive current or "on" time.
4. Insufficient electrical or thermal conductivity of electrode.
5. Insufficient coolant.



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.

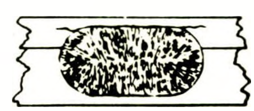


FIGURE 47. (Continued)

FIGURE 48. INCIPIENT MELTING AND CENTRAL CRACKS IN SPOT-WELDED A-286 ALLOY SHEETS (Ref. 45)

The difficulties which may arise when joining dissimilar metals depend mainly on the composition difference between the metals to be joined. If they are similar as in the case of precipitation-hardening stainless steels to the 300-series stainless steels the problems will not be great if good welding practice is used. If they are widely different as in the case of joining precipitation-hardening stainless steels to aluminum many problems may be encountered which result from the formation of brittle phases. Most of these brittle phases exhibit inferior mechanical properties. Welding of these joint systems usually results in a technique which does not melt the stainless steel and the resultant joint is essentially a braze weld. Such widely different alloys can also be joined by brazing or diffusion welding when proper joint preparations are used. Joint preparation often includes precoating one or both of the base metals or the inclusion of a third metal.

When GTA or GMA welding a precipitation-hardening stainless steel to other similar alloys, for example, 17-7 PH to AM-350 or 17-7 PH to Inconel X, the standard practice, including preparations and precautions, is the same as when welding the alloy to itself. The major requirement is that a filler metal be used which is compatible with both alloys and produces joints with adequate mechanical properties. Hastelloy W has been used widely as a filler metal for welding these dissimilar combinations. It was developed for this purpose. Its composition provides an ideal matrix when used to weld many different dissimilar hardenable alloy combinations.

Electron-beam welding has been used to weld the precipitation-hardening stainless steels to other alloys. This is done to take advantage of the minimum effects of the weld on the base metals and also reduce costs. An example is the turbine wheel shown in Figure 49. High-temperature resistant nickel-base turbine blades are welded to a heat-treated A-286 disc. The mechanical properties of the fabricated wheel components were not significantly affected. Electron-beam welding

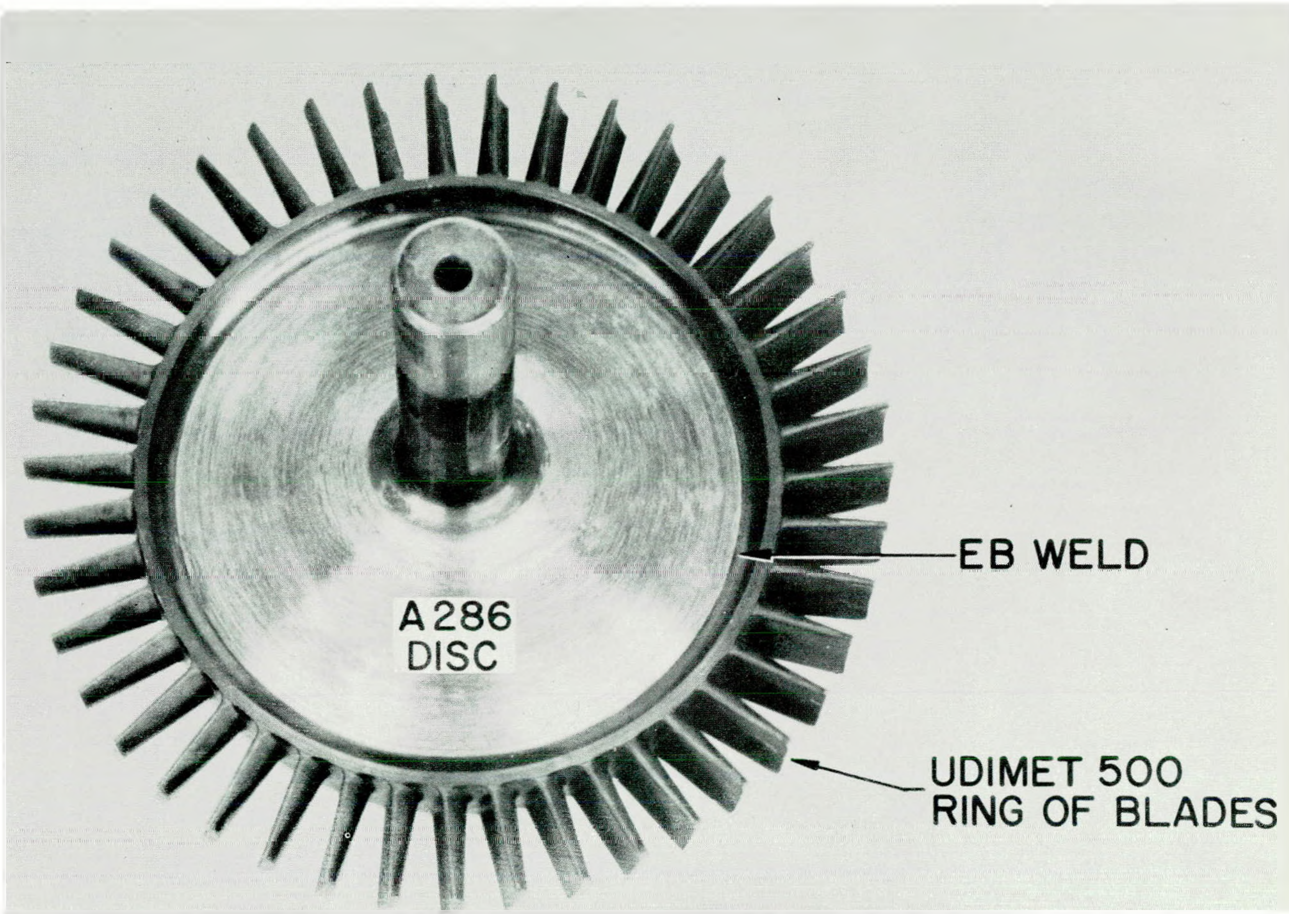
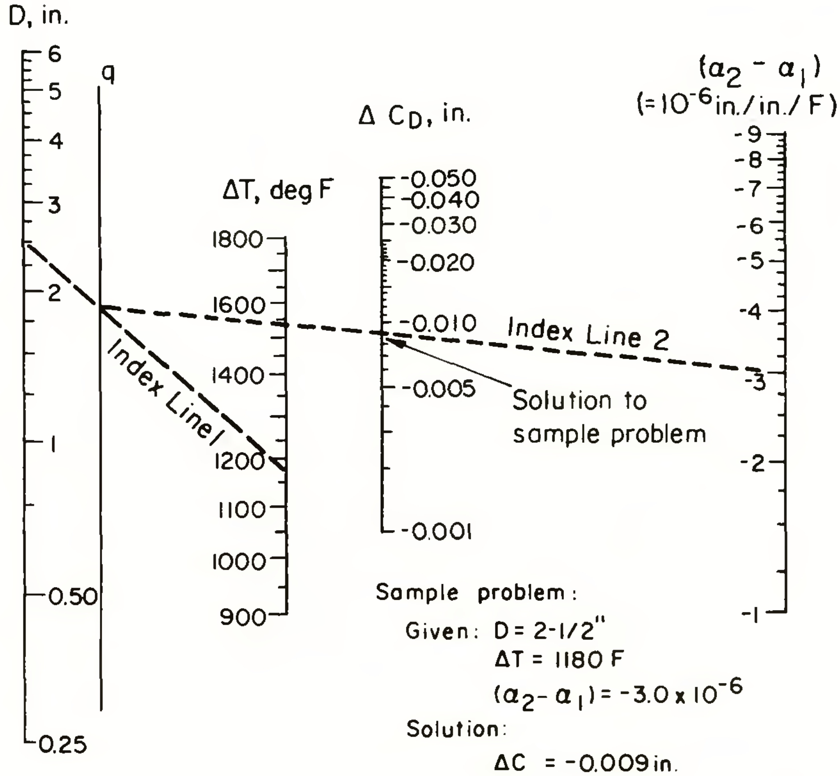


FIGURE 49. ELECTRON-BEAM-WELDED BIMETAL TURBINE WHEEL
(Ref. 84)



NOTES:

(1) This nomograph gives change in diameter caused by heating. Clearance to promote brazing filler metal flow must be provided at brazing temp.

(2) D = nominal diameter of joint, inches
C_D = change in clearance, inches
T = brazing temp minus room temp, F
α_1 = mean coefficient of thermal expansion, male member, in./in./deg F
α_2 = mean coefficient of thermal expansion, female member, in./in./deg F

(3) This nomograph assumes a case where α_1 exceeds α_2, so that scale value for $(\alpha_2 - \alpha_1)$ is negative. Resultant values for ΔC_D are therefore also negative, signifying that the joint gap reduces upon heating. Where $(\alpha_2 - \alpha_1)$ is positive, values of ΔC_D are read as positive, signifying enlargement of the joint gap upon heating

FIGURE 50. NOMOGRAPH FOR FINDING THE CHANGE IN DIAMETRAL CLEARANCE IN JOINTS OF DISSIMILAR METALS FOR A VARIETY OF BRAZING SITUATIONS (Ref. 72)

can also be used to join the precipitation-hardening stainless steels to other nickel-base alloys, martensitic stainless steels, and otheralloys. Ductility of the joint will usually be equivalent to that of the least ductile joint component.

Brazing is perhaps the most satisfactory method for making joints between the precipitation-hardening stainless steels and other alloys. After proper consideration is given to the heat treatments required, the proper choice of brazing filler metal to suit these treatments and compatibility with both joint parts, the techniques used are the same as for most metals. A very important factor to be considered when brazing dissimilar metals is the difference in thermal expansion between them. Joints must be designed so that the clearance between parts at brazing temperature will promote capillary flow of the brazing alloy. The nomograph, Figure 50, will assist in calculating the proper clearances. The coefficient of expansion of some metals and alloys of interest are given in Table XXXI; data for other alloys can be found in standard handbooks. The useful brazing filler metals were given in Tables XXIX and XXX.

Corrosion resistance should also be an important consideration when choosing the design, material and brazing filler metal for dissimilar metal joints. The subject is too complex for coverage in this report. Corrosion handbook data are not always directly applicable to brazed assemblies due to the dissimilar metal corrosion couples involved. Unless directly relative data are available, laboratory studies should be used to establish the feasibility of a particular joint system in a particular corrosive environment.

In general, technology which is applicable to the brazing of the Type 300-series stainless steels to unlike metals is applicable to similar joints in the precipitation-hardening stainless steels. There must always be an awareness to the effects of the brazing thermal treatments on the properties of the precipitation-hardening alloy, however.

TABLE XXXI. COEFFICIENT OF THERMAL EXPANSION OF SOME COMMON ALLOYS

Alloy	Coefficient of Expansion (32-212 F) 10^{-6} in/in/F
Type 302 stainless steel, annealed and cold rolled	8.0
Type 304L stainless steel, annealed	8.0
Type 321 stainless steel, annealed and cold rolled	8.3
Type 410 stainless steel, annealed and heat treated	5.1
AM-350, solution treated and hardened	6.8
15-7 Mo, Condition TH 1050	6.1
17-7 PH, Condition TH 1050	6.1
A-286, solution treated, quenched and aged	9.4
AISI 4340 steel, annealed	6.3
AISI 1020 steel, annealed	6.5
René 41	7.5
Inconel, annealed	6.4
Inconel X, annealed	7.6
Nickel	7.2
Aluminum	13.1
Tungsten, sintered	2.2
Molybdenum, 1/2% Ti, stress relieved	3.4
Tantalum, annealed	3.6
Columbium, annealed	4.0
Titanium, commercially pure	4.7

CONCLUSIONS AND RECOMMENDATIONS

The precipitation-hardening stainless steels can be welded by most welding processes. With proper attention to heat treatment, filler metal choice, welding technique, cleanliness, etc., high-quality high-strength joints can be readily produced in most alloys.

Fusion welding of the precipitation-hardening stainless steels results in a weld metal and heat-affected-zone microstructure containing stable austenite. Research and development studies are needed which will show best how to control the formation of stable austenite. In this way welds with properties more nearly approximating those of the base metal could be obtained without resorting to complete postweld heat treatments.

It is also difficult to develop full strengths in the weld metal because the microsegregation encountered is difficult to homogenize. Research is needed on the influence of welding conditions on microsegregation in precipitation-hardening stainless steel weld metals.

Precipitation-hardening stainless steels are divided in three different classes or types: martensitic (Stainless W, 17-4 PH, 15-5 PH), Semiaustenitic (17-7 PH, PH 15-7 Mo, AM-350, AM-355), and Austenitic (A-286, 17-10P, HNM). In general, the welding of these alloys becomes increasingly difficult as the alloy content increases. The PH steels (lower alloy) steels present fewer problems than the austenitic xteels such as A-286. A-286 will tolerate few variations from the established procedures.

MARTENSITIC PRECIPITATION-HARDENING STAINLESS STEELS

In general these steels have excellent weldability. They are not crack sensitive on cooling because of the low carbon content, nor are they susceptible to the hot cracking as associated with other copper-bearing stainless steels. When welding castings, attention must be paid the composition because hot cracking may be encountered. This cracking has been attributed to microheterogenity in the casting structure. The 17-4 PH steel casting alloy should contain only 3 percent copper as compared to 4 percent copper for wrought products. Hot cracking due to carbon may be encountered when welding the martensitic steels to carbon or low-alloy steels. Recommended welding techniques for these joints are those which minimize dilution of the weld metal.

Preheating and postweld heat treatments are not essential. Preheating is beneficial when welding heavy sections or when joints are made under restraint.

Some martensitic alloys do not possess great ductility or toughness. Consequently the foremost precaution necessary when designing, making and using welded joints is to avoid notches which may initiate cracking.

Since response to heat treatment is very dependent on the alloy composition, serious attention must be paid filler metal choice, joint fitup, joint cleanliness, and other technique variables which may cause composition changes. It should also be mentioned that composition variations within specification limits may also affect the heat-treatment schedules used. Close liaison with the steel producer is recommended to develop the proper heat-treatment variations to produce weldments of maximum utility.

There are no recommendations for research on the martensitic precipitation-hardening stainless steels which are not covered by the general areas covered above.

SEMIAUSTENITIC PRECIPITATION-HARDENING STAINLESS STEELS

Much of what has been said of the techniques and recommended welding practices for the martensitic type steels is also applicable to the semiaustenitic type.

The 17-7 PH alloy is the most common of the semiaustenitic types. It is most often welded in sheet metal thicknesses and in this form requires no unusual welding procedures. Preheating and posting are not required. Filler metals are available to meet most final strength needs. When welding without the use of a filler metal, problems may be encountered in meeting ductility and toughness requirements. Nitrogen is recommended as a shielding gas additive to overcome hot-cracking and ductility problems on single-pass welds. Porosity can result if nitrogen is used on multipass welds.

Aluminum-bearing alloys require technique development to overcome surface films on the surface of the weld pool. With proper techniques these films do not hurt weld properties or prevent good welds. The use of alternating welding currents and an inert-gas shield of eitherhelium or a helium-argon mixture is recommended. Careful control of voltage current, gas flow, and especially travel speed can also minimize the formation of surface films.

When resistance welding 17-7 PH sheet materials, material preparation (cleaning) should be carefully controlled. Poorly cleaned surfaces cause excessive metal expulsion, porosity, and electrode sticking. The best properties are obtained when resistance welds are made just before or after the final hardening treatment.

The PH 15-7 Mo alloy requires more attention to welding procedures than other semiaustenitic alloys. If ductile welds are required at high strength levels very precise control of filler metal compositions and welding operations are a necessity. Special helium-nitrogen gas mixtures are necessary to properly weld PH 15-7 Mo without filler metal addition.

The general recommendations made at the beginning of this section are applicable to the semiaustenitic precipitation-hardening stainless steels.

AUSTENITIC PRECIPITATION-HARDENING STAINLESS STEELS

It has been indicated that the austenitic alloys are the most difficult of the precipitation-hardening classes to weld. A-286 is the most common of these. In thin sections and in the absence of restraint, it is not difficult to weld. A-286 in heavy gages is classed as a difficult-to-weld alloy. Troubles begin at thicknesses below 0.25 inch. Hot cracking is the result of a loss of ductility, due to eutectic melting at the grain boundaries, in the temperature range 1150-1350 F. Low heat inputs and minimum restraint on cooling are recommended to minimize cracking. Weld cracking when encountered may be stopped using a different filler metal. Heat-affected-zone cracking has been the subject of much research and more is recommended. A basic study of the causes of heat-affected-zone cracking in heavy gage A-286 steel is recommended. The most fruitful area for research on this subject would be in a basic study of the mechanism of heat-affected-zone cracking.

There is also a need for continued development of filler metals for alloys such as A-286 which more nearly equal the composition of the base metal and do not cause cracking.

Welding procedures and limitations which are recommended for the austenitic precipitation-hardening alloy A-286 are:

(1) Weld in the solution-treated condition. Do not weld or repair weld the hardened alloy.

(2) Weld carefully cleaned joints only. Clean between passes.

(3) Use multipass welds and high travel speeds when welding heavy gages.

(4) Avoid all restraint if possible.

(5) Use butt welds wherever possible, metal-to-metal fitup and careful alignment.

(6) Use inert-gas arc welding with automatic voltage control.

Other austenitic alloys, 17-10P and HNM, are even more difficult to weld. Underbead cracking due to the high phosphorus content is almost impossible to overcome. Research is needed to develop good weldability in these alloys which have a combination of properties for certain specific applications. The microsegegration problem is acute in these alloys and should be included as part of any future research as recommended previously. They were developed for use where good strength and low magnetic permeability are required.

APPENDIX A

WELDING PROCESSES

WELDING PROCESSES

Welding processes that have been used for joining precipitation-hardening stainless steels are described briefly in the following. These processes are described in considerable additional detail in the published literature (Refs. 26, 85).

SHIELDED METAL ARC

Shielded metal-arc welding is usually done manually. The heat required to melt the filler metal and joint edges is produced by an arc between a covered electrode and the work. The electrode is composed of a metal rod coated with materials which when heated by the arc produce (1) a gas which shields the arc area from the atmosphere, (2) promotes electrical conduction across the arc, (3) produces slags which refine the molten pool, provide some protection from the atmosphere, and add alloying elements, and (4) provide materials for controlling bead shape. Figure A-1 is a sketch which shows the basic operation of this process.

GAS TUNGSTEN-ARC WELDING

In this process, which may be used manually or with automatic equipment, the heat to melt both filler metal and joint edges is produced by an arc between a tungsten (nonconsumable) electrode on the work. A shield of protective gas surrounds the arc and weld region. Filler metal may or may not be added to the weld. If it is, it is not normally a part of the arc circuit and is called a "cold wire" addition. The process is often called the GTA or TIG process.

Argon, helium, or a mixture of the two gases are used for shielding against the atmosphere. These gases are chemically inert, they do not react with other materials. Argon is more extensively used than helium.

Figure A-2 is a sketch of a gas tungsten-arc system.

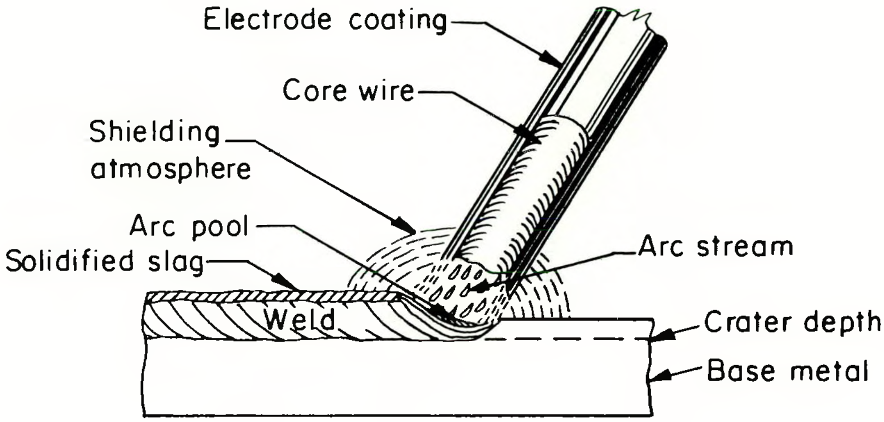


FIGURE A-1. SKETCH OF SHIELD-METAL-ARC WELDING OPERATION (Ref. 26)

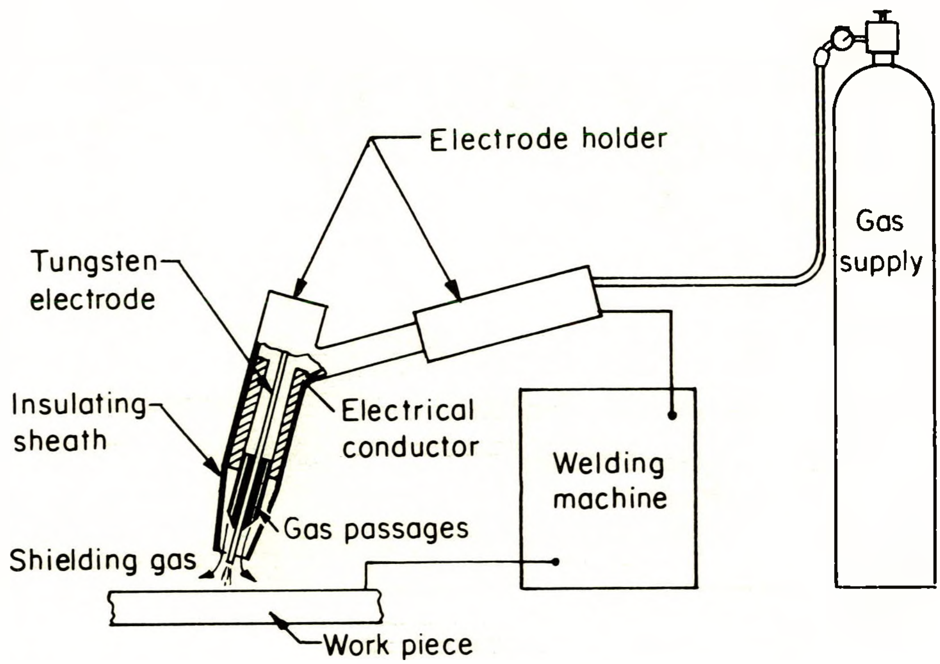


FIGURE A-2. SKETCH OF A GAS TUNGSTEN-ARC WELDING SYSTEM (Ref. 26)

GAS METAL-ARC WELDING

In this process, it is used both manually and with automatic equipment; the heat to melt filler metal and the joint edges is produced by an arc between a metal wire (consumable) electrode and the work. Arc and weld are shielded from the atmosphere by a shield of protective gas. The electrode is a small-diameter wire (about 0.035 to 0.065 in diameter for stainless steel) with no coating. The process is often called the GMA or MIG process.

Argon, helium, argon-helium mixtures, and argon-oxygen mixtures are all used for shielding gases. Argon with 1 or 2% oxygen is generally used with stainless steels. Figure A-3 is a sketch of a gas metal-arc welding system.

SUBMERGED ARC WELDING

The heat to melt the filler metal and joint edges is obtained from an arc between a base-metal electrode or electrodes and the work. The arc and weld zone is shielded by a blanket of flux which covers the joint and the end of the electrode. The arc is buried beneath the flux. The flux is a granular mineral material whose composition and properties are designed to:

(1) Provide protection from the air during welding.

(2) Provide materials to deoxidize and alloy the weld metal.

(3) Provide (when melted) a conductive path for the welding current.

(4) Provide a slag which molds the surface of the weld.

Generally, an amount of flux about equal to the weight of filler wire is melted during the welding operation. It is this melted portion of the flux which accomplishes most of the actions listed above. The unmelted portion of the flux is picked up by vacuum cleaning equipment and recirculated to the weld head. Figure A-4 is a sketch which shows the details of this process.

PLASMA-ARC WELDING

This process melts the filler metal and joint edges by using the heat produced by passing a gas through an arc and an orifice to produce high-temperature plasma.

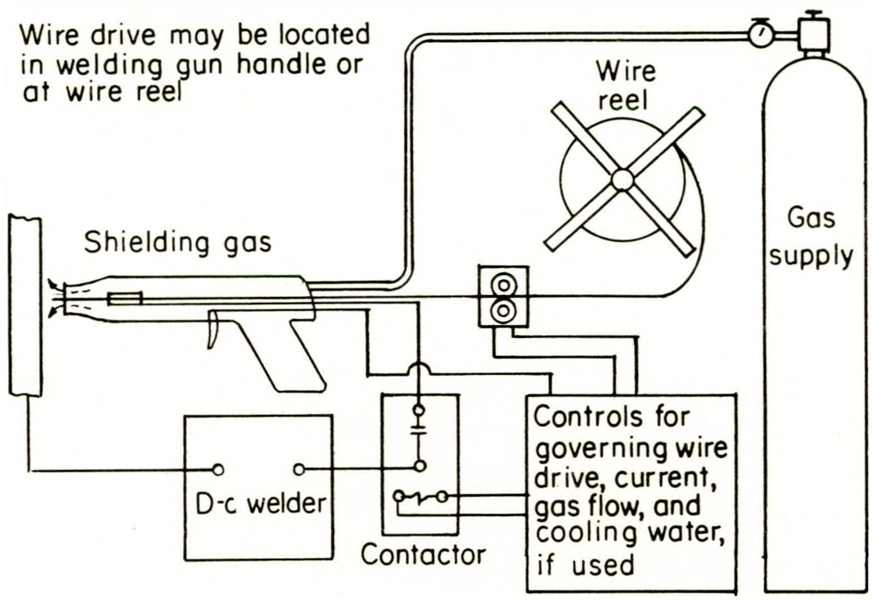


FIGURE A-3. SKETCH OF A GAS METAL-ARC WELDING SYSTEM (Ref. 85)

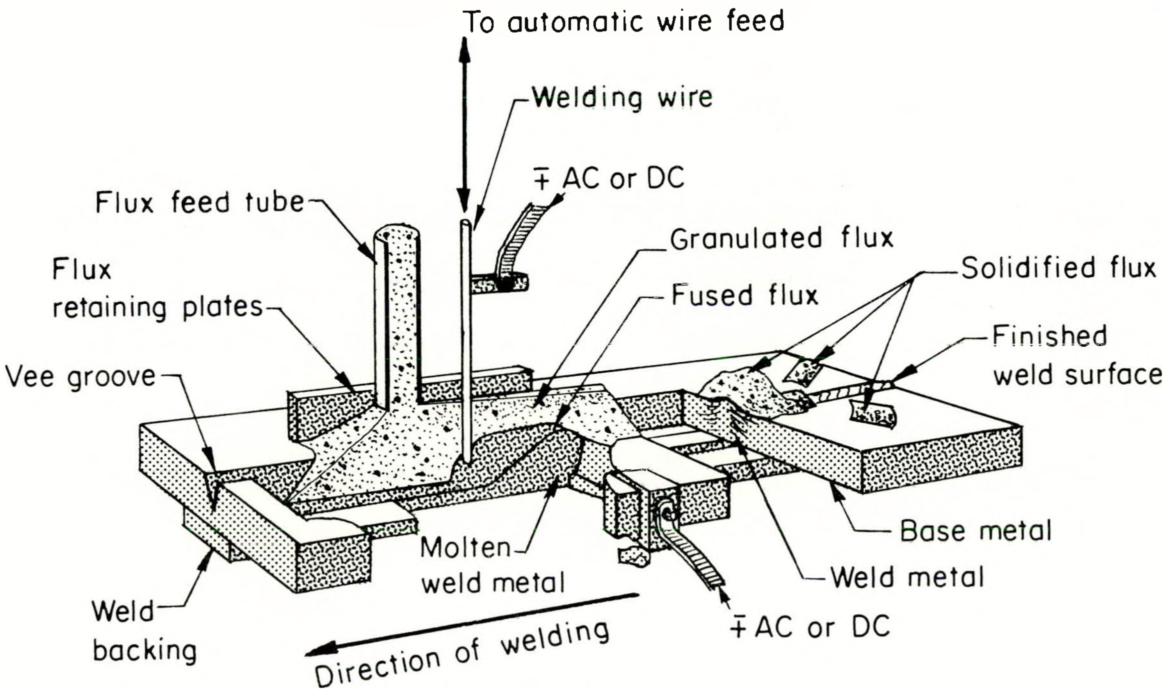


FIGURE A-4. SKETCH OF SUBMERGED-ARC WELDING OPERATION (Ref. 26)

Welding is done using a "transferred" arc which means that the work has to be part of the welding electrical circuit. This process is a specialized adaption of the gas tungsten-arc process. In welding, inert gases are usually used to form the plasma. An additional inert gas shield is used to protect arc, plasma, and weld from the air. The advantages of the process over gas tungsten-arc welding are:

(1) Higher energy concentration

(2) Improved arc stability

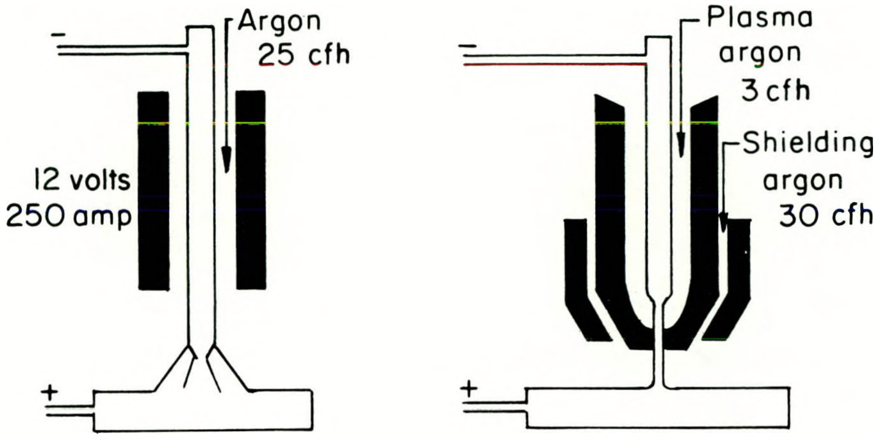
(3) Higher energy transfer.

Using certain gas flow and electrical power settings the arc plasma torch can be turned into an effective cutting tool. Plasma cutting is particularly effective with stainless steels since it does not depend on oxidation to facilitate cutting. Figure A-5 is a sketch of a plasma-arc welding system.

ELECTRON-BEAM WELDING

This is a fusion-welding process which does not use an arc as a heat source. The work is bombarded by a high-energy, high-density stream of electrons. Practically all of the elctron energy is transformed into heat when the electrons impact the work. As originally developed, electron-beam welding was done in an evacuated chamber. In about 1963, some capability for welding at pressures up to atmospheric was developed. While this loses the advantage of the high-purity atmosphere which the vacuum represents, it increases the adaptability of the process.

One outstanding feature of electron-beam welds is the very narrow welds (high depth-to-width ratio) that can be made with the process. It is possible to produce welds only 1/16 inch wide in steel plate 1/2-inch-thick plate. Equipment of two types is available. One type uses accelerating voltages below 60,000 volts and the other uses accelerating voltages above 60,000 volts. The two types have characteristics which make them useful for a wide variety of work. In most electron-beam welders, the work is not a part of the electrical circuit, although it must be grounded.



a. Comparison Gas-Tungsten Arc and Plasma Torch

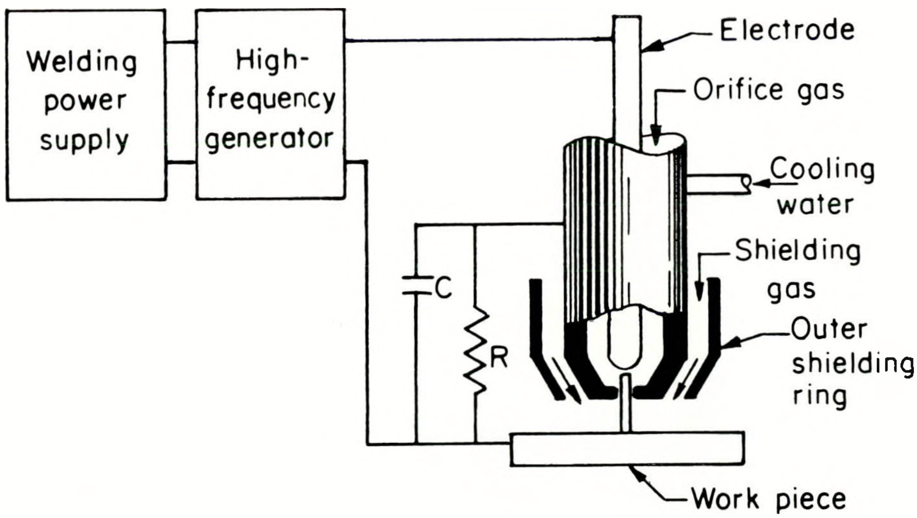


FIGURE A-5. SKETCH OF PLASMA-ARC TORCH AND SYSTEM
(Ref. 85)

Electron-beam welders are in effect X-ray tubes and produce X-radiation. Care must be taken to assure that personnel is shielded from this radiation.

Figure A-6 shows sketches of two electron-beam welding systems.

RESISTANCE SPOT, SEAM, AND PROJECTION WELDING

The heat required for fusion in these processes is obtained by the resistance of the parts being welded to a relatively short time flow of high-density electric current. The current is introduced into the parts by electrodes of one type or another. Force is applied through the electrodes to maintain contact between the parts to assure a continuous electric circuit and to forge the heated parts together. Normally a small amount of metal is melted at the faying surfaces of the joint. It is the coalescence of this melted metal which creates the weld. Spot welding is diagrammed in the sketch in Figure A-7.

A wide variety of equipment is used for resistance welding. Different types of current are used, although about 90% of commercial installations are 60-cycle alternating current.

The three types of welds are characterized by the following:

(1) Spot welds are individual welds whose shape and size is determined by the electrodes. A series of spot welds is usually used to make a joint.

(2) Seam welds are a series of overlapping spot welds made with circular rotating electrodes.

(3) Projection welds are spot welds whose location is determined by projections formed into the parts to be welded.

Sketches showing the basic characteristics of the three types of welding are shown in the sketch in Figure A-8.

FLASH WELDING

Flash welding is a butt welding process in which the entire area of the surfaces to be welded are heated by a flow of electrical current across the joint.

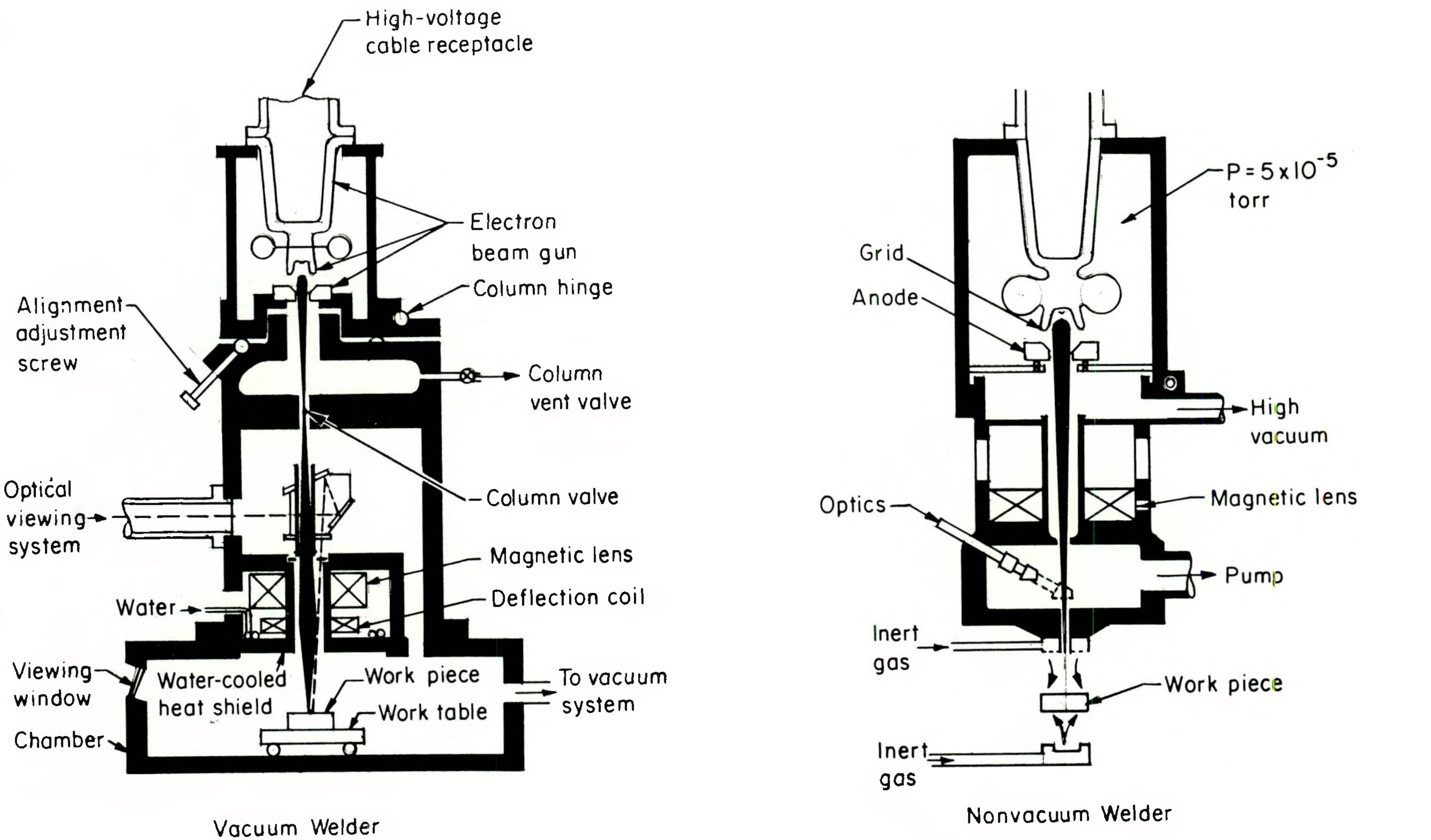


FIGURE A-6. SKETCHES SHOWING TWO TYPES OF ELECTRON-BEAM WELDING MACHINES (Ref. 24)

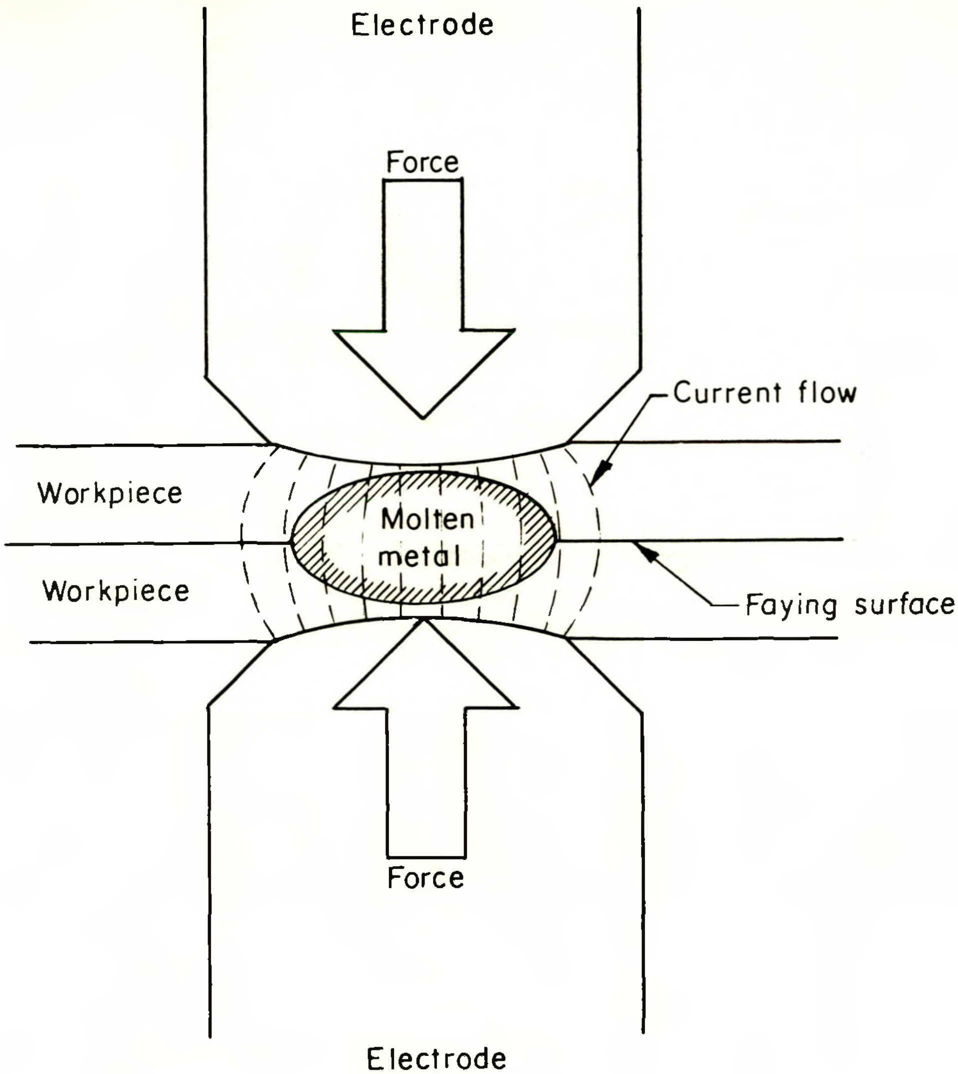


FIGURE A-7. SKETCH SHOWING ELECTRICAL FLOW AND HEAT GENERATION IN A SPOT WELD

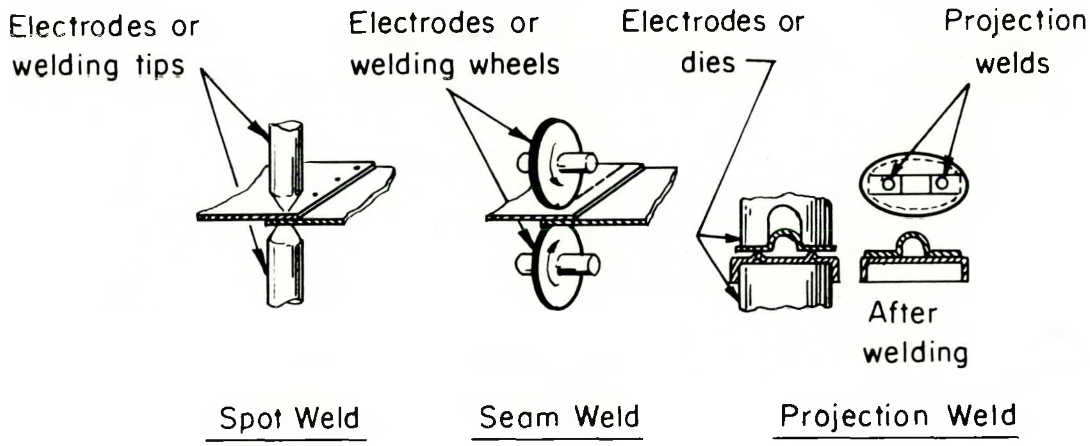


FIGURE A-8. SKETCHES SHOWING CHARACTERISTICS OF SPOT, SEAM, AND PROJECTION WELDING (Ref. 26)

The flow of current produces a flashing action which is the fusing of contacting points of metal on the surfaces being welded. Flashing plus resistance heating melts the faying surfaces. When the proper temperature is reached, force is applied to upset the parts together. The upset squeezes out the molten metal and produces a solid-state weld. Flash welding is actually a solid-state welding process, although molten metal is involved in preparing the faying surfaces for welding. Figure A-9 is a sketch which shows the basic characteristics of the process.

BRAZING

Brazing is a process in which a filler metal having a melting point below that of the base metal is used to make a joint. The process is called brazing when temperatures above 800 F are required to make the joint. It is called soldering when temperatures below 800 F are used. Brazed joints normally have large areas and very small thickness. Fluxes may be used to clean and protect the joint area during heating. When fluxes are not used, rigorous precleaning and high-purity atmospheres are required to produce good joints. The filler metal is melted in contact with the joint area. Capillary forces cause the metal to flow into the joint. Because capillary forces are important in determining the extent and quality of the joint, it is necessary to provide and maintain proper clearances in the joint during the joining operation. Clearances of 0.002 inch to 0.005 inch are common. Smaller or larger clearances may prevent flow of the filler metal into the joint. With larger clearances, even preplaced filler metals may flow out of the joint when they melt.

SOLID-STATE WELDING

Solid-state welding includes any process where two or more pieces of metal are metallurgically joined without the formation of a liquid phase. A metallurgical joint is one in which the weld is the result of the action of atomic forces rather than mechanical interlocking. All solid-state welding operations require forces which press faying surfaces into contact with each other. These forces

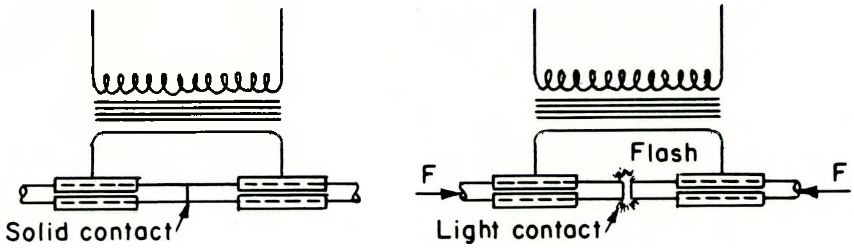


FIGURE A-9. SKETCH SHOWING BASIC CHARACTERISTICS OF FLASH-WELDING PROCESS (Ref. 26) may or may not be high enough to cause gross upset. Solid-state welding is discussed in detail in Reference 66. Solid-state welding includes a number of processes, but they can be divided into two classes:

(1) Diffusion welding

(2) Deformation welding

Diffusion Welding. In this type of solid-state welding, diffusion across the joint interface is primarily responsible for forming the weld. Only a small amount of deformation occurs during the process. Diffusion welding is done at elevated temperatures. This makes it easier to obtain the microplastic flow required to produce intimate contact of the faying surfaces and decreases the time required to obtain the amount of diffusion and grain growth required to complete the joint. Dissimilar metals may or may not be used in the joint to increase diffusion rates.

Deformation Welding. Deformation welding includes those processes in which gross plastic flow is the major factor in weld formation. Diffusion is not normally required for weld formation, although it may contribute if welding is done at elevated temperatures. The bonding mechanism with this process is not known precisely. It is generally believed that gross deformation breaks up the surface films which prevent intimate contact at the faying surfaces, forces clean surfaces into contact, and perhaps provides the energy needed to complete weld formation. Deformation welds are produced at temperatures from room temperature (cold welding of aluminum and copper) to temperatures just below the melting point (upset-butt welding of steel).

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APPROVAL

WELDING OF PRECIPITATION-HARDENING STAINLESS STEELS

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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