

AD633247

NASA TECHNICAL
MEMORANDUM

NASA TM X-53432

NASA TM X-53432

October 1965

WELDING PROCEDURES FOR TITANIUM AND TITANIUM ALLOYS

By J. J. Vagi, R. E. Monroe, R. M. Evans, and D. C. Martin

Prepared Under the Supervision of the
Research Branch, Redstone Scientific Information Center
Directorate of Research and Development
U. S. Army Missile Command
Redstone Arsenal, Alabama

NASA

*George C. Marshall
Space Flight Center,
Huntsville, Alabama*

CLEARINGHOUSE FOR FEDERAL SCIENTIFIC AND TECHNICAL INFORMATION			
Hardcopy	Microfiche		
\$6.00	\$1.25	233	PP 00
ARCHIVE COPY			

Coall 1

TECHNICAL MEMORANDUM X - 53432

WELDING PROCEDURES FOR TITANIUM AND
TITANIUM ALLOYS

By

J. J. Vagi, R. E. Monroe, R. M. Evans, and D. C. Martin*

ABSTRACT

This report covers the state of the art of welding procedures for titanium and its alloys.** Methods employed in the past and present are described. Many of the conventional welding and brazing processes are used for joining titanium and its alloys. Information on the use of these processes, when available, was condensed or extracted and included in this report. Necessary additional processing such as pre-weld cleaning, joint preparation, postweld cleaning, and postweld operations are also included since they form an integral part of the welding processes without which successful welding cannot be accomplished. Joining processes that have been used only experimentally also are described briefly.

The need for proper preweld cleaning operations and proper shielding to prevent contamination of titanium welds is emphasized throughout.

This report does not exhaustively cover the selection of titanium alloys for specific applications or mechanical properties obtained from joints. These areas were not included in the scope of this program. The reader is reminded of the importance of these areas in obtaining desired service performance in structures fabricated from titanium.

*Principal Investigators, Battelle Memorial Institute,
Contract No. DA-01-021-AMC-11651(Z)

**Adhesive bonding and mechanical joining are covered in other reports.

NASA - GEORGE C. MARSHALL SPACE FLIGHT CENTER

PAGES _____
ARE
MISSING
IN
ORIGINAL
DOCUMENT

NASA - GEORGE C. MARSHALL SPACE FLIGHT CENTER

TECHNICAL MEMORANDUM X - 53432

WELDING PROCEDURES FOR TITANIUM AND
TITANIUM ALLOYS

By

J. J. Vagi, R. E. Monroe, R. M. Evans, and D. C. Martin

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. H-76715
Report No. RSIC-470

Subcontracted to

Battelle Memorial Institute
505 King Avenue
Columbus, Ohio
Contract No. DA-01-021-AMC-11651(Z)

PREFACE

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

This report describes practices for welding titanium and titanium alloys. It is intended to provide information useful to designers and manufacturing engineers. The information in this report has been selected primarily as a guide for selecting conditions, equipment, and fabricating techniques for welding titanium. Common problems encountered in welding and brazing titanium and its alloys are identified, and precautions for avoiding the problems are described.

The report summarizes information obtained from equipment manufacturers, titanium producers, technical publications, reports on Government contracts, and from interviews with engineers employed by major titanium fabricators. A total of 133 references, most of them covering the period from 1957 to the present, are cited. In addition, much detailed data covered by reports and memoranda issued by the Defense Metals Information Center are used. A recent Aircraft Designers Handbook on Titanium and Titanium Alloys prepared for the Federal Aviation Agency by Battelle also provided much background information. The assistance afforded by these previous programs has helped in the preparation of this report.

In accumulating the information necessary to prepare this report, the following sources within Battelle were searched for publications from 1957 to the present: Defense Metals Information Center, Main Library, Slavic Library. Information was obtained also from information centers outside Battelle, viz., the Redstone Scientific Information Center and the Defense Documentation Center. Descriptors employed for recovering information from these information centers are given in Appendix A.

Personal contacts also were made by visit or telephone with the following individuals and organizations:

Durwood G. Anderson
Airite Division
Electrada Corporation
Los Angeles, California

Howard Cary
Hobart Technical Center
Troy, Ohio

R. Chihoski
John Rudy
The Martin Company
Denver, Colorado

Melvin C. Clapp
Columbus Division
North American Aviation, Inc.
Columbus, Ohio

R. S. Emlong
E. R. Funk
Astro Metallurgical Corporation
Wooster, Ohio

J. L. Fleming
Aluminum Company of America
Pittsburgh, Pennsylvania

G. Garfield
Aerojet-General Corporation
Downey, California

Grumman Aircraft Engineering
Corporation
Bethpage, Long Island
New York

A. M. Krainess
Space and Information Systems
Division
North American Aviation, Inc.
Downey, California

K. C. Linepense
Linde Division
Union Carbide Corporation
Newark, New Jersey

J. Manfre
Crucible Steel Company of
America
Pittsburgh, Pennsylvania

D. R. Mitchell
Titanium Metals Corporation of
America
New York, New York

F. L. Murphy
Pratt & Whitney Aircraft Division
United Aircraft Corporation
East Hartford, Connecticut

V. H. Pagano
Materials Laboratory
U. S. Army Tank-Automotive
Center
Warren, Michigan

J. Gordon Parks
Methods Research and Develop-
ment Branch
Manufacturing Engineering
Division
George C. Marshall Space Flight
Center
National Aeronautics and Space
Administration
Huntsville, Alabama

Reactive Metals, Inc.
Niles, Ohio

William S. Rudin
Sciaky Brothers, Inc.
Chicago, Illinois

A. Schoeni
Ling-Temco Vought, Inc.
Dallas, Texas

Howard Siegel
McDonnell Aircraft Corporation
St. Louis, Missouri

Sumner Smith
Menasco Manufacturing Company
Burbank, California

Fred W. Vogel
Modern Machine Shop
Watertown Arsenal
Watertown, Massachusetts

W. O. Sunafrank
General Dynamics/Fort Worth
Fort Worth, Texas

The authors wish to thank each of these individuals and their organizations for contributions. They also wish to thank Vernon W. Ellzey and Albert G. Imgram, of Battelle, Project Technical Coordinators, and Walter H. Veazie, Battelle Information Specialist, for their assistance during this program.

TABLE OF CONTENTS

	Page
SUMMARY	1
INTRODUCTION	2
WELDING FUNDAMENTALS	3
Materials	3
Component Materials	3
Process Materials	8
Process Selection	12
Joint Design	13
Cleaning	21
Grease and Oil	22
Scale Removal	24
Handling and Storage	25
Evaluating Cleanliness	25
Shielding	26
Tooling	40
Heat Input	41
Shrinkage - Distortion	42
Residual Stress	43
Stress Distribution	44
Stress Effects	46
Stress Relieving	49
Specifications	51
Defects	52
Porosity	54
REPAIRS	55
WELDING PROCESSES	56
TIG Welding	57
Equipment	57
Materials	57
Welding Conditions	60
Tack Welding	63
Properties	64
Applications for TIG Welding Titanium Alloys	64

TABLE OF CONTENTS (Continued)

	Page
MIG Welding	84
Equipment	84
Materials	92
Tooling and Fixtures	93
Welding Conditions	94
Properties	95
Applications for MIG Welding Titanium Alloys	101
Arc Spot Welding	103
Equipment	104
Materials	104
Welding Conditions	104
Electron-Beam Welding	104
Equipment	105
Materials	105
Welding Conditions	105
Properties	107
Applications for Electron-Beam Welding Titanium Alloys	107
Plasma-Arc Welding	110
Keyhole Action	113
Equipment	113
Welding Conditions	115
Applications	116
Resistance Spot Welding	117
Equipment	118
Joint Design Considerations	121
Welding Conditions	122
Properties	126
Applications	133
Roll Spot Welding	135
Seam Welding	139
Applications	140
Flash Welding	143
Equipment	144
Joint Design and Joint Preparation	144
Inert-Gas Shielding	144
Conditions	144

TABLE OF CONTENTS (Continued)

	Page
Properties	147
High-Frequency Welding	154
Brazing	154
Filler Metals.	154
Brazing Methods	157
Properties	157
Applications	160
Solid-State Welding	163
Diffusion Welding	164
Deformation Welding	169
 DISSIMILAR METAL JOINTS	 177
MIG Spot Welding Aluminum to Titanium	178
TIG Plug Welding	180
Resistance Spot Welding	181
Capacitor Discharge Welding	182
 CONCLUSIONS AND RECOMMENDATIONS.	 182
Welding Metallurgy	183
Cleanliness.	183
Filler Metals	183
Welding Conditions	184
Tack Welding	184
Contamination and Porosity	184
Cracking.	185
Thick Titanium Plate	185
Stress Relief	185
Repair Welding	185
 APPENDIX A	
DESCRIPTORS FOR LITERATURE ON FABRICATION OF TITANIUM AND TITANIUM ALLOYS BY WELDING	 187

TABLE OF CONTENTS
(Continued)

Page

APPENDIX B

DESIGNATIONS, PROPERTIES, AND TREATMENTS OF TITANIUM AND TITANIUM ALLOYS	193
REFERENCES	203

LIST OF ILLUSTRATIONS

Figure	Title	Page
1.	Surface Area to Volume Ratio for Welding Filler Wires	9
2.	Welding-Wire Defects	9
3.	Typical Joints in Titanium and Titanium Alloys . . .	14
4.	Stiffened-Skin Component	15
5.	Flow Sheet Showing Possible Relation of Welding to Other Operations	15
6.	Typical Fusion-Weld-Joint Designs	17
7.	Joint Designs for Special Applications of MIG Welding of Titanium Alloys	20
8.	Consumable-Land Joint Design	21
9.	Back-Up-Ring Joint Design	21
10.	Flow Chart of Cleaning Procedure for Titanium Alloys	22
11.	Tank-Type Controlled-Atmosphere Welding Chamber for Manual or Machine, TIG or MIG Welding Titanium Alloys and Other Reactive Metals	27
12.	Controlled-Atmosphere Chambers for TIG Welding Small Subassemblies	28
13.	Adaptation of a Small Size Chamber for TIG Welding an Oversize Part	29
14.	Flexible-Plastic Controlled-Atmosphere Welding Chamber	29
15.	Inert-Gas-Shielding Arrangements for Conventional Materials Compared with Titanium Alloys	31
16.	Torch-Trailing-Shield Arrangements	32

LIST OF ILLUSTRATIONS (Continued)

Figure	Title	Page
17.	Detachable Torch-Trailing-Shield Assembly	33
18.	Modified Manual TIG Welding Torch-Shielding Nozzle	34
19.	TIG-MIG Torch-Trailing-Shield Assembly with Leading Shield Baffle for Welding Titanium Alloys . .	34
20.	External Shielding Baffles Used to Protect Butt Welds in Titanium Tubing and Pipe	35
21.	Shielding Baffles for an Outside-Corner Weld . . .	36
22.	Backing Shield	36
23.	Shielding Devices for Protecting Root Sides of Butt Welds in Tubing, Pipe, and Cylinders	37
24.	Shielding Arrangements for Protecting the Root Sides of Flange-to-Tubing Welds	38
25.	Cross Section of Original Coil Designed for Welded Spacers and Supports	39
26.	Tack-Welded Mechanical Fastener for the Coil Spacers Shown in Figure 25	39
27.	Coils in Various Stages of Completion Showing Mechanical Supports and Tack-Welded Nuts	39
28.	Types of Weld-Joint Distortion	42
29.	Distribution of Residual Stresses in a Butt Weld . .	45
30.	Distribution of Residual Stresses Around Spot Weld .	47
31.	Fusion-Weld Defects	53
32.	A Combination Torch-Trailing-Shield Arrangement .	58

LIST OF ILLUSTRATIONS (Continued)

Figure	Title	Page
33.	The Use of Starting and Runoff Tabs	63
34.	Calcium Hypochlorite Plant Heat-Exchanger Coils Made From Commercially Pure Titanium	67
35.	Out-of-Position Butt Weld Being Made in the Open Atmosphere Using Torch Shielding Combined With Supplementary Shielding Equipment.	67
36.	Heat-Exchanger Subassemblies Welded in a Controlled Atmosphere Chamber	68
37.	Detail of the Mechanical Support Showing That the Nuts Are Tack Welded	68
38.	Photograph Taken Through a Borescope of a Typical Weld Root	70
39.	Inspection of the Root Pass of the Butt Weld Shown in Figure 38	70
40.	Segmented Welding Fixture With Solid Copper Back-Up Shoes Mounted on Positioner	71
41.	Mercury Space Capsule	73
42.	Fixture Holds First Two Panels of Outer Conical Skin for TIG Welding	73
43.	Rotating Fixture Moves the Work Past Stationary TIG Torch at 7 ipm to Join Two Sections of Spherical Bulkhead. Segmented Fingers Hold Edges of Joint in Alignment	74
44.	Vigilante Wing Leading Edge	75
45.	Typical Cross Section of Welded Titanium Leading Edge	75
46.	Wing Leading-Edge Joint Designs	76

LIST OF ILLUSTRATIONS
(Continued)

Figure	Title	Page
47.	Arc-Seam Tee Weld-Joint Design	76
48.	General View of the Sine-Wave Welding Machine . .	78
49.	Welding of Thin Corrugated Titanium Sheet	78
50.	Sine-Wave Welding Station Area	79
51.	Completed Rib for the American RS-70 Aircraft . .	79
52.	MIG Welding-Equipment Arrangement for Welding in the Open Atmosphere	86
53.	MIG Welding Arrangement in a Controlled- Atmosphere Welding Chamber	86
54.	Typical Wire-Drive System for MIG Welding . . .	87
55.	Wire-Straightening Rolls	87
56.	Entry of Wire into Wire-Feed Cable	88
57.	Wire Entry into Drive Rolls	88
58.	Wire Distortion From Excessive Drive-Roll Pressure	89
59.	Cleanliness Factor as Applied to the Wire-Feed Cable	89
60.	MIG Welding Setup Shows Sharp Bends in Wire-Feed Cable	91
61.	Hose-and-Cable Support Arrangement Employed to Eliminate Wire Whip During MIG Welding	91
62.	Illustration of Tank-Cupola Components Fabricated Using the MIG Welding Process	102

LIST OF ILLUSTRATIONS (Continued)

Figure	Title	Page
63.	Typical Joint Dimensions for Welds in 2-Inch-Thick Ti-13V-11Cr-3Al Titanium Alloy Plate . . .	103
64.	Schematic Diagram of an Electron-Beam Welding Machine	106
65.	Electron-Beam Welded Titanium Pressure-Vessel Sphere	110
66.	Examples of Electron-Beam Welding for Salvage of Costly, Precision Parts	111
67.	Schematic Representation of Plasma-Arc Welding Operation	113
68.	Mechanized Plasma-Arc Welding Torch	114
69.	Tungsten and Copper Electrodes Used for Straight and Reverse Polarity Operation, Respectively . . .	114
70.	Conventional Resistance-Spot-Welding Equipment . .	119
71.	Spot-Weld Strength Versus Welding Current for Spherical-Faced and Truncated-Cone Electrodes . .	120
72.	The Effect of Minimum Contacting Overlap on the Type of Resulting Failure for Tension-Shear Specimens	121
73.	The Effect of Spot Spacing on Weld Geometry . . .	122
74.	Inference of Spot-Welding Current on Strength and Tension/Shear Ratio for 0.035-, 0.062-, and 0.070-Inch-Thick Ti-6Al-4V Alloy	125
75.	Tension-Shear Spot-Welded Specimen Before and After Strength Testing	131
76.	Cross-Tension Spot-Welded Specimen Before and After Strength Testing	131

LIST OF ILLUSTRATIONS (Continued)

Figure	Title	Page
77.	Jig for Cross-Tension Test	131
78.	Spot Welding Attaches Stiffeners to Sidewall Skin Assembly of the Mercury Capsule	133
79.	Typical Resistance-Welding Applications in Various Spacecraft Sections	134
80.	Typical Rib Subassembly With Hour-Glass-Shaped Doubler Spot Welded to Rib	136
81.	Typical Rib Subassembly With Short-Angle Stiffeners Spot Welded to the Rib	136
82.	Typical Rib Subassembly With Long-Angle Stiffeners Welded to the Rib	136
83.	Panel Ready for Resistance Spot Welding of Stiffeners	137
84.	A Spot-Welding Operation on the Upper Skin Subassembly	138
85.	Project Mercury Spacecraft, Built of Titanium, Required 20,500 Inches of Spot Weld Per Capsule	139
86.	Schematic of Seam Welds Used in Mercury Capsule	142
87.	Inner and Outer Mercury Capsule Skins Are Seam Welded	142
88.	Three-Phase, 200 Kva, Seam-Welding Machine Joining Titanium Panels 0.002 Inch Thick to Base Sheet 0.020 Inch Thick	143
89.	Transformer Capacity Versus Weld Area	145
90.	Maximum Machine Upset-Pressure Requirements Versus Weld Area	145

LIST OF ILLUSTRATIONS
(Continued)

Figure	Title	Page
91.	Total Metal Allowance Versus Stock Thickness . . .	146
92.	Production Yoke With Stabilizer Panels Attached . .	150
93.	Flash-Welded Foil Stabilizer Yoke Assembly . . .	150
94.	A Yoke Subassembly in Position to Be Flash Welded .	151
95.	Welded Yoke Subassembly Prior to Removal of Flash.	152
96.	Typical Examples of the Economy of Flash-Welded Ring Products	153
97.	High-Frequency Welding Methods for Manufacturing Titanium Tubing	155
98.	Double-Wall Retort System for Brazing Titanium Alloys Sandwich Panels	161
99.	Approximate Locations of Elevon Surface Panel, Nacelle Panel, and Elevon Trailing Wedge	165
100.	Exploded View of Roll-Welded Pack Prior to Hot Rolling	170
101.	Typical Applications of Roll-Welded Corrugated Sandwich Construction	171
102.	Apparatus for Pressure-Gas Welding	173
103.	Close-Up View of the Pressure-Gas Welding Station .	174
104.	Cross Section of Gas Metal-Arc Spot Weld Joining 0.025-Inch Aluminized Steel and 0.064-Inch 3003 Aluminum With 4043 Aluminum Alloy Filler Metal, No Pilot Hole	180

LIST OF TABLES

Table	Title	Page
I.	Dimensions of Typical Joint Designs for Titanium Alloys	18
II.	Single-U-Groove Joint-Design Details	19
III.	Chemical Composition of Electrode Materials for TIG Welding	59
IV.	Conditions for Manual TIG Welding Titanium and Titanium Alloys	61
V.	Conditions for Machine TIG Welding Titanium and Titanium Alloys	62
VI.	TIG Weld Property Data Sources	65
VII.	Variations of a Modified Double-Vee-Joint Design Used for Experimental TIG Weldments and for a 2 x 30 x 30-Inch Final Plate Weldment on 2-Inch-Thick Commercially Pure Titanium Plate	81
VIII.	Welding Conditions Used in Conjunction With Variations in Weld Design for the Various Experimental TIG Weldments and the Final 2 x 30 x 30-Inch Plate TIG Weldment on 2-Inch-Thick Commercially Pure Titanium Plate Welded With Commercially Pure Titanium Filler Wire	82
IX.	Base Metal and Weld Metal Tensile and Compression Test Results on Commercially Pure 2-Inch-Thick Plate TIG Weldments - Welded With Commercially Pure Titanium Filler Wire	83
X.	MIG Welding Conditions for Various Titanium Alloys	96
XI.	Gas Metal-Arc Welding Conditions for Fabrication of Ti-4Al-4V Titanium Tank Cupola	97
XII.	Tensile Properties of MIG Weld Metals in Titanium Alloys	98

LIST OF TABLES (Continued)

Table	Title	Page
XIII.	Transverse Tensile Properties of MIG Weldments in Titanium and Titanium Alloys	99
XIV.	MIG Weld Property Data Sources	100
XV.	Electron-Beam Welding Conditions	108
XVI.	Electron-Beam Weld Property Data Sources	109
XVII.	Plasma-Arc Welding Conditions for Square Butt Joints in Titanium	115
XVIII.	Recommended Practices for Spot Welding Stainless Steels	124
XIX.	Resistance Spot Welding Conditions for Several Titanium-Base Alloys	127
XX.	Room Temperature Properties of Spot Welds in Several Titanium-Base Alloys	128
XXI.	Spot-Weld Property Data Sources	129
XXII.	Seam-Welding Conditions and Room-Temperature Properties of Resistance Seam-Welded Joints in Titanium	141
XXIII.	Flash-Welding Conditions	147
XXIV.	Room-Temperature Tensile Properties of Flash- Welded Joints	148
XXV.	Bend Ductility and Fatigue Strength of Flash-Welded Joints	149
XXVI.	Titanium Brazing and Soldering Patents From the "Titanium Abstracts" of the Industrial Chemical Industries Ltd. (ICI).	158

LIST OF TABLES
(Continued)

Table	Title	Page
XXVII.	Shear Strengths of Titanium Brazed Joint	159
XXVIII.	Summary of Diffusion Welding Processes for Titanium Alloys	168
XXIX.	Tensile, Notched Tensile, and Impact Properties of Pressure Welds in Ti-6Al-4V Tubing	176
XXX.	Welding Parameters and Typical Tensile Shear Strengths of Gas Metal-Arc Spot Welds in Various Metal Combinations	179
XXXI.	Strength of Joints Between Commercially Pure Titanium and 0.255-Inch-Thick Low-Carbon Steel Using a Vanadium Intermediate	181
B-1.	Physical Properties of Titanium Alloys and Some Commonly Welded Metals	213

TECHNICAL MEMORANDUM X - 53432

WELDING PROCEDURES FOR TITANIUM AND TITANIUM ALLOYS

SUMMARY

Titanium and titanium alloys can be welded by a variety of methods. Most welding processes used in the past for joining more common metals have been used to successfully join titanium. Many new metals-joining processes also have been used with success in production and experimental applications. It is expected that the older established joining processes will continue to be used successfully, and that applications of the newer joining processes will gain wider use for titanium as more experience and knowledge is developed.

Difficulties in welding titanium and titanium alloys originate from several basic sources. The high reactivity of titanium with other materials, poor cleaning of parts before joining, and inadequate protection during joining can lead to contamination, porosity, and embrittlement of the completed joints. There are many fabricators currently joining titanium, however, by various processes. The successful joining of various titanium-alloy products has been accomplished through the use of good welding practices and a knowledge of the factors that affect titanium-weld-joint quality.

Many of the difficulties experienced in joining titanium and titanium alloys can be minimized or eliminated by following the procedures described in this report. When proper techniques are employed, welding of titanium is not an unusually difficult operation. An awareness of the cleanliness needed to successfully weld titanium is essential, and good cleaning practices must be followed throughout the welding fabrication. Brazing of titanium is still limited by difficulties encountered in selecting suitable filler alloys that satisfy performance criteria.

INTRODUCTION

Titanium and titanium alloys have a number of desirable properties and, when suitably combined, these properties make the metal the best material for a variety of service applications. These properties include:

- (1) Excellent fatigue resistance
- (2) Good notch toughness
- (3) Stability over wide temperature range
- (4) Low coefficient of thermal expansion
- (5) Low thermal conductivity
- (6) Outstanding corrosion characteristics for some of the most troublesome industrial chemicals
- (7) Excellent resistance to erosion and cavitation from high-velocity fluid flow
- (8) No scaling below 800 F, although discoloration of the metal may occur
- (9) Inert in electrochemical operations, when charged as an anode in electrochemical circuit.

These properties are important in a variety of applications including airframes, jet engines, aerospace equipment, chemical or processing equipment, and electroplating equipment. Whether manufactured from bar, plate, sheet, or forgings, some type of joining operation often is required to assemble components or subassemblies as a step in completing the final product.

The joining of titanium by welding and brazing processes is described in this report. Previous reports in this series have described adhesive bonding and mechanical fastening of titanium. Emphasis is being placed in these reports on the details of joining procedures. This report is organized into three major sections: (1) Joining fundamentals that cover those aspects of titanium joining that are common to several joining methods, (2) Joining processes that cover equipment procedures, typical joining conditions, and applications, and (3) Dissimilar metal joining in which titanium is one of the materials being joined.

WELDING FUNDAMENTALS

Successful titanium welding involves a careful consideration of many factors related to the actual joining operation. These factors are common to most joining processes and include such items as material selection, process solution, cleaning, tooling residual stresses, repairs, etc. Collectively these factors constitute the fundamental basis of a successful joining procedure. The following sections discuss these basic considerations, particularly as they relate to titanium joining.

MATERIALS

Joining operations involve two types of materials: (1) those that make up the component being joined and (2) those used or supplied in the joining operation.

Component Materials. Component materials are selected to obtain desirable combinations of mechanical and physical properties under the imposed service conditions.* Consideration of all the factors involved in the selection of component materials is important but, in this report, only those factors related to joining operations will be discussed.

Important features of titanium alloys that must be considered to successfully join this highly reactive material are:

- (1) The extreme sensitivity of titanium to embrittlement by small amounts of some impurities
- (2) The very high reactivity of titanium, not only at welding temperatures but at temperatures as low as 1200 F
- (3) The effects of the heating and cooling cycles involved in joining operations on the mechanical properties of the alloys
- (4) The inherently brittle structures, which are almost always formed when titanium is joined to other metals
- (5) The specific titanium alloy composition to be used.

The sensitivity of titanium and titanium alloys to embrittlement imposes limitations on the joining processes that may be used. Small amounts of carbon, oxygen, nitrogen, or hydrogen impair ductility

* Appendix B (DMIC Memorandum 171, July 15, 1963) tabulates the physical and mechanical properties of many titanium alloys. Information on titanium-alloy producers also is included.

and toughness of titanium joints. As little as 5000 parts per million of these elements will embrittle a weld beyond the point of usefulness. Titanium has a high affinity for these elements at elevated temperatures and must be shielded from normal air atmospheres during joining. Consequently, joining processes and procedures that minimize joint contamination must be used. Dust, dirt, grease, fingerprints, and a wide variety of other contaminants also can lead to embrittlement and porosity when the titanium or filler metal is not properly cleaned prior to joining. Contamination that arises either from the open atmosphere or from dirt on the filler metal or surfaces to be joined must be strictly avoided for the successful joining of titanium and titanium alloys.

Recognition of several metallurgical characteristics of titanium is important if we are to understand the reasons for using the specific joining methods discussed later. These characteristics, (1) chemical activity, (2) interstitial alloying, (3) substitutional alloying, and (4) strengthening mechanisms, are discussed in the following sections.

Chemical Activity. When heated to joining temperatures, titanium and titanium alloys react with air and most elements and compounds, including most refractories. Therefore, gas-fusion and arc-welding processes where active gases and fluxes are in contact with hot metal are not used. The reaction products cause brittle welds. Titanium can, however, be welded by inert-gas-shielded or electron-beam fusion welding and spot, seam, flash, induction-pressure, gas-pressure, and other welding and joining processes. With the inert-gas-shielded arc-welding processes, argon or helium shields the welds from air and prevents weld contamination. Electron-beam welding takes place in a vacuum. In spot and seam welding, the molten titanium in the weld is surrounded by the titanium-base metal so the welds are protected from contamination. In flash and pressure welding, air may be in contact with the weld, but most of the contaminated metal is pushed out of the weld area and any remaining impurities diffuse into the metal away from the weld interface. Inactive flux backups have been developed for use in combination with inert-gas shielding for welding titanium.

Brazing and solid-state-welding processes for titanium generally are limited to those techniques that involve vacuum or inert-gas atmospheres.

Interstitial Alloying. Of the few elements that can form interstitial solid solutions in titanium, only carbon, oxygen, nitrogen, and hydrogen are of specific interest in the joining of titanium.

Carbon, nitrogen, and oxygen all behave in about the same way in titanium. Small amounts of these elements cause significant embrittlement of titanium welds. The effects of these elements on weld ductility and toughness are both progressive and additive (Ref. 1)*.

Because of this, it is difficult to establish a definite amount of any single interstitial element that causes a distinct change from good to bad properties. During joining of titanium, contamination by carbon, oxygen, hydrogen, and nitrogen must constantly be guarded against; when these elements are found in titanium joints it is because:

- (1) They are deliberate alloying additions to some forms of titanium
- (2) They may be present as residual impurities
- (3) They may be picked up as contaminants from various processing steps.

Hydrogen behaves somewhat differently in titanium; nevertheless, its presence in titanium welds can be extremely harmful. Hydrogen is never deliberately added to titanium and should be kept at as low a concentration as possible in all processing operations.

Interstitial elements have potent effects on properties of titanium alloys. Consequently, caution is necessary when comparing titanium alloys or different heats of the same alloy. Variations in impurity content, or interstitial content, can cause significant changes in toughness. Therefore, it is important to consider the effects of all impurity content and alloying elements when selecting welding procedures, processing procedures, and other parameters.

The interstitial level that can be tolerated in welded joints depends on the use to which the welds will be put and the alloy that is being welded. Weld toughness is decreased by lower interstitial levels than those that will affect ductility. Therefore, greater care should be taken to insure against weld contamination in fabricating assemblies that are subjected to impact loading. Also, welds in some alloys are more ductile, and have a higher toughness than welds in other alloys. Welds with a high basic ductility or toughness can tolerate higher interstitial levels. Unalloyed or lower alloy or extra-low interstitial (ELI) filler wire is often used to improve weld ductility.

The interstitial level that can be tolerated in welds is lower than the corresponding tolerance level in base material. Interstitials that

*References are given on page 182.

are present in the base metals prior to welding or are introduced during welding may cause weld embrittlement.

Substitutional Alloying. The most generally recognized effects of substitutional-alloy additions in titanium relate to the type of alloy formed by the specific addition or additions. Titanium alloys are classified as pure titanium, alpha alloys, alpha-beta alloys, or beta alloys, depending on their metallurgical structures. Each titanium alloy behaves according to the characteristics of its alloy type during joining. The initial base-material condition (cold worked or heat treated in some manner) is equally as important as alloy content, as will be shown in the next section.

Commercially Pure and Alpha Alloys. All commercially pure titanium and alpha alloys are weldable. The mechanical properties of joints in either commercially pure titanium or alpha alloys are not affected by welding operations or brazing thermal cycles on annealed sheet material. Alloys of this type that have been strengthened by cold working will exhibit a loss of strength in weld heat-affected zones or brazements. Very little use is made, however, of cold working to increase the strength of either commercially pure or alpha-type alloys. Welded joints in annealed alpha-titanium material are ductile and exhibit strengths that are equal to those of the base metal. Alpha alloys with a maximum of usable strength are obtained by using a level of substitutional-alloy addition that is close to the maximum solubility. The 7Al-12Zr titanium alloy is of this type and is the highest strength all-alpha alloy currently available that exhibits good weldability.

Alpha-Beta Alloys. The mechanical properties and ductility of alpha-beta alloys can be affected greatly by heat treatment. The response of these alloys to heat treatment depends upon the exact alloy content. Therefore, very few generalized statements about weldability of alpha-beta alloys can be made. Welding or brazing these alloys may significantly change the strength, ductility, and toughness as the result of the thermal-cycle exposure during joining. The selection of an alpha-beta alloy for use in an application requiring joining should be based on the known effects of the alloy content and the intended application. Alloys that contain about 3 per cent of either chromium, iron, manganese, or molybdenum, and more than 5 per cent of vanadium either singly or in combination with each other are seldom used in fusion-welding applications because of the resulting low weld ductility. When welding alloys contain percentages of these elements in excess of the amounts given above, it is sometimes possible to improve weld ductility by a postweld heat treatment. However, the

use of heat treatment is not always effective in improving ductility. The thermal stability of welded alpha-beta alloys is another area of concern if the intended application involves prolonged service at elevated temperatures.

Alpha-beta alloys are sometimes welded with either commercially pure or alpha-alloy filler metals. This is done to lower the alloy content of the weld fusion zone. The use of filler metals of this type lowers the beta-phase content of the fusion zone and generally results in improved weld ductility and toughness. The composition of the heat-affected zone, however, remains unchanged. In alpha-beta alloys that are subject to heat-affected-zone embrittlement, special filler metal alloys are ineffective in obtaining an overall improvement in weldment properties.

Beta Alloys. The all-beta alloy, 13Cr-11V-3Al, depends very strongly on either cold work or heat treatment to obtain desirable strength properties. In these conditions, welded joints are readily made, but the resulting weld strength is considerably lower than that of the base plate. Postwelding operations designed to raise the weld-strength level either are not practical or result in severe embrittlement of the beta alloy. The reasons for this are not well known, but are apparently related to different aging responses of structures that differ in grain size, grain structure, or orientation. All-beta alloys are also susceptible to thermal instability. Their use in a fully annealed condition is generally not warranted because of the low strengths available.

Strengthening Mechanisms. Titanium alloys can be strengthened by cold working (strain hardening) and by heat treatments. The strengthening mechanisms used for titanium alloys are important because of their effects on weldability of alloys as based on mechanical properties. Some alloys are considered to be weldable if the welds are not given any postweld heat treatment. However, quite often welds in such alloys are much lower in strength than the heat-treated base metals. Attempting to increase the strength by a postweld heat treatment may be successful, but quite often some other property (such as ductility) is degraded.

The importance of strengthening mechanisms as a consideration in the weldability of titanium alloys can be illustrated in another way by considering the following statements.

- (1) The properties of titanium-base alloys are determined by alloy content and a controlled-mechanical and thermal-processing history.
- (2) Welding imposes variable thermal cycles on material in the joint area that are unlike any other exposure conditions normally used on titanium alloys.
- (3) The effect of welding thermal cycles on the properties of titanium alloys may be insignificant or very significant.
- (4) The apparent weldability of any given titanium alloy can be altered considerably by either the initial base-material condition or postweld thermal or mechanical treatments.

Strengthening mechanisms also are important items to consider in planning brazing operations for titanium.

Process Materials. The principal materials used in joining operations are filler metals, protective shielding gases, and, on rare occasions, protective fluxes.

Filler Metals. Some fusion-welding processes involve the addition of metal from sources other than the base metal. Wire is generally used and added at a controlled rate. Wire added during TIG welding is called "filler wire" or "cold wire". Wire used in MIG welding also is called filler wire, or it may be called "electrode wire".

Titanium wire for welding must meet high-quality standards. The same is true for most welding wire. This requirement results from the high surface area to volume ratios characteristic of the common wire sizes used in welding (see Figure 1). Obviously, any wire-surface-layer contamination represents a sizable addition to a weld. Also, it is much more difficult to process titanium to wire without contamination than is the case with other products. For example, wire cannot be processed by any method comparable to the pack-rolling procedures used for thin sheet.

Wire products sometimes contain defects. The terminology used to describe various wire defects is illustrated in Figure 2. None of these defects can be tolerated in titanium wire intended for welding structural components of high-performance airframes.

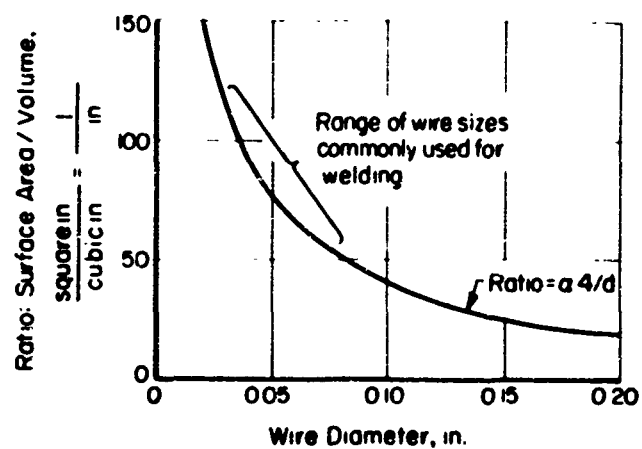


FIGURE 1. SURFACE AREA TO VOLUME RATIO FOR WELDING FILLER WIRES

Defect	Drawing Stock	Wire
Seam		
Lap		
Center burst		
Crack		

FIGURE 2. WELDING-WIRE DEFECTS

Any of the surface defects may contain foreign matter (drawing compound, oxide, etc.)

The availability of good-quality titanium welding wire in the past and today has been debated extensively. Some welding engineers feel that high-quality titanium wire just does not exist. Others do not think there is a "welding wire problem". The real answer probably lies somewhere between these two extremes.

The "titanium welding wire problem", if there is one, must be resolved before some fusion-welding processes can be used for certain applications. Titanium-welding-wire development has suffered from the lack of a sizable market. Unalloyed titanium commercially pure wire has been the major marketable item. Experience with the various titanium alloys has been limited. The required quality level and reliability in titanium-alloy wire probably can be developed once a market is evident.

Filler wires for welding titanium are produced by the major titanium fabricators and by a number of specialty-wire manufacturers.

Filler metals also are used in brazing and some solid-state-welding processes. Requirements pertinent to these applications are discussed in the appropriate process sections.

Protective Shielding Gases. When molten, or even just cherry red, titanium acts like a blotter for gases containing carbon, hydrogen, nitrogen, oxygen, and water vapor. Small amounts of these gases can embrittle titanium alloys beyond the point of usefulness. Even trace amounts of these gases can have large effects on properties of titanium alloys. Extensive tests have shown that argon used to protect the weld zone had to contain less than 500 ppm of air by volume when welding Ti-5Al-2.5Sn (Ref. 2). Bend tests showed a 50 per cent reduction in ductility when air contamination was increased from 100 ppm or less to 500 ppm. Consequently, when joining titanium and its alloys, any melted or heated metal must be protected from coming into contact with air and other atmospheres containing these potentially harmful elements.

Air around a titanium joint must be replaced by an inert gas and it must be replaced whether the joint is fully penetrated or not. In actual practice, inert gases, argon and helium, or mixtures of argon and helium are used for shielding titanium with all fusion-welding processes. Electron-beam fusion welding normally is done in a vacuum at pressures low enough to preclude air contamination. Brazing and solid-state joining are usually done in inert-gas atmospheres or vacuum. Inert-gas shields help blanket all of the heated metal with inert gas. The inert gases do not react with titanium whether the

metal is hot or cold and there is no embrittling effect from these gases. If the normal surrounding air contacts the heated metal it will react with it to promote porosity, embrittlement, cracking, or other serious effects. In addition to shielding, the inert gases argon and helium are used to provide distinct welding arc characteristics and weld features. Arc voltage in helium is about 30 to 50 greater than in argon for a given welding current. The heat energy liberated in helium is about twice the heat given off in argon. This means that faster welding speeds can be obtained with helium shielding. Helium also provides greater weld penetration and permits welding of thicker gages more readily. Argon is used for welding thinner gages where lesser heat may be desirable. Arc length can be changed in argon without appreciably changing the heat input to the work. This is an important factor when the electrode cannot be brought close to the work or when arc length may vary as in manual welding operations. Mixtures of shielding gases also are used to obtain characteristics that are intermediate between those of the pure gases. Selection of the particular shielding gas, therefore, is made to provide desired welding arc characteristics in addition to preventing contamination. Also, gases such as hydrogen, carbon dioxide, and oxyacetylene mixtures that are normally used in joining other metals cause severe embrittling effects when used in joining titanium; consequently, they are not used. Special grades of inert gas containing additives, such as oxygen, that are used in some welding should not be used in welding titanium.

High-purity inert gases are needed for joining titanium. Special welding grades of inert gases are available commercially. The major concern with inert gas is insuring that the basic-gas quality is not degraded during flow through the joining equipment. The number of disconnectable fittings used in the gas system should be minimized. All such fittings must be kept in good condition and must be tight to prevent aspirating air and moisture into the shielding gas stream. Damaged or loose fittings can allow air or water leaks to contaminate the inert-gas shield and the joint.

Protective Fluxes. Titanium and titanium alloys have been welded using a proprietary-flux back-up, conventional MIG-welding technique. In feasibility studies, 3/4-inch-thick commercially pure titanium and 7/16-inch-thick ELI Ti-5Al-2.5Sn plates were welded in the flat position (Ref. 3). Torch-trailing-shield arrangements were used to protect the access side of the welds while the underbead side was protected with the proprietary flux. The flux was placed in the separation between two back-up bars. The fused flux forms a cocoon on the back sides of the welded plates and affords good

protection from the atmosphere. The fused flux was removed by scraping or wire brushing and washing in water (Ref. 4).

Similar techniques have been used for manual and mechanized TIG welding titanium and there are indications that the flux material also may be useful for submerged-arc-welding applications (Ref. 3).

On the basis of preliminary results, it appears that fluxes for welding titanium have merit although there are no known commercial uses as yet.

PROCESS SELECTION

Titanium has been joined by many common welding and brazing processes. Widespread use has been made of the following processes:

- (1) TIG welding (tungsten inert gas)
- (2) MIG welding (metal inert gas)
- (3) Electron-beam welding
- (4) Resistance spot-, roll spot-, seam welding.

Limited use has been made of many other joining processes including:

- (1) Arc spot welding
- (2) Plasma-arc welding
- (3) Brazing
- (4) Diffusion welding
- (5) Roll welding
- (6) Pressure-gas welding
- (7) Flash welding
- (8) High-frequency resistance welding.

Processes such as oxygen-gas fusion welding, submerged-arc welding, coated-electrode welding, and arc welding with active gases are not used for joining titanium because of the resulting embrittlement of the joint area.

As with many other metals, selection of a joining process for titanium often is influenced by the physical characteristics of the part to be joined. Fortunately, the varied characteristics of joining processes lead to a very broad range of possible applications. Most titanium joints can be made by any one of a number of joining processes. However, welding finds major usage in subassembly fabrication and a few large structural components. Cost, available equipment, maintenance,

reliability, accessibility, thickness, and overall component size also are important factors in assessing the proper usage of welding and alternative joining methods.

Joint design also can influence the selection of the joining process. Design can limit the number of potentially usable processes and exclude those processes that are either not usable or would be very difficult to adapt for the particular application. Figure 3 illustrates several joint designs and lists the processes that normally would or would not be used for joining; it is apparent that several processes can be selected for making each joint when considered from a purely capability viewpoint. Other factors reviewed earlier may reduce the number of potentially useful processes to a fewer number than those indicated.

The relationship of joining to other fabrication operations is an important aspect in process selection. A simplified subassembly-process flow chart follows to show some of the possibilities. The part used as an example is a contoured stiffened skin too large to make from a single titanium sheet. The materials involved are skin sheets and formed stiffeners as sketched in Figure 4. The flow chart, Figure 5, shows that many possible approaches might be used to fabricate this single part. The important point here is to remember that the fabrication operations immediately before and after joining are closely related to successful part fabrication. Good joint fitups are needed and all titanium parts must be properly cleaned before joining. Stress relieving of complex (and perhaps any) weldments immediately after welding is sometimes essential.

JOINT DESIGN

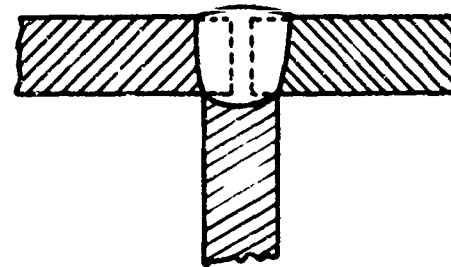
Suitable joint designs must be selected for all types of joining operations, but they are particularly important in welding. Joints with square abutting edges for arc or electron-beam welding for the thinner gages of titanium normally require machining to provide a good fit-up. Thicker gages require a more complex joint preparation. Typically, such preparation involves machining bevels or contours on the abutting edges. Part tolerances also are an important consideration in establishing good joint designs. Close tolerances are always preferred, but they cannot always be planned for in production parts. With titanium it is also essential that the joint design selected be one that can be properly shielded from contamination if welding is to be done in air.

Joints designed for TIG, MIG, or electron-beam welding titanium alloys normally are prepared by machining so as to provide a good



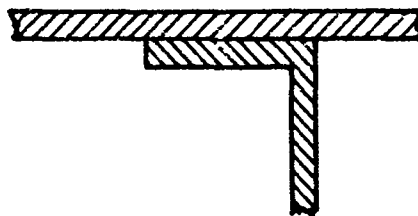
a. Butt Joint

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



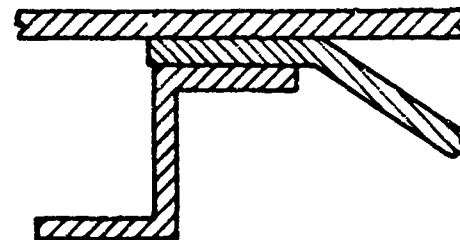
b. Fabricated Tee

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



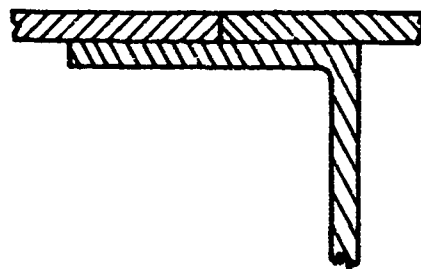
c. Sheet-Stringer Lap

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



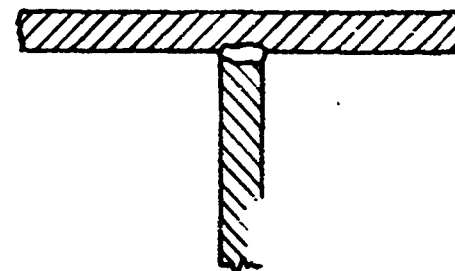
d. Multilayer Lap

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



e. Sheet Splice With Doubler

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



f. Cap or Tee

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

FIGURE 3. TYPICAL JOINTS IN TITANIUM AND TITANIUM ALLOYS

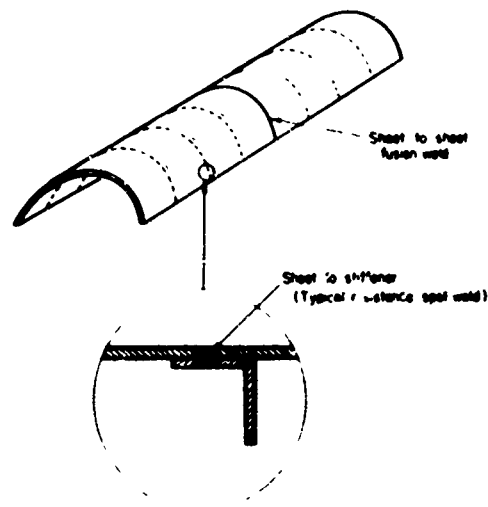


FIGURE 4. STIFFENED-SKIN COMPONENT

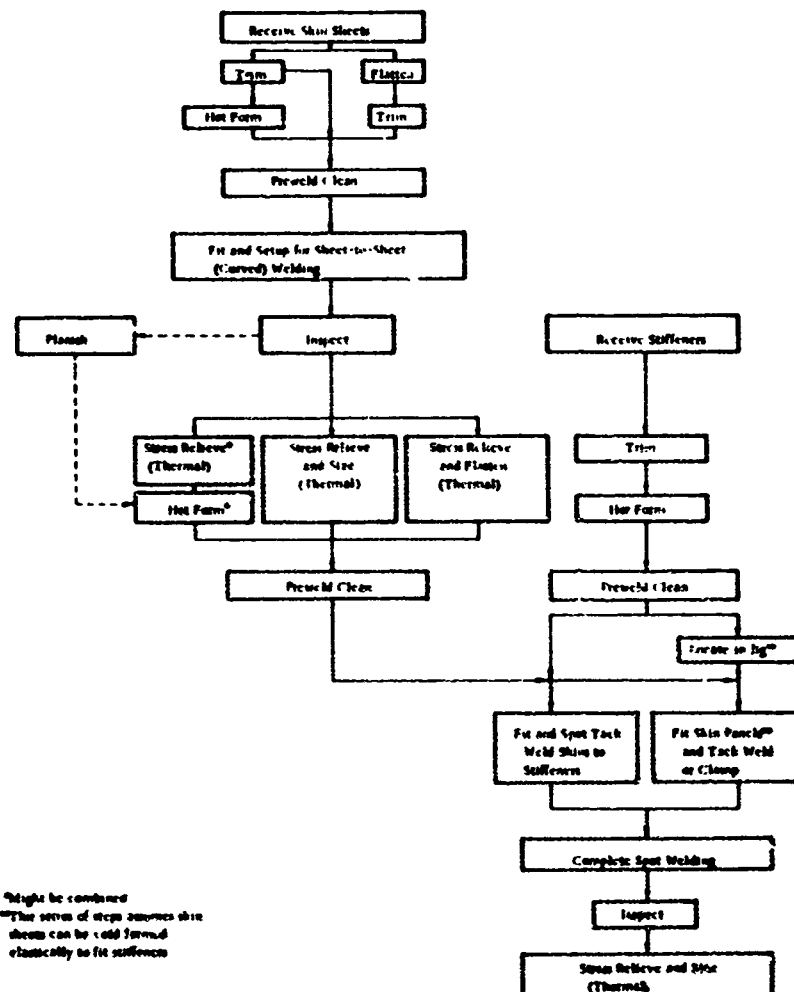


FIGURE 5. FLOW SHEET SHOWING POSSIBLE RELATION OF WELDING TO OTHER OPERATIONS

joint fit-up. Unless the parts are well fitted together, burnthrough or excessive deposits that may crack can result. The joints are machined by milling, shaping, and grinding. Draw files often are used to remove burrs and to help clean the surfaces before welding. Although many fabricators regularly use draw filing as part of their normal joint-preparation procedures, some fabricators believe that draw filing produces burrs that contribute to porosity; consequently, the latter hesitate to use draw files for titanium-joint preparation.

Preparation of edges to be welded is performed by conventional methods such as machining and grinding. Oxyacetylene-flame cutting followed by light manual grinding also has been used to prepare weld grooves in the 6Al-4V titanium alloy (Refs. 5, 6). The edges can be dye-penetrant inspected to assure the absence of surface defects. Cracks can occur in the flame-cut edge during cutting. Also, delayed cracks can form so grinding should be done immediately following the flame-cutting operation (Ref. 7).

Typical weld-joint designs for fusion welding titanium alloys are shown in Figure 6 (Ref. 8). Information available regarding joint dimensions is given in Table I. Dimensional details of U-joints are given in Table II. Other special joint-design details for MIG welding are shown in Figure 7 (Refs. 5, 9). A consumable-land joint design shown in Figure 8 also has been used for welding titanium (Ref. 9); the thickened portion of the joint is melted during welding and serves as the filler metal. This joint design is useful when satisfactory filler metals are not available. However, the joint must be prepared from thicker parent metal sheet or plate or the edge must be upset to permit machining. The joint design shown in Figure 9 incorporating a back-up ring also has been used for welding titanium (Ref. 9). The back-up ring is used to help hold the molten metal in place and to help control the underbead-weld geometry. Since the back-up ring is fused during welding, it becomes an integral part of the weldment. In the only known application of this joint design for welding titanium, the back-up ring was not machined away. For other applications, the back-up ring probably can be machined away. In most applications, however, welding is performed without back-up rings.

Resistance welding usually involves joints that consist of overlapping layers of material. Multiple layers may be included in a single joint. In resistance welding such factors as edge distances and inter-spot spacings are an important consideration in the selection of a suitable joint design. Another important factor is the initial sheet separation. Sheet separation must not be so great that unusually high forces are required to bring the surfaces into contact.

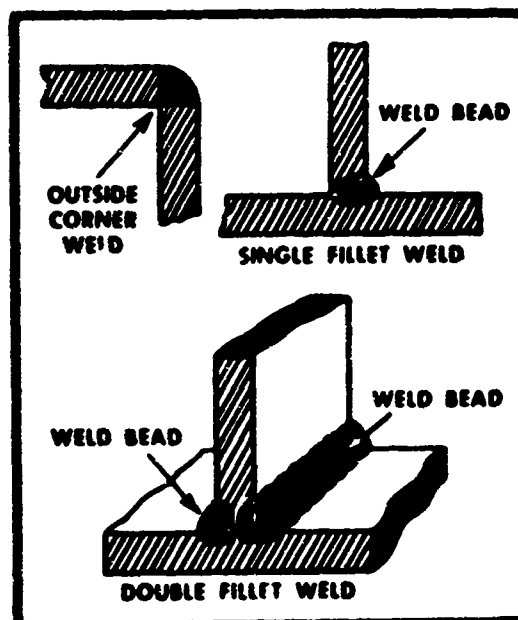
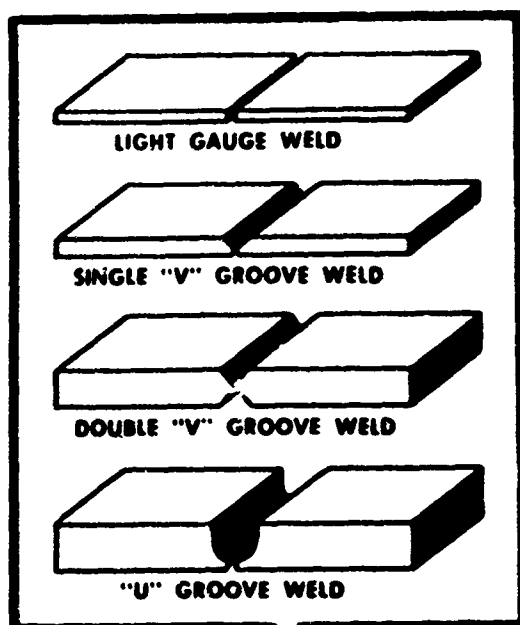
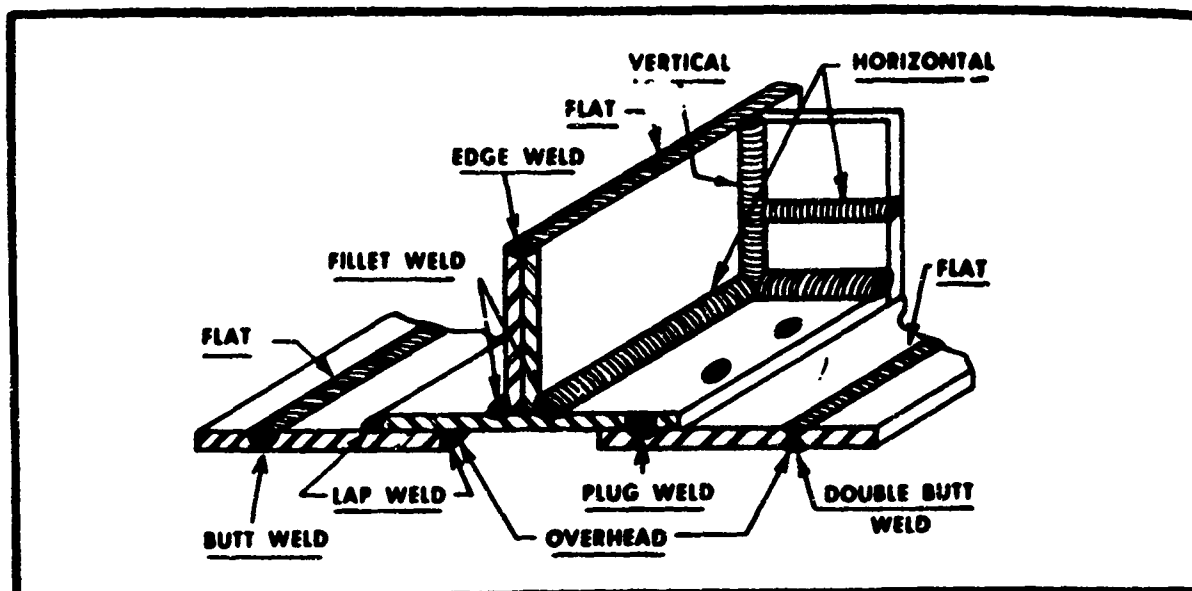


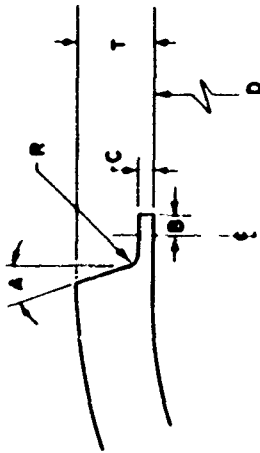
FIGURE 6. TYPICAL FUSION-WELD-JOINT DESIGNS (REF. 24)

TABLE 1 DIMENSIONS OF TYPICAL JOINT DESIGNS FOR TITANIUM ALLOYS

Drawing	Weld Type	Thickness Range in	Weld-Pass Type	Electrode Type	Electrode Diam. in	Filler Wire Diam. in	Land L. in	Root Opening (RO)	Angle of Bevel, deg	Width in	Reference
	Square butt	0.010-0.062	Single	Tungsten (a)	1/16	None	--	0	--	--	10
		0.060-0.090	Double	Tungsten	--	None	--	0	--	--	10
		0.031-0.125	Single or Double (b)	Tungsten	1/16	None	--	0	--	--	11
		0.031-0.125	Single	Tungsten	1/16-1/8	1/32-1/16	--	0-0.1 T (c)	--	--	11
	Single V	0.062-0.125	Single	Tungsten	1/16-3/32	1/16	0.040(d)	0-0.10T	30-60	0.10-0.25T	11, 12
		0.040-0.125	Multiple	Tungsten	--	--	0.030	--	40	--	10
		0.125-0.250	First	Tungsten	1/16-3/32	None	--	0-0.10T	30-60	0.10-0.25T	11
			Second	Tungsten	1/16-3/32	3/64-1/16	--	--	--	--	11
		0.125-0.500	First	Tungsten	3/32-1/8	None	--	0-0.10T	30-90	0.10-0.25T	11
			Second	Consumable	1/16	--	--	--	--	--	11
	Double V	0.125-0.500	Single-multiple	Consumable	1/16	--	--	0-0.10T	30-90	0.10-0.25T	11
		0.250-0.500	Double-multiple	Tungsten	1/16-3/32	1/16	--	0-0.20T	50-120	0.10-0.25T	10, 11, 13
		0.250-0.750	Double	Consumable	1/16	--	--	0-0.10T	50-90	0.10-0.25T	11
		0.625	Double-multiple	Consumable	1/16	--	0	0.250	45	--	5
		0.750-1.500	Double-multiple	Consumable	1/16	--	--	0-0.10T	50-90	0.10-0.25T	11
		2.0	Double-multiple	Consumable	1/16	--	0.032	0.12, 0.00c	45	--	5
	Single U	0.250-0.500	First	Tungsten	1/16-3/32	1/16	--	0-0.10T	15-30	0.10-0.25T	11
			Second	Tungsten	1/16-3/32	3/16	--	--	--	--	11
		0.250-0.750	First	Tungsten	1/16	None	--	0-0.10T	15-30	0.10-0.25T	11
			Second	Consumable	1/16	--	--	--	--	--	11
		0.250-1.000	Multiple	Consumable	1/16	--	--	0-0.10T	15-30	0.10-0.25T	11
	Double U	0.750-1.500	Double-multiple	Tungsten	1/16-3/32	1/16	--	0-0.10T	15-30	0.10-0.25T	11
		0.750-1.500	Double; rat	Tungsten	1/16	None	--	0-0.10T	15-30	0.10-0.25T	11
			Double-multiple	Consumable	1/16	--	--	--	--	--	11
		0.750-2.000	Double-multiple	Consumable	1/16	--	--	0-0.10T	15-30	0.10-0.25T	11
	Fillet	0.031-0.125	Single or double	Tungsten	1/16	None-1/16	--	0-0.10T	0-45	0-0.25T	11
		0.125-0.500	Single or double	Tungsten	1/16-3/32	1/16	--	0-0.10T	30-45	0.10-0.25T	11
		0.250-1.000	Single or double	Consumable	1/16	--	--	0-0.10T	30-45	0.10-0.25T	11
		1.375	Multiple	Consumable	--	--	0	0	45	--	9

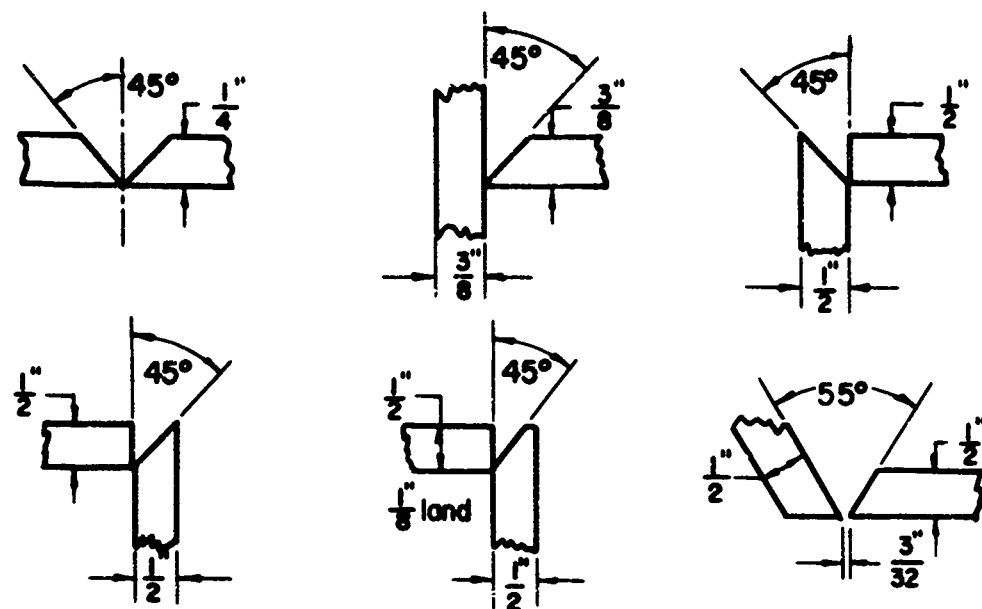
(a) Thoriated tungsten electrodes.
 (b) Double pass, one pass each side.
 (c) T = thickness of base material.
 (d) For $t \geq 0.060$ in.

TABLE II. SINGLE-U-GROOVE JOINT-DESIGN DETAILS (REF. 14)

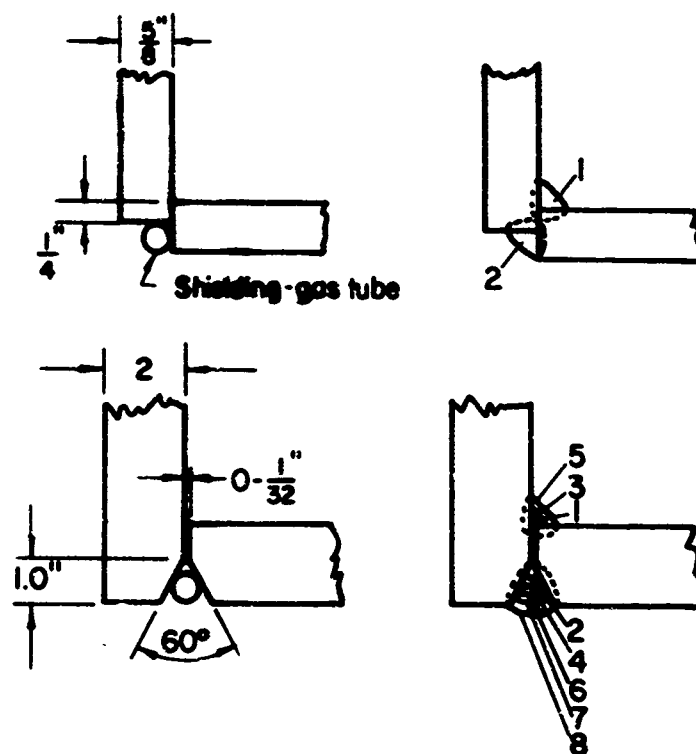


T, in.	D (D), in.	C, in.	B(a), in.	R, in.	A, deg
0.111 ^{+0.010} _{-0.000}	6.518	0.040 ^{±0.005}	0.060 ^{±0.005}	0.090 (from ξ)	0
0.147 ^{±0.002} (reference)	5.578 ^{±0.005} (reference)	0.030/0.035	0.030/0.035	0.090 (from ξ)	7 ⁺⁰ ₋₇
0.150 (reference)	11.964 (reference)	0.040 ^{±0.005}	0.060 (reference)	0.090 (from ξ)	7 ^{±5}
0.157/0.148	12.400	0.045/0.035	0.055/0.065	0.090 (from ξ)	7 ^{±5}
0.184 ^{±0.003}	16.188 (reference)	0.030 ^{±0.005}	0.048 ^{±0.005}	0.090	7 ^{±5}
0.074 ^{±0.003}	4.596 (reference)	0.032 ^{±0.005}	0.025 ^{±0.005}	0	60 (from end of part)
0.095 ^{+0.005} _{-0.000} (reference)	5.100 (reference)	0.040 ^{±0.005}	0.030 ^{±0.005}	0.090	0
0.096 ^{+0.002} _{-0.003}	7.066 (reference)	0.040 ^{±0.005}	0.060 ^{±0.005}	0.090	0
0.095 (reference)	6.000 (reference)	0.030 ^{±0.005}	0	0.090	0
0.095 ^{±0.005}	6.924	0.040 ^{±0.005}	0.020 ^{±0.005}	0.090 (0.060 from end of part)	0
0.218/0.213	12.370	0.045/0.040	0.055/0.065	0.095/0.085 (from ξ)	7
0.222/0.213	16.032	0.045/0.035	0.060	0.090 (from ξ)	10 ⁺⁵ ₋₀
0.287/0.278	19.24	0.045/0.035	0.060	0.090 (from ξ)	10 ⁺⁵ ₋₀

(a) Shrinkage requirement.



a. Several Special Joint Designs for Welding Titanium Alloys (Ref. 9)



b. Corner - Joint Designs (Ref. 5)

FIGURE 7. JOINT DESIGNS FOR SPECIAL APPLICATIONS OF MIG WELDING OF TITANIUM ALLOYS



FIGURE 8. CONSUMABLE-LAND JOINT DESIGN (REF. 15)



a. Before Welding



b. After Welding

FIGURE 9. BACK-UP-RING JOINT DESIGN (REF. 15)

Many of the joint designs used for resistance welding are not intended to transmit transverse tensile loads. Joints of this type are sometimes referred to as scab or attachment joints.

All joints designed for resistance welding must normally be accessible from both sides of the parts being joined. Sufficient clearance must be maintained to allow for the extension of the electrodes and electrode holders to properly contact the sheets.

CLEANING

Careful preweld cleaning is essential to the successful joining of titanium alloys. Proper surface preparation is important to (1) remove scale, dirt, and foreign material that can contaminate the joint, (2) help control weld porosity in arc-welding operations, and (3) insure uniform surface conditions and thereby improve weld consistency in resistance-spot- and seam-welding operations. A flow chart of a successful cleaning operation is shown in Figure 10 (Ref. 16).

Prior to resistance welding the cleaning of the surfaces of sheets as received from the mill with any of the commercial solvents that leave no residue often is satisfactory. However, if elevated-temperature forming has been performed, the light oxide scale should be removed. Otherwise the oxide skin on the adjacent surfaces being joined will be fused into the weld nugget, which can lead to a drastic reduction in the ductility of the welded joint. Poor or variable cleaning can have another bad effect in resistance welding. Much of the

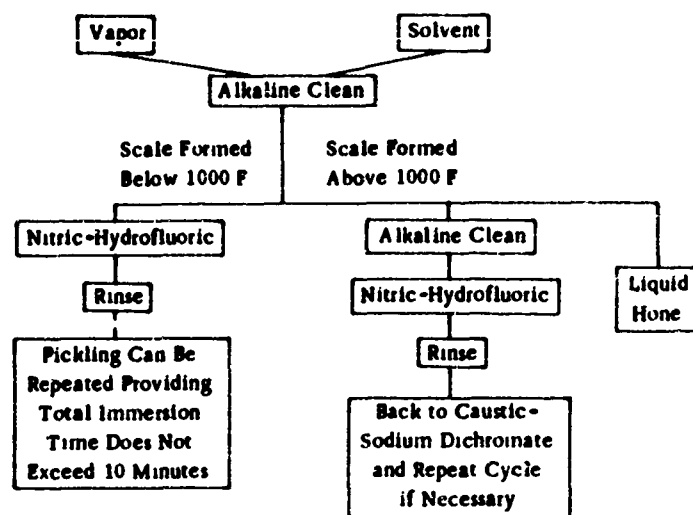


FIGURE 10. FLOW CHART OF CLEANING PROCEDURE FOR TITANIUM ALLOYS (REF. 16)

initial heat generated during the early stages of resistance welding is localized at the joint interface. This happens because the electrical resistance through the interfaces is generally higher than the resistance of the bulk material. Thus, the surface resistance of the mating surfaces is an important factor controlling the heat generated during the weld cycle, and it is important that this resistance not fluctuate widely. The surface resistance of any metal is controlled largely by the surface preparation or cleaning techniques that are used prior to welding.

Grease and Oil. Grease and oil accumulated on titanium parts during machining and other operations must be removed prior to joining to avoid contamination. Scale-free titanium often is degreased only; titanium having an oxide scale is degreased prior to descaling operations. Degreasing may be accomplished in any of the following ways:

- (1) Steam clean
- (2) Alkaline wash or dip in a dilute solution of sodium hydroxide
- (3) Solvent wash methyl ethyl ketone, methyl alcohol, toluene, acetone, or other chlorine-free solvents

- (4) Hand wipe with solvent-dampened, clean, lint-free cloths immediately before welding. Plastic gloves are recommended for this type of operation. Reactions between solvents and some of the compounds in rubber gloves can leave deposits on the joint that cause porosity.

The steps followed in a typical cleaning procedure for machined parts prior to joining are as follows (Ref. 17):

- (1) Degrease with toluene, alkaline-steam cleaners, or commercial degreasing equipment. (Residues from silicated or chlorinated solvents have been blamed for cracking of some titanium weldments. Consequently, this use for cleaning titanium is prohibited by many fabricators.)
- (2) Force air dry with clean, dry air
- (3) Alkaline clean (commercial cleaners)
- (4) Water rinse with running water or a spray rinse at ambient temperature until a pH of 6 to 8 is reached. pH paper is used for this determination
- (5) Water rinse for 4 to 6 minutes with deionized water at ambient temperature
- (6) Alcohol rinse for 15 to 30 seconds with alcohol at ambient temperature. Alcohol rinse is optional
- (7) Dry by blowing with hot dry air or nitrogen gas.

Parts showing evidence of surface contamination immediately prior to assembly should be rejected and must be recleaned. If the surface contamination is light dust settled out of the atmosphere, the parts are wiped with solvent-dampened cloths and dried just prior to the joining operation.

Chlorinated solvents, such as trichloroethylene and silicated solvents, should not be used to degrease titanium.* Stress-corrosion cracking in weld areas during subsequent processing has been attributed to the use of chlorinated solvents (Ref. 1). Cleaning of parts containing crevices should be analyzed carefully to avoid trapping solutions that can cause porosity. Good rinsing and drying procedures are important in these operations. Residue from the degreasing treatment must not be allowed to remain in the joint area.

*Some solutions used in dye-penetrant testing may contain chlorinated solvents. Use of these materials should be carefully checked out prior to approving their use on titanium.

Temperature-sensitive crayon and paint markings and pencil and ink markings also should be removed from areas that are heated during joining operations. These materials can contaminate either the underlying metal or the weld metal and result in embrittlement or porosity.

Scale Removal. Light scales are formed on titanium at temperatures up to about 1100 F. This scale is generally thin and can be removed by chemical pickling. Chemical pickling is often the most efficient and economical process for scale removal compared with mechanical techniques (Ref. 18). The most commonly used pickling baths are solutions of hydrofluoric acid, nitric acid, and water. These baths contain from 2 to 5 per cent HF and 30 to 40 per cent HNO_3 . A pickling bath used by many fabricators contains 5 per cent HF, 35 per cent HNO_3 , balance water, and a 30-second immersion time. After pickling, the parts are rinsed in water and dried. Pickling treatments also are used to prepare scale-free material for spot- and seam-welding operations. Pickling should be avoided when possible on assemblies that contain crevices that may entrap the acid solution.

The steps followed by one fabricator in removing light scale are as follows:

- (1) Degrease to remove oil or grease
- (2) Alkaline clean
- (3) Rinse
- (4) Immerse in scale conditioner
- (5) Rinse
- (6) Immerse in HF- HNO_3 pickle. Stains resulting from the HF- HNO_3 pickle can be removed by a 30-second immersion in a 45 to 55 per cent HNO_3 pickling solution.

Prolonged immersion can remove too much material, so pickling procedures must be developed and controlled carefully.

When heated to temperatures above 1100 F the scale formed on titanium is thicker than the scale formed below 1100 F. Removal of the heavier scale requires a more complex treatment than is required for removal of light scale. Chemical or salt-bath treatments, mechanical treatments, or combinations of these treatments are used. Molten-salt baths, which are basically sodium hydroxide to which oxidizing agents or hydrogen have been added to form sodium hydride,

are commonly used to remove this scale in preparation for welding. Caution is needed in using these molten-salt baths. Bath compositions and temperatures must be carefully controlled to prevent the introduction of excessive amounts of hydrogen into the titanium.

Both the molten-salt-bath treatments and mechanical scale-removal operations are followed by a pickling operation to insure complete scale removal and to remove subsurface contaminated metal if necessary. Removal of scale can be aided by scrubbing with a brush and reimmersing (Ref. 16). Caution is necessary when pickling titanium. Titanium can absorb hydrogen readily when improper pickling procedures are used. During subsequent welding operations, porosity can occur from hydrogen absorbed during pickling operations. Pickling baths that contain HF with little or no HNO_3 acid cause hydrogen absorption. HNO_3 inhibits hydrogen pickup during the reaction between titanium and HF. At least a 7 to 1 HNO_3 to HF weight ratio normally is recommended.

Handling and Storage. All part handling after cleaning and before joining must be controlled. So-called "white glove" operations are often used to prevent contamination after careful cleaning. Cleaned material should be joined within a few hours or wrapped with lint-free and oil-free wrapping for storage until needed. Some recleaning of material that has been in storage may be required before certain joining operations.

Between cleaning and joining operations, the parts may be exposed to the open atmosphere. During such exposure, dust and fine dirt particles may settle out on the joint surfaces and adjacent areas. The "fallout" dirt also can contaminate titanium joints. In many instances, these dust particles are removed by carefully wiping the joint area with lint-free cloths dampened with a solvent such as methyl ethyl ketone.

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

Evaluating Cleanliness. The effectiveness of cleaning methods is evaluated by various methods. The most unpopular method is discovering porosity, cracks, or other evidence of contamination in a completed weldment.

A common method for evaluating the cleanliness of a part emerging from descaling and pickling operations is to observe water breaks during the water rinse. No water break indicates a clean surface while the presence of a water break indicates some foreign material remaining on the surface.

Limited contact-resistance measurements have been made to compare the effectiveness of several cleaning methods prior to resistance-spot welding Ti-3Al-13V-11Cr alloy in the solution-treated condition (Ref. 19). Average contact-resistance values obtained for three cleaning methods were as follows:

Belt sanding	111 microhms
2.5% HF, 30% HNO ₃ , bal H ₂ O (2.5 minutes)	158 microhms
Proprietary solvent (5 minutes)	160 microhms

Measurements of contact resistance can provide useful information on the effectiveness and consistency of cleaning operations.

SHIELDING

Protection of titanium from contamination during joining operations can be accomplished in several ways.

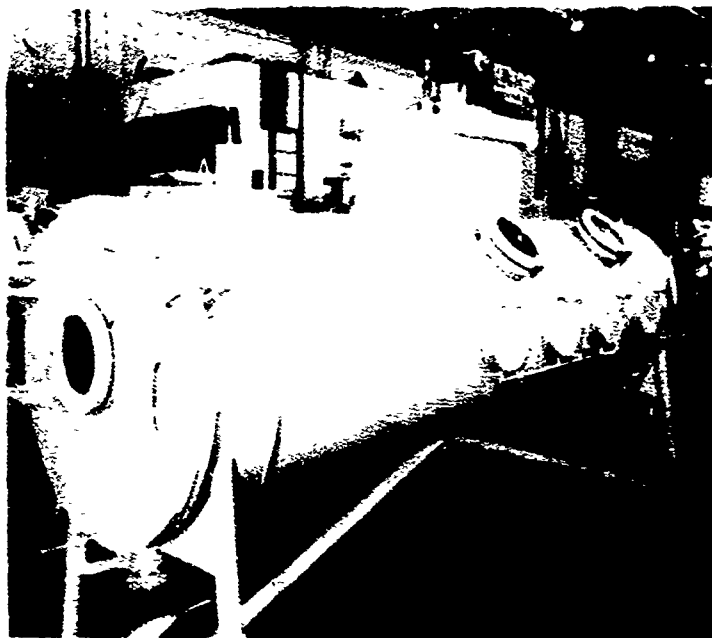
- (1) Perform the operation inside an inert-gas-filled chamber
- (2) Perform the operation with flowing inert gases through the welding torch, back-ups, fixtures, and auxiliary tooling
- (3) Perform the operation in a good vacuum in a closed chamber.

A wide variety of tooling has been designed to contain and/or supply inert gases for shielding titanium welds. Although these shielding devices vary in constructional detail, they all serve the same basic purpose, i. e., protecting the weldment from gases that can contaminate the hot metal.

Several types of shielding and controlled-atmosphere chambers have been used to weld titanium and other reactive metals. Such chambers are designed to contain the entire component to be welded, or in some cases, merely the weld-joint area. The air in the chamber is replaced with inert gas by (1) evacuation and backfilling, (2) flow

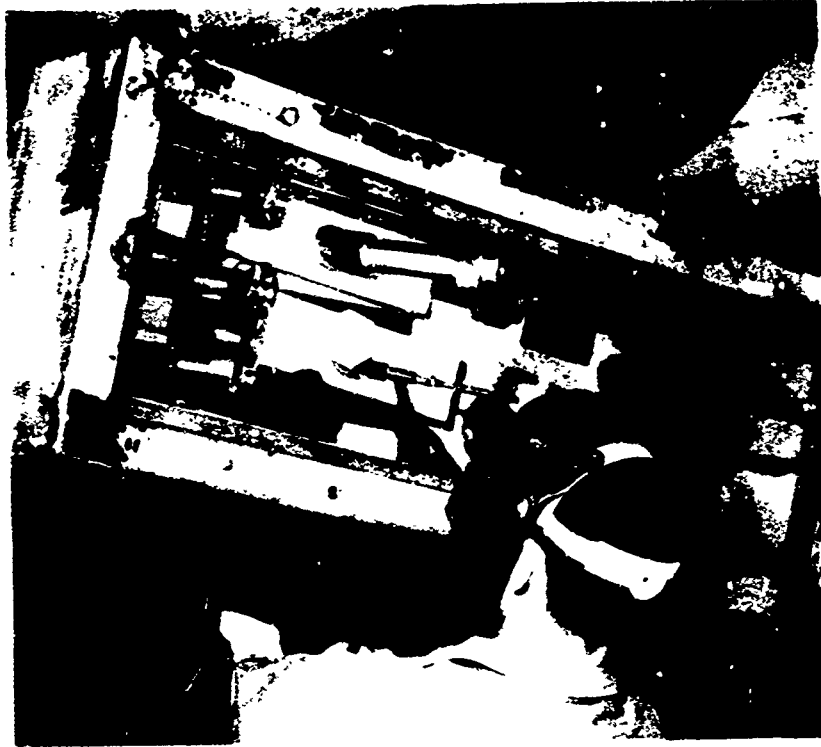
purging, or (3) collapsing the chamber and refilling it with inert gas. Welding chambers are particularly useful in the welding of complex components that would be difficult to fixture and protect properly in the air. Use of a welding chamber, however, is not a cure-all. The inert gas in many welding chambers is of much poorer quality than the inert gas contained in the conventional flowing shields. Leakage of air or water vapor into a chamber atmosphere must be avoided to do a good job in welding titanium. Monitor devices that will disclose contamination of a chamber atmosphere are available.

A tank-type controlled-atmosphere welding chamber for manual and machine, TIG and MIG welding of titanium alloys is shown in Figure 11 (Ref. 20). Many small chambers are made from plastic domes and steel or stainless steel spheres; stainless steel is preferred because it does not rust and is easy to clean. Several small-size chambers for welding small subassemblies are shown in Figure 12 (Refs. 21, 22). The adaptation of a small-size chamber to welding an oversize part is shown in Figure 13 (Ref. 22); only the localized area that is heated needs to be inert-gas shielded. Flexible-plastic chambers are illustrated in Figure 14 (Ref. 23).

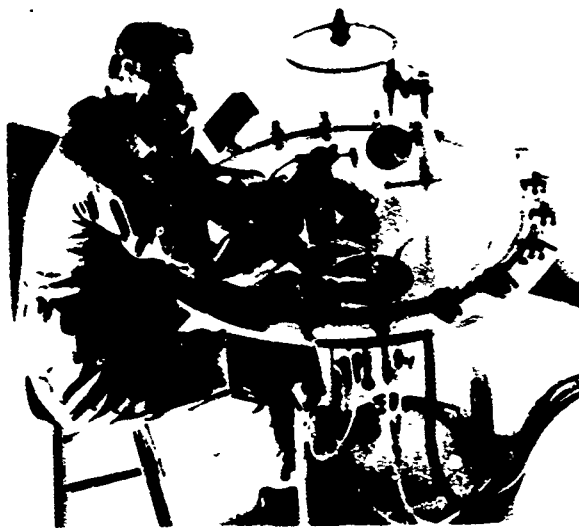


N73600

FIGURE 11. TANK-TYPE CONTROLLED-ATMOSPHERE WELDING CHAMBER FOR MANUAL OR MACHINE, TIG OR MIG WELDING TITANIUM ALLOYS AND OTHER REACTIVE METALS (REF. 20)



a. Welding of Subassemblies in a Controlled-Atmosphere-Box-Type Chamber (Ref. 21)



b. Close-Up of Transparent-Plastic-Dome-Type Welding Chamber (Ref. 22)

FIGURE 12. CONTROLLED-ATMOSPHERE CHAMBERS FOR TIG WELDING SMALL SUBASSEMBLIES

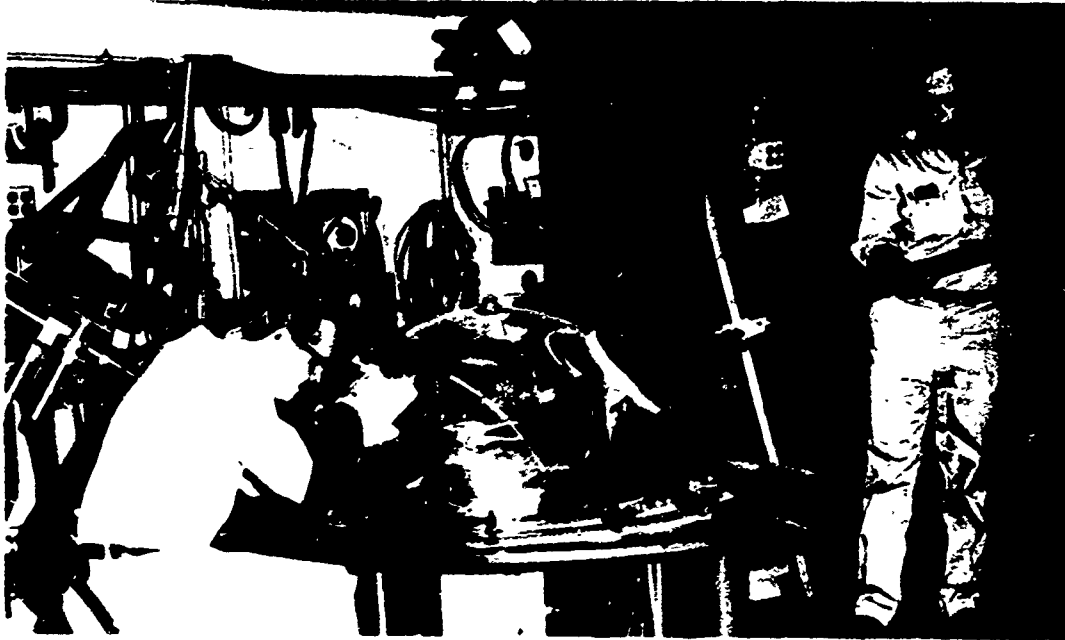


FIGURE 13. ADAPTATION OF A SMALL SIZE CHAMBER FOR TIG WELDING AN OVERSIZE PART (REF. 22)

The welding chamber has two pairs of glove ports. In this operation, one glove port is used for insertion of a titanium part too large to fit inside the chamber.



FIGURE 14. FLEXIBLE-PLASTIC CONTROLLED-ATMOSPHERE WELDING CHAMBER (REF. 23)

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

For in-air welding with the TIG and MIG processes, shielding is provided in several ways.

- (1) Flowing inert-gas shield through the torch to shield the molten weld pool and adjacent surfaces
- (2) Flowing inert-gas shield through a trailing shield to protect the weldment as it cools (usually to below 1200 F)
- (3) Flowing inert-gas shield through hold-down and back-up bars. Shielding gases flowing through the hold-down bars provides additional shielding for the face side of the weld. The back-up gas flow protects the root side of the weld during welding and during cooling of the weld metal.

A variety of inert-gas-shielding devices have been developed for in-air welding of titanium alloys. However, all are designed primarily for blanketing the hot titanium metal from the surrounding air atmosphere. Figure 15a illustrates shielding methods for aluminum and stainless steels, as compared with the hold-down and back-up shielding parts used with titanium alloys, Figure 15b.

Examples of torch-trailing-shield arrangements for TIG and MIG welding are shown in Figures 16a and 16b (Ref. 6), respectively. The trailing shield shown in Figure 16b is detachable as shown in Figure 17 (Ref. 5). The detachable-trailing-shield concept provides for interchangeable trailing-shield units for use with other joint designs or degrees of accessibility.

Phenolic-plastic nozzles in TIG-welding electrode holders have been blamed for carbon pickup (Ref. 10). This effect can be overcome by replacing the phenolic nozzles with ceramic or metal nozzles. As titanium needs good shielding, the torch nozzle should be larger than for other metals. A torch nozzle can be modified as shown in Figure 18 (Ref. 8). The copper shavings act as a diffuser so the inert gas will flow down over the weld in a soft cloud. For manual welding, this device generally gives better results than a trailing shield and it is easier to manipulate. Porous-metal diffusers are often used in the

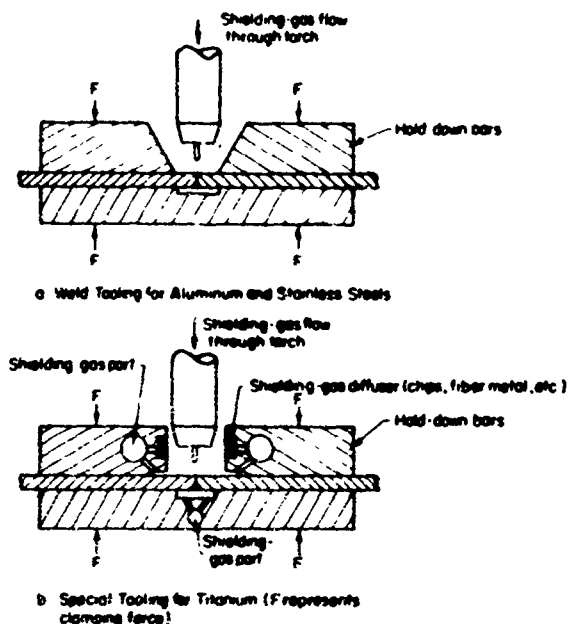
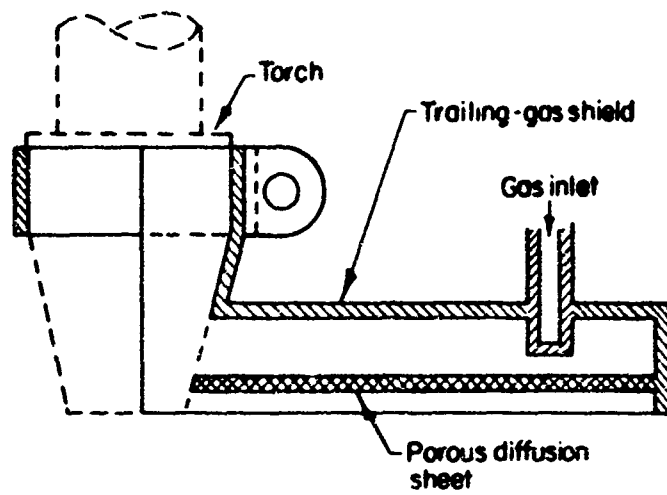
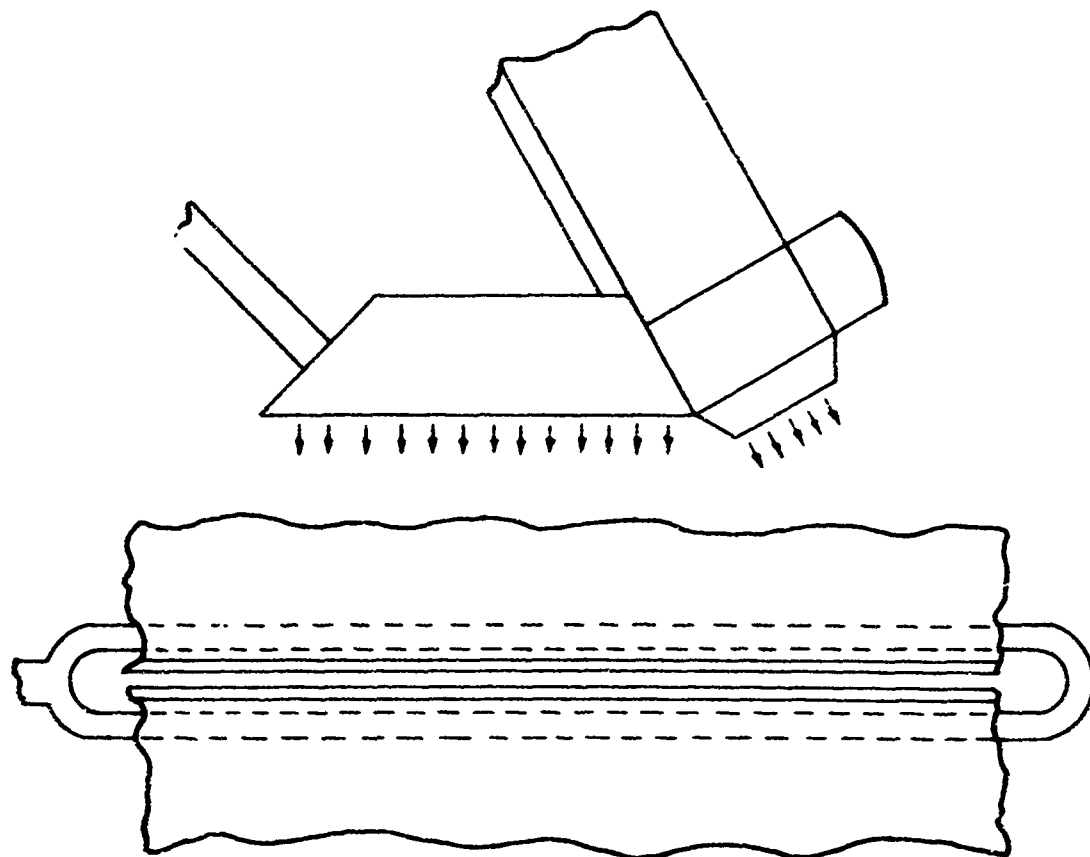


FIGURE 15. INERT-GAS-SHIELDING ARRANGEMENTS FOR CONVENTIONAL MATERIALS COMPARED WITH TITANIUM ALLOYS

trailing shields to help obtain better coverage of the hot metal by inert gas at lower flow rates. For machine MIG welding, a flat metal baffle as shown in Figure 19 (Ref. 8), attached to the leading side of the torch is advisable; otherwise, small metal globules (spatter) would leave the protective gas atmosphere, become oxidized, and drop down on the joint line where they would be drawn into the weld and cause weld contamination and porosity. Studies of the effects of air currents and blasts were made for a typical TIG-welding arrangement (Ref. 24). As was expected, inert gases flowing from 1/2- and 5/8-inch nozzles in still air gave satisfactory coverage, but in some instances proved excessive and wasteful. When cross currents of 40 to 300 fpm were introduced, the picture changed drastically. Air currents greater than 60 fpm had detrimental effects on titanium welds, greater than 180 fpm was harmful to aluminum welds, and at 330 fpm stainless steel welds were harmed if the nozzle was not kept as close to the work as possible. Side shielding also can be provided through the hold-down bars shown in Figure 15b or by means of baffles as shown in Figures 20 (Ref. 21) and 21 (Ref. 8). The baffles help to retain the inert-gas shield in desired areas and help prevent stray drafts from disturbing and deflecting the shield-gas-flow pattern.



a. Tig-Welding Torch-Trailing-Shield Combination



b. Mig-Welding Torch-Trailing-Shield Arrangement

FIGURE 16. TORCH-TRAILING SHIELD ARRANGEMENTS

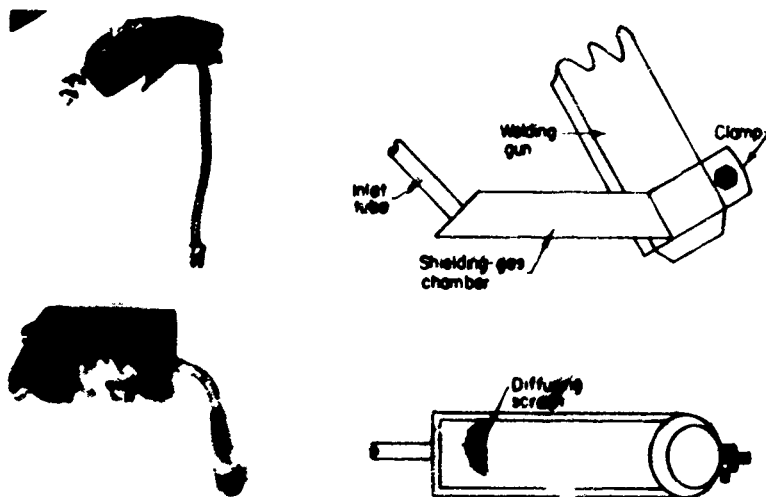


FIGURE 17. DETACHABLE TORCH-TRAILING-SHIELD ASSEMBLY (REF. 5)

Top left - wide shield for wide joint opening and capping passes; bottom left - narrow shield for root passes and narrow joint openings.

Similar concepts are used to protect the nonaccess (root) side of a weld joint. Figures 22, 23, and 24 (Refs. 21, 5, 6, 8) illustrate several methods of preventing root contamination.

Advantage also is taken of the fact that argon tends to settle and displace air. Conversely, helium is best suited for displacing air when a rising gas flow is desirable. For in-air welding, trailing shields designed for MIG welding are usually considerably longer than those used in TIG welding. This is to insure good protection for the larger volumes of material that are heated during MIG welding and as a result cool more slowly.

Inert-gas-shielding considerations also are important in designing joints for welding. Figure 25 (Ref. 21) shows the original design of a coil cross section with welded spacers or supports. Adequate external shielding would be extremely difficult if not impossible to achieve due to the gap at the root of the fillet weld out away from the contact point of the spacer. Furthermore, if the ends of the spacer bars were machined to fit the curvature of the pipe air could be trapped and embrittle the root side of the fillet weld. Figures 26 and 27 (Ref. 21) show the design modifications to eliminate welding required in the original design and a completed assembly, respectively. The change was to a mechanical support.

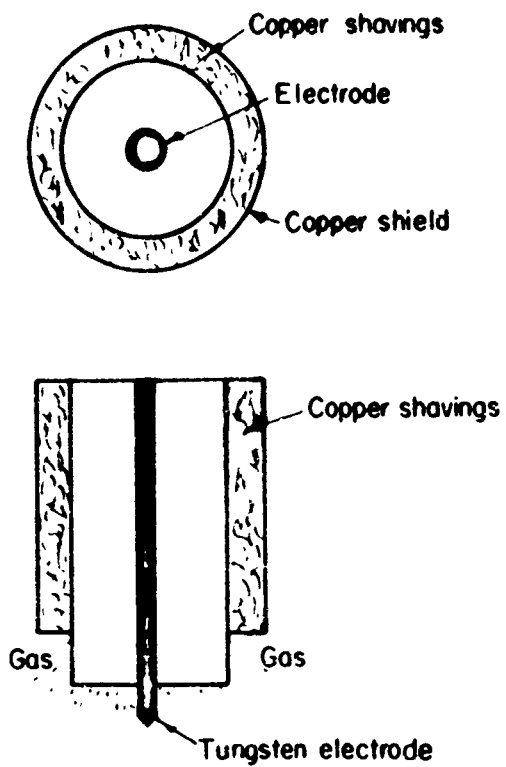


FIGURE 18. MODIFIED MANUAL TIG WELDING TORCH-SHIELDING NOZZLE (REF. 8)

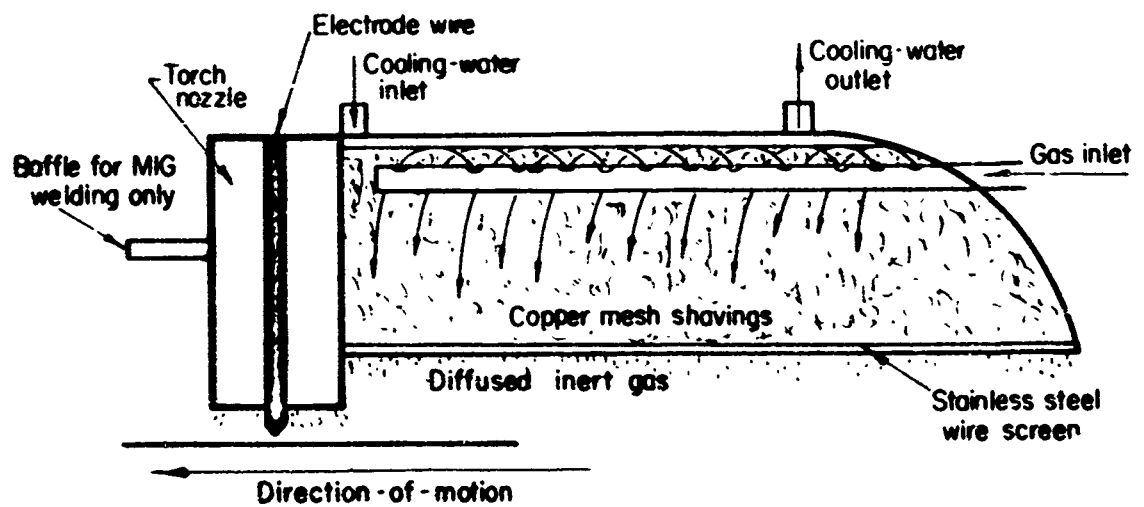


FIGURE 19. TIG-MIG TORCH-TRAILING-SHIELD ASSEMBLY WITH LEADING SHIELD BAFFLE FOR WELDING TITANIUM ALLOYS (REF. 8)



a. External Shielding Baffle for
Butt Welding Pipe Close to Bends



b. External Shielding Device, Except Sliding
Cover, Used in Making Straight Butt Welds

FIGURE 20. EXTERNAL SHIELDING BAFFLES USED TO PROTECT BUTT WELDS IN TITANIUM TUBING AND PIPE (REF. 21)

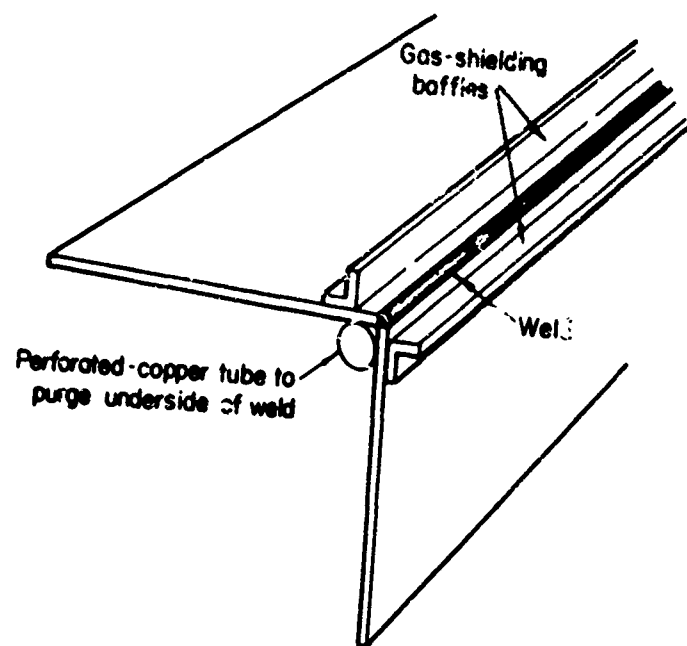


FIGURE 21. SHIELDING BAFFLES FOR AN OUTSIDE-CORNER WELD (REF. 8)

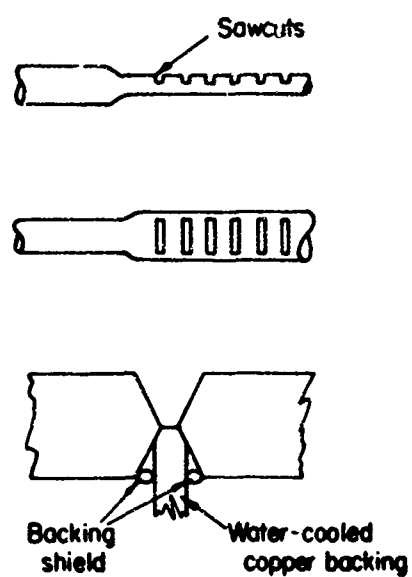
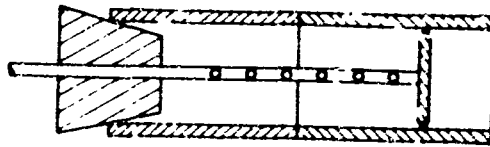
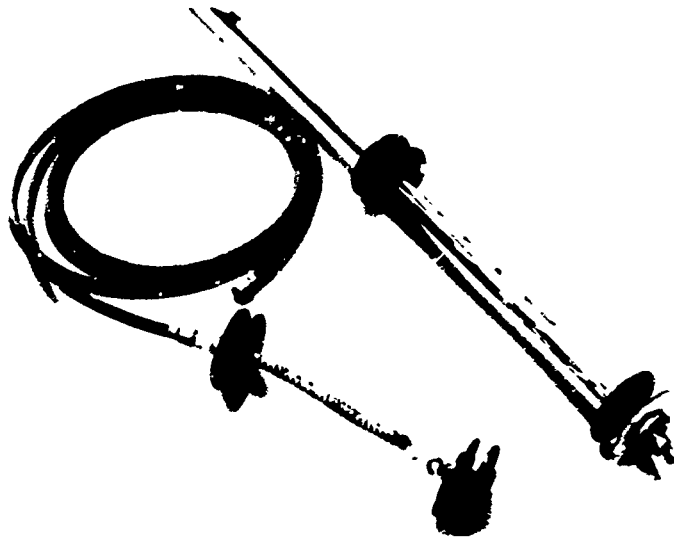


FIGURE 22. BACKING SHIELD (REFS. 5,6)

At right is complete backing-shield device for Army first-pass crack-susceptibility test plates and for H-plate cross bars.

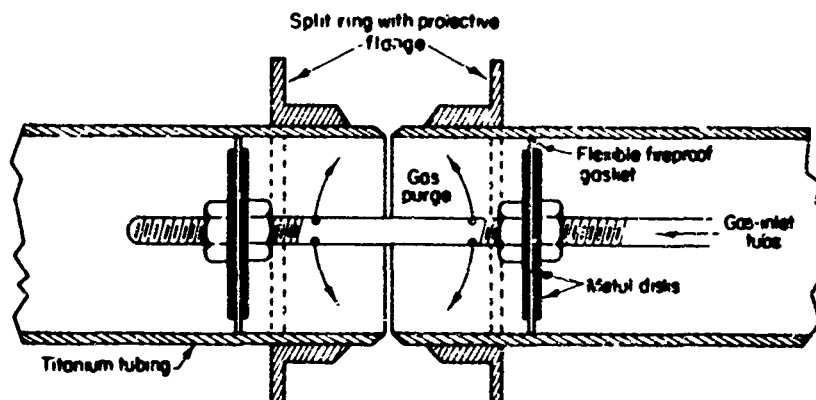


a Root Shielding of Tubing Joint



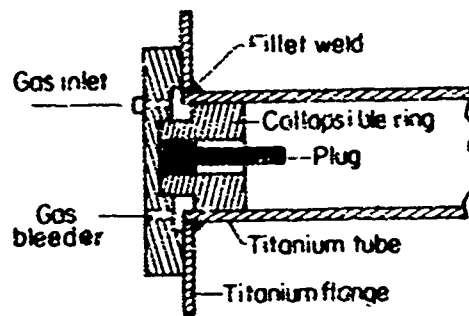
b. Two Internal Purging Devices (Ref. 21)

Top fixture is for straight runs; lower fixture is designed for use around bend and curves.

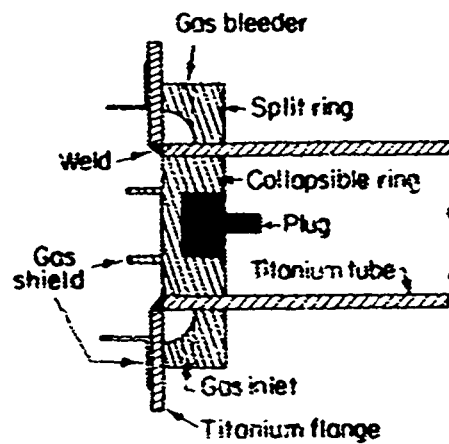


c. Internal and External Shielding Devices (Ref. 8)

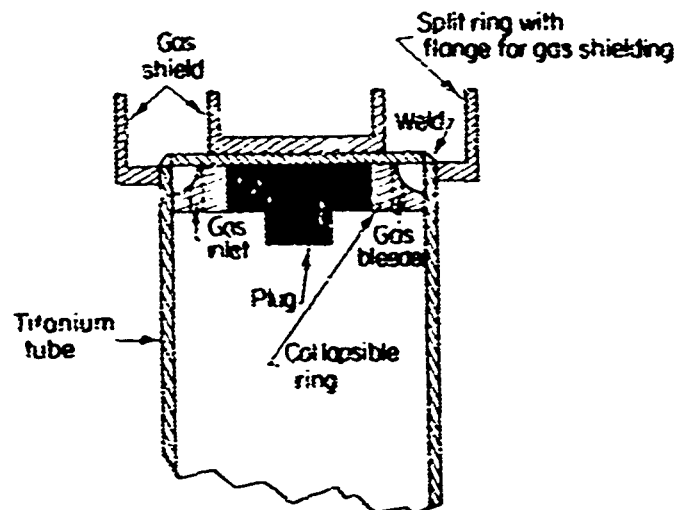
FIGURE 23. SHIELDING DEVICES FOR PROTECTING ROOT SIDES OF BUTT WELDS IN TUBING, PIPE, AND CYLINDERS



a. Fixture for Fillet Welding Flange to Tubing



b. Fixture for Flush Welding Flange to Tubing



c. Fixture for Blank-End Welding

FIGURE 24. SHIELDING ARRANGEMENTS FOR PROTECTING THE ROOT SIDES OF FLANGE-TO-TUBING WELDS (REF. 8)

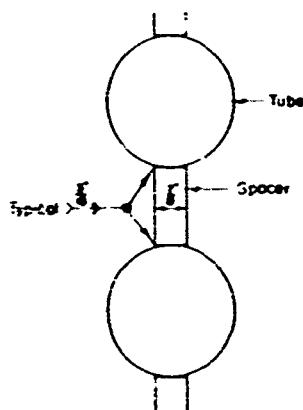


FIGURE 25. CROSS-SECTION OF ORIGINAL COIL DESIGNED FOR WELDED SPACERS AND SUPPORTS (REF. 21)

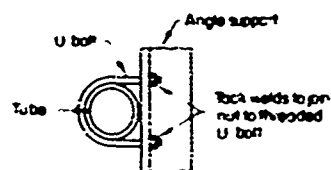


FIGURE 26. TACK-WELDED MECHANICAL FASTENERS FOR THE COIL SPACERS SHOWN IN FIGURE 25 (REF. 21)

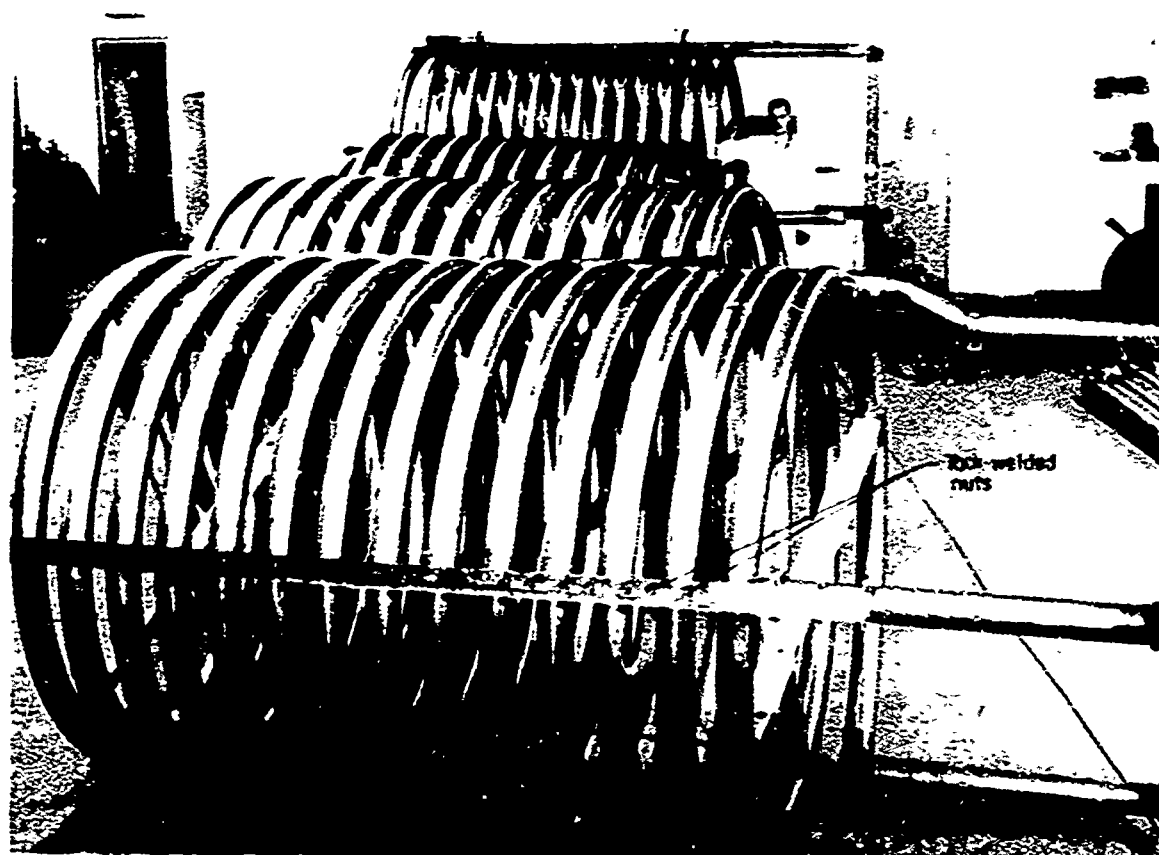


FIGURE 27. COILS IN VARIOUS STAGES OF COMPLETION SHOWING MECHANICAL SUPPORTS AND TACK-WELDED NUTS (REF. 21)

TOOLING

The tooling used in joining titanium may differ markedly from tooling normally used in joining other materials. Contamination, porosity, distortion, and penetration can be affected by tooling; special techniques have been developed to help minimize or eliminate these effects. Tooling per se may range from simple clamps to hold parts in position to more elaborate holding devices designed for specific parts. Simple tooling is adequate for welding titanium when other means are used to insure adequate shielding, for example, electron-beam or arc welding in an enclosed chamber. However, for fusion-welding operations conducted outside of chambers, tooling can provide a much more effective safeguard against weld contamination than other shielding devices. Tooling often is used to cool the weld area rapidly so that exposure in the temperature range of high chemical reactivity is minimized. Such tooling is referred to as "chill" type.

Welding and stress-relief fixtures must never come in contact with trichloroethylene for degreasing purposes, because of the stress-corrosion problem. Rigid tools are a necessity. For example, the Ti-5Al-2.5Sn alloy has a yield strength of 110 ksi at room temperature, and every weld is going to develop that amount of pull in at least one and perhaps several directions. A weak tool will be pulled out of shape allowing the weldment, in turn, to distort.

Materials that come in contact with titanium on both root and face sides of welds include copper, aluminum, stainless steel, carbon steel, and other common materials. Often, these materials are used in the form of bar-type inserts or sheet- or plate-type facing plates for fixtures. Top-side hold-down bars extend the full length of the weld and often contain inert-gas passages for weld face and root shielding.

Considerable trouble with welding operations is inevitable unless weld-joint preparations are accurately machined, and the joints are held properly in the welding fixtures.

The tooling used in resistance welding titanium is generally similar to tooling used in resistance welding other materials. Resistance-welding tooling consists of suitable fixtures or jigs to hold the parts in proper position for welding. 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 in designing tooling for use with titanium. Generally, this means that nonmetallic

or nonmagnetic components should be used exclusively, and the tooling should not contaminate the titanium.

HEAT INPUT

The term "heat input" is widely used in the welding industry to characterize many of the conditions typical of arc welding. Limiting heat inputs are defined by:

- (1) The minimum energy required to melt sufficient metal to form a weld
- (2) The maximum usable energy level that will produce an acceptable weld
- (3) A maximum level that will not degrade properties of a particular material.

With titanium, it is best to use heat inputs just above the minimum required to form the weld. Greater heat inputs expose the titanium welds to conditions that promote contamination distortion and other bad effects. An exact measure of heat input is not readily made, but good empirical formulae are known for each welding process. Intra-process comparisons of heat inputs are not always valid and should be viewed with caution.

Lowest heat inputs are obtained with electron-beam welding. Then, as a general rule, heat inputs typical of normal welding conditions increase as follows:

- (1) Single-pass TIG - no filler
- (2) Single-pass TIG - with filler
- (3) Multipass TIG - with filler
- (4) Single-pass MIG
- (5) Multipass MIG.

Other general trends useful in estimating heat input are:

- (1) Welds made with helium shielding gas have a lower heat input than similar welds made with argon shielding.
- (2) Higher welding speeds result in lower heat inputs.
- (3) High currents or voltages result in high heat inputs (at any given speed).
- (4) Small melted zones are characteristic of low heat inputs.

SHRINKAGE - DISTORTION

Fusion-weld processes are characterized by thermal cycles that cause localized shrinkage. This shrinkage often causes distortion of the parts being joined. Figure 28 illustrates the changes in shape that occur as the result of welding just a simple butt joint. More complex weldments obviously involve much more complex shrinkage and distortion patterns.

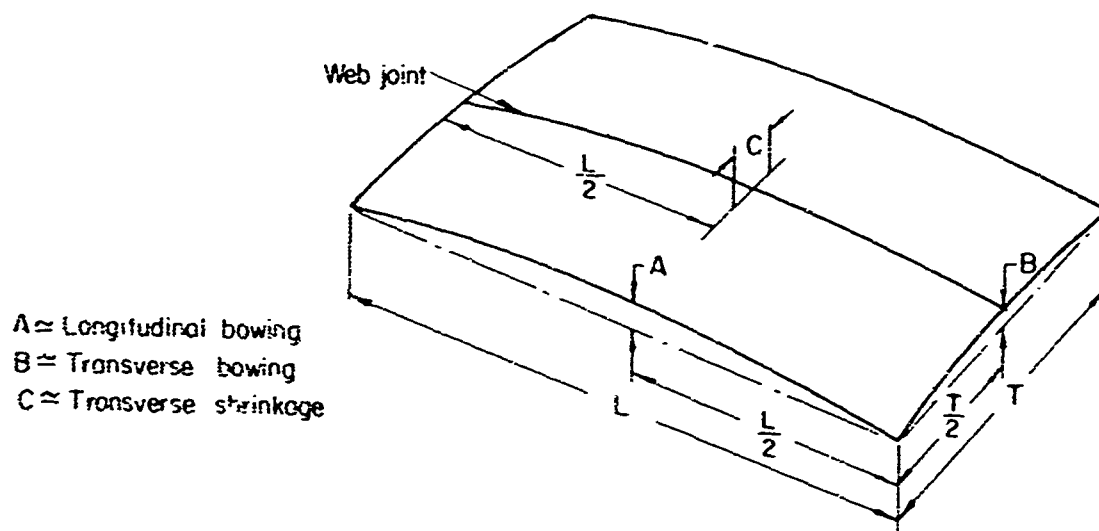


FIGURE 28. TYPES OF WELD-JOINT DISTORTION

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

Weld shrinkage must be planned for, since there is no absolute way to avoid it. Thus, a knowledge of expected shrinkage values for typical weld configurations is needed before production welding applications. Also, a logical sequence of welding components involving several welds must be established with shrinkage in mind. With the proper welding sequence, shrinkage can be turned to good use to minimize distortion. This is accomplished by properly balancing the various shrinkage forces developed.

Shrinkage also can be controlled to some extent by the restraint imposed by tooling. Use of this technique is sometimes helpful in preventing serious part distortion. (Caution: Freedom from

distortion does not mean that a weldment is not highly stressed! Quite often the converse is true.)

Shrinkage and distortion are minimized by using low heat inputs. Thus, the listing given earlier also is valid for showing the relative tendencies of fusion-welding processes to produce these changes. Unnecessary weld reinforcement also is undesirable from the standpoint of keeping shrinkage and distortion as low as possible.

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

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

RESIDUAL STRESS

Shrinkage inevitably leaves residual stresses in fusion weldments. Residual stresses are defined as those which exist in a body without any external force acting. The residual stresses in a welded joint are caused by the contraction of the weld metal and the plastic deformation produced in the base metal near the weld during welding. Residual stresses in a welded joint are classified into: (1) "residual welding stress", which occurs in a joint free from any external constraint and (2) "reaction stress" or "locked-in stress", which are induced by an external constraint.

Residual stresses generally are not a problem in brazed or solid-state-welded joints.

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

A typical distribution of residual stresses in a butt weld is shown in Figure 29. The stress components concerned are those parallel to the weld direction, designated σ_x and those transverse to the weld, designated σ_y . The distribution of the σ_x residual stress along a line transverse to the weld, YY, is shown in the Figure 29b. Tensile stresses of high magnitude are produced in the region of the weld; these taper off rapidly and become compressive after a distance of several times the width of the weld, then gradually approach zero as the distance from the weld increases.

The maximum residual stress in the weld is determined by:

- (1) Expansion and contraction characteristics of the base metal and the weld metal during the welding thermal cycle
- (2) Temperature versus yield strength relationships of the base metal and the weld metal.

Much research in mild-steel weldments has shown that the maximum stress is as high as the yield stress of the weld metal. However, in a recent investigation (Ref. 25), the maximum stresses in weldments made with heat-treated SAE 4340 steel were around 50,000 to 80,000 psi, considerably less than the yield strengths of the weld metal (around 150,000 psi) and the base metal (224,000 psi). In limited investigation on titanium-alloy weldments, maximum residual stresses ranging from 35,000 to 85,000 psi have been observed, depending upon the type of base metal and welding processes (Refs. 26-28). However, the effects of base metal and weld metal properties and welding processes on the magnitude of residual stresses on titanium-alloy weldments have not been established.

Out-of-flat base plate also can contribute to restraint problems in welding (Ref. 5). As-received materials that are wavy and out of flat lead to a condition of misalignment when placed in the welding fixture. Where this condition creates fabrication difficulties it is necessary to flatten the plates. This working when added to the already high level of restraint can increase susceptibility to cracking, or cracking can occur during the flattening operation.

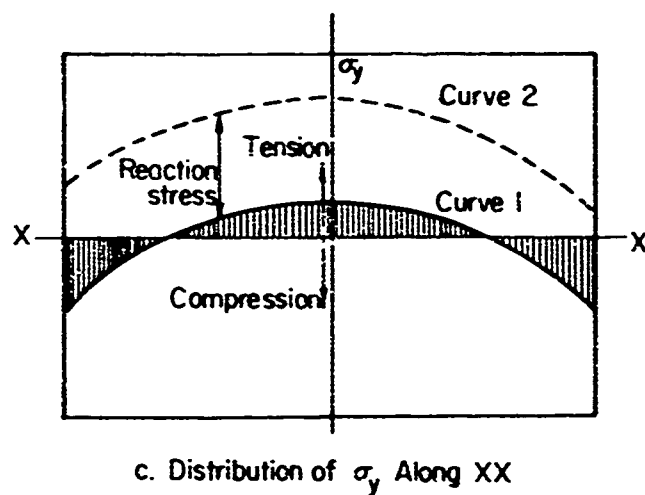
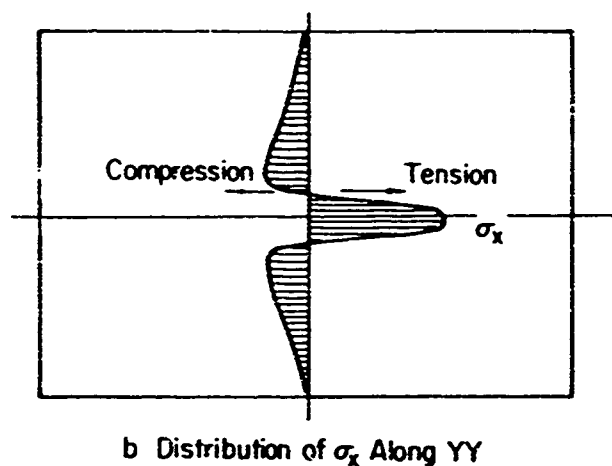
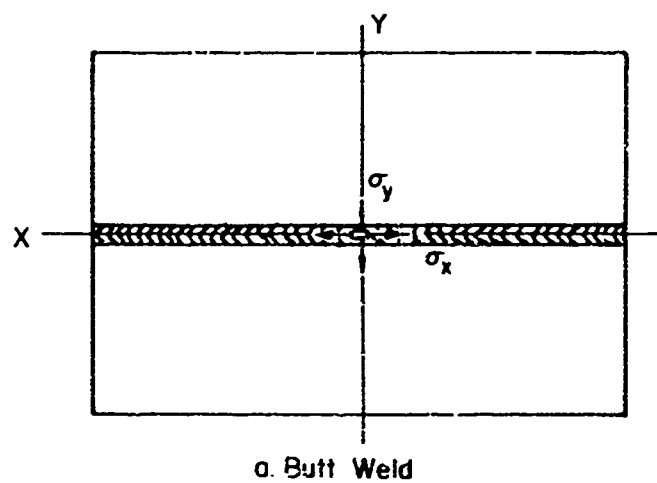


FIGURE 29. DISTRIBUTION OF RESIDUAL STRESSES IN A BUTT WELD

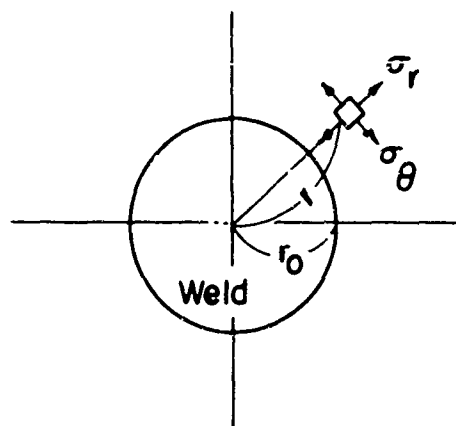
The residual stress distribution in a spot-welded joint is very dependent on the joint pattern or weld pattern used. The simplest case to consider is the residual stress due to a single spot weld. Figure 30 is a schematic representation of the distribution of residual stresses in the area near a single spot weld. The components of stress of most concern are those in the radial direction and those in the circumferential direction. The relation between the distance from the weld center and the radial-residual stress is shown by Curve 1 in the figure. Tensile stresses as high as the yield strength of the material may exist in the weld zone. Outside the actual weld zone the tensile residual stress decreases as the distance from the weld area is increased. Curve 2 shows the distribution of the circumferential stress. Again, very high tensile stresses exist within the weld zone; however, outside the weld these stresses are compressive and again fall off as the distance from the weld is increased. From Curve 2 it is apparent that there is an extremely sharp stress gradient around the circumference of any spot weld where the stresses undergo a complete reversal from very high tensile values to high compressive values.

The actual stress distributions in a spot weld in an area very close to the weld are not nearly as simple as shown in Figure 30. Very concentrated stresses often exist in the heat-affected zone close to the original interface of the sheets.

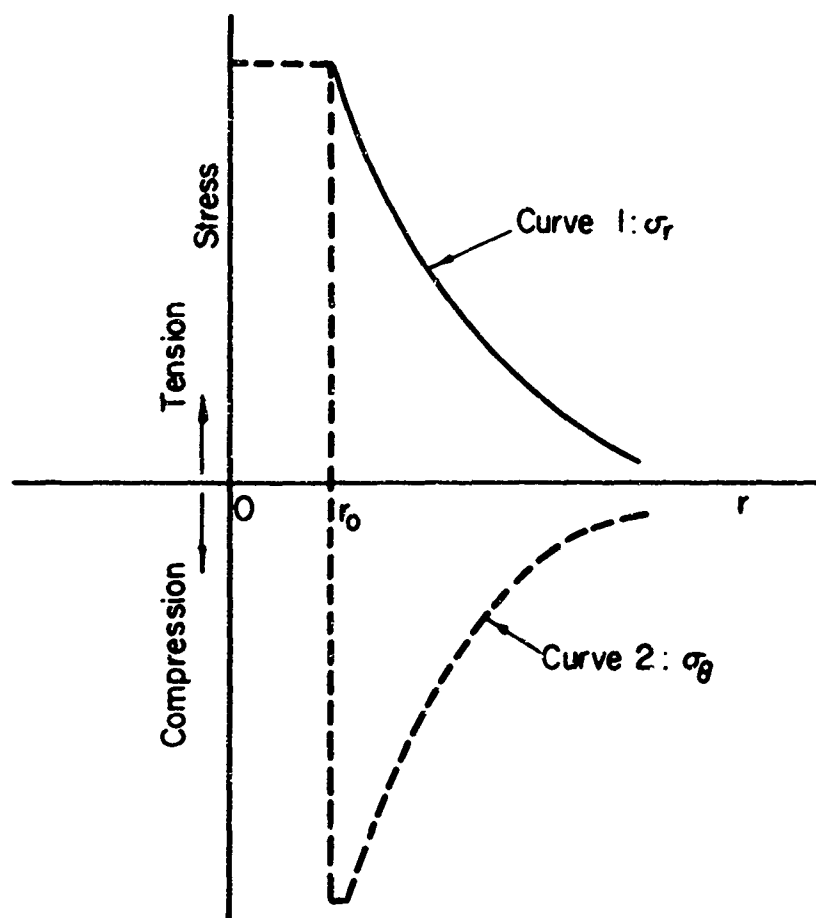
When several spot welds are considered instead of just a single spot, the resulting residual stress patterns are even more complex. An approximate distribution of the residual stress pattern produced by a series of spot welds can be obtained by the superposition of the residual stress distributions produced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

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

Stress Effects. For many years there was a trend among engineers to discount the effect of residual stress, since it had been proven that the effect of residual stress is almost negligible when a welded structure fails in a ductile manner. During the last several



a. Stress Components



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

FIGURE 30. DISTRIBUTION OF RESIDUAL STRESSES AROUND SPOT WELD

years much information has been obtained on the effect of residual stress on brittle fracture in steel weldments. It has been found that residual stresses decrease the fracture strength of weldments only when certain conditions are satisfied, but that the loss of strength can be drastic when these conditions are satisfied. No systematic investigation has been made on the effects of residual stresses on fractures in titanium-alloy weldments. The following discussions are based on information on steel weldments and the limited data on titanium-alloy weldments.

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

- (1) Ductile fracture. Ductile fracture occurs at high stresses after general yielding. The effect of residual stress on fracture strength is negligible.
- (2) Brittle fracture. When a notch is located in areas where high residual tensile stresses exist, brittle fracture can initiate from the notch at a low applied stress and then propagate through the weldment. Extensive research has been conducted during the last several years on the low-stress brittle fracture of steel weldments. No systematic investigations have been made on the low-stress brittle fracture of titanium-alloy weldments. Some failures have been observed which indicate that residual stresses may have caused premature failures in titanium-alloy weldments.
- (3) Stress-corrosion cracking and hydrogen-induced cracking. Stress corrosion of titanium or titanium alloys can cause cracking or degradation of properties under some combinations of time, temperature, stress, and environment. Stress-corrosion cracking and hydrogen-induced cracking can occur under low, applied stresses, even under no applied stress. Residual welding tensile stresses promote the cracking, while residual compressive stresses suppress the cracking.
- (4) Fatigue fracture. The effect of residual stress on fatigue fracture is still a controversial subject. Many investigators have reported fatigue-test results which they claim were affected by residual stresses. However, others believe that the effect of residual stress on fatigue is not significant.

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

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

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

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

Thermal stress-relieving treatments are commonly employed for many materials, including a number of titanium alloys. These treatments can be combined quite effectively with hot-sizing operations to control both the existing residual stresses and to produce parts to close dimensional tolerances. Thermal stress-relieving treatments produce much more uniform changes in the residual stress patterns than do mechanical stress-relieving treatments. For most titanium alloys, a treatment between 1000 and 1450 F for a period of time ranging from one-half to several hours is required for stress relieving. Possible interactions between a thermal stress-relieving treatment and other changes in a material that may affect its properties must be anticipated. For example, age hardening will occur in the 6Al-4V titanium alloy within the weld zone over a certain temperature range. If this age hardening is allowed to occur, it may reduce the

beneficial effects of stress relieving. A similar effect is noted with the Ti-13V-11Cr-3Al alloy, although for different reasons. With this alloy exposure to the normal stress-relieving temperature range will result in a drastic loss of bend ductility in the weld zone; thus, it is necessary to find other methods of relieving the residual stresses. This has been done by combining mechanical and thermal treatments to alter the residual stress patterns in the circumferential joints of rocket motor cases (Ref. 1).

Residual stresses in resistance welds can be altered and to some extent eliminated by either mechanical or thermal stress-relieving treatments. The application of mechanical stress-relieving methods to spot welds is difficult because of the complexity of the residual stress patterns and the limitations generally imposed by joint configurations. At best, mechanical techniques can probably only result in a redistribution of the residual stress pattern and not the complete elimination of residual stress. On the other hand, thermal stress relieving can be used effectively to eliminate all residual stresses resulting from resistance welding. It is difficult to see how such treatments can be employed effectively though, unless the treatments are conducted in vacuum furnaces. The major problem with methods of thermal stress relief is that it would be almost impossible to prevent some contamination of the surfaces of titanium components in the overlap area characteristic of resistance-welded structures. Cleaning after such a thermal stress-relief treatment would impose equally severe problems.

Perhaps the most fruitful method of controlling residual stresses in resistance-welded joints will be by the selection of suitable process parameters.

INSPECTION

Most joined components are inspected for two reasons. First, it is often desirable or necessary 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. Second, various inspection procedures 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. Unfortunately, no suitable nondestructive inspection technique exists for detecting weld contamination of titanium weldments.

Use is being made of indications based on surface discoloration during welding. However, the presence or absence of a discolored surface is not a reliable method of detecting contamination of titanium welds with interstitial elements. Surface discoloration, when obtained in welding titanium, is extremely important. Surface colors indicate that the welding atmosphere was contaminated. On the other hand a clean-weld and heat-affected-zone area does not necessarily indicate clean welds. Titanium is so reactive that contaminants can penetrate to below the surface without discoloring the surface.

The ease with which inspection can be accomplished varies with different joint geometries. Butt joints, T-joints, and corner joints are generally much easier to inspect than joints involving overlapping layers of material.

Inspection of resistance welds to insure adequate quality is difficult. X-ray techniques appear to be the only suitable nondestructive inspection method. Even this method is subject to limitations in its usefulness. Because of the difficulties associated with inspecting resistance welds, the economic necessity of not allowing a large number of defective welds to get through processing, and the difficulty of repairing defective resistance welds considerable emphasis is being placed on supplementing or supplanting postweld inspection procedures with in-process controls.

SPECIFICATIONS

Most of the materials and processes used in titanium joining are covered by some type of specification. The basic specifications are generally MIL standards (Refs. 29, 30) or other applicable Federal Government specifications. However, the most pertinent and important facets of titanium-joining technology are often not covered by these specifications. Therefore, most titanium fabricators have developed company specifications, which are used in lieu of, or in the absence of suitable Federal specifications (Refs. 31-33). These company specifications are almost always more restrictive and definitive than any comparable Government-type specification. This is probably because the company specifications are generally written with a more limited coverage in mind than is the case with many Government specifications.

The available company specifications are not entirely adequate to control the fabrication of all titanium products. However, existing

specifications form a firm foundation for the preparation of suitable specifications for new applications.

The lack of an adequate inspection method for determining weld contamination makes it necessary to place a high degree of reliance on process specifications for fusion-welding processes. Such specifications should spell out in some detail the requirements for preweld cleaning, and operations to prevent contamination.

Almost all resistance-welding specifications require certification of the welding machine that will be used and establishment of a suitable welding schedule prior to the actual start of welding operations. Most specifications then require that various types of test coupons be welded prior to, during, and after any production welding run. Such procedures, while not foolproof, are the best available for use with existing types of equipment and process control.

Applicable military specifications (Ref. 29) allow the welding of any titanium alloy that has satisfactorily passed tests designed to establish that resistance welding does not harden the weld zone or reduce weld ductility. The requirements state that the direct tension strength of a spot weld must not be less than 25 per cent of the minimum shear strength required when tested in an as-welded condition. It is also required that any spot welds subjected to subsequent thermal exposure shall exhibit a similar minimum tension strength after such thermal exposure.

DEFECTS

The definition of joint defects is arbitrary. Although many years of experience have been gained with welding codes and specifications that either prohibit or allow certain features characterized as defects, very little of this experience is based on statistically sound engineering data. As a result, features recognized as defects are generally limited in accordance with very 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.

Typical arc-weld features that are sometimes classified as defects are shown in Figure 31.

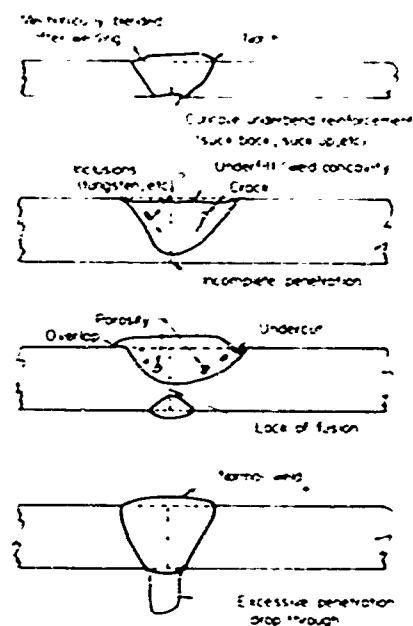


FIGURE 31. FUSION-WELD DEFECTS

Not shown: (1) Arc strike,
(2) Discoloration, and
(3) Contamination.

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, few welding codes or specifications allow 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.

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 which are obviously undesirable, the remaining external defects are 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 preparation, 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.

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

With the knowledge currently available about the performance of titanium-fusion weldments, a conservative engineering approach to defects should be followed. Because of the prevalence of porosity in titanium-fusion weldments, it would be desirable to determine more realistically the extent to which porosity can be allowed, or develop simpler means of minimizing porosity than those currently available.

Porosity. The prevalence of porosity problems in titanium welding warrants special mention. A special report on this subject is available (Ref. 34). The Summary from this report is repeated below:

"Porosity in fusion welds in titanium has been encountered to some extent in all programs using this joining method. While measures to control cleanliness and to employ good welding techniques have successfully reduced the occurrence of porosity, specific identification of the various causes of porosity is still lacking.

"Some factors suspected of causing porosity in titanium welds are:

- (1) Hydrogen. Many of the things, which when eliminated reduced porosity, are sources of hydrogen.
- (2) Cleanliness of Joint Area. Mechanical cleaning of edges to be welded and adjacent surfaces reduces porosity and improves uniformity of welds. Two factors shown to increase porosity are fingerprints and handling with dirty rags or lint-bearing gloves. Plasticizers dissolved from rubber gloves by solvents, especially alcohol, have been identified as a cause of porosity. 'Soapy' residue in cloths used for wiping cleaned joint areas also has been identified as a cause of porosity.

- (3) Contamination in Filler Wire. Surface inclusions worked into the filler wire during drawing have been identified as a major cause of porosity.
- (4) Welding Procedures and Techniques. There is evidence that some of the parameters associated with welding procedures also affect porosity. Many of these are interrelated and the offending parameters are not well identified; however, improper technique in tack welding and wide joint gaps in fusion welding have been identified as causes of porosity. Other parameters that play a part in causing porosity are rates of heat input, rates of cooling, welding speeds, arc voltages, and rates of gas flow."

Anyone encountering porosity problems should obtain this report as it contains a good summary of published information on the subject.

Unpublished data (Ref. 35) generally confirm this summary and in addition, data showing the effects of edge preparation, pickling, preheat, and welding variables on porosity formation are available.

Porosity in titanium welds can be controlled if the procedures that have been developed by the many investigations in the area are followed.

REPAIRS

Repair of weldments is not desirable. However, it is an almost inevitable occurrence in production operations. An important aspect of repair welding is determining what caused the defect which must be repaired. With titanium, this is important, not only for its feedback value to minimize the need for subsequent repairs, but also to determine a suitable repair-welding procedure.

Cracks, which occur rarely in titanium-fusion weldments, are generally the result of contamination from some external source. For example, copper from back-ups, hold-downs, and wire guide tubes may get into a weld if the equipment malfunctions during welding. In order to effect a successful repair, the material contaminating the titanium must be removed first. Fusion welds that are contaminated as a result of poor shielding may require complete removal of the first weld made and its replacement.

Whenever it is practical, the same welding fixtures and process used on the original weld should be used for the repair. When this is not possible, it is common practice to use manual TIG welding for repair operations. The same shielding precautions used in the original welding procedure should be followed for all exposed surfaces.

TIG fusion welds in thin sheet and electron-beam welds have been repaired simply by remelting the defective zone of the original weld. The same process and conditions were used for making the repairs.

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

WELDING PROCESSES

Many welding processes can be used successfully on titanium components. These processes are described in the following sections. Included are discussions of the following processes:

- (1) TIG welding
- (2) MIG welding
- (3) Arc spot welding
- (4) Electron-beam welding
- (5) Plasma-arc welding
- (6) Resistance spot welding
- (7) Roll spot welding
- (8) Seam welding
- (9) Flash welding
- (10) High-frequency welding
- (11) Brazing
- (12) Solid-state welding.

Not included are discussions of adhesive bonding, mechanical fastening, and various other specific welding processes. Adhesive bonding and mechanical fastening of titanium are being covered in other reports in this series being prepared for publication. Welding processes omitted from this report are either not suitable for use on titanium or are seldom used.

A listing of titanium alloys that are often considered for use in welded structures and a relative weldability rating for these alloys appears in Appendix B.

TIG WELDING

The TIG welding process is used extensively for joining titanium alloys and many other high-quality materials. It is particularly suited for the joining of very thin materials, and is adaptable to manual, semiautomatic, or fully automatic operation. It can be used on almost any thickness, but as the thickness increases above 0.1 inch, other fusion-welding processes offer important advantages.

In TIG welding, all of the heat required to melt the joint edges is supplied by an arc between a tungsten electrode in the welding torch and the workpiece. The arc and surrounding area are kept free of air by a flow of inert gas around the tungsten electrode. TIG welds can be made with or without filler metal additions. For many applications only the edges of the parts to be joined are melted. Sometimes additional metal is added to the weld by using a filler wire. Filler wire is always added when the joint is open or contains a specially prepared groove. The addition of filler wire to closed, square butt joints increases the tolerance of TIG welding for slight variations in the joint fitup. This can be quite important in welding titanium, since the metal is very fluid when melted.

Most TIG welding of titanium has been done in the flat welding position. Other welding positions have been used to a limited extent. When welding titanium in other positions, the changes in shielding-gas behavior should be anticipated. Welds made in the horizontal position would be expected to be slightly more prone to porosity entrapment than welds made in other positions.

Equipment. Conventional TIG welding power supplies, torches, and control systems are used effectively in welding titanium. No significant changes in welding characteristics or weld properties that can be attributed to the use of any specific type of welding equipment have been reported. Most fabricators use conventional power supplies having drooping volt-ampere characteristics. High-frequency arc starting is used to avoid tungsten inclusions that are often found with touch starting techniques. The conventional TIG welding equipment selected for use must be supplemented with auxiliary shielding devices of the types described in earlier sections of this report.

The shielding chambers used for TIG welding titanium can be of several basic designs. Inert gases replace the air in the chamber by evacuating and backfilling, by flow purging, or by collapsing the chamber and backfilling. Shielding chambers are used when welding titanium parts that cannot be protected satisfactorily in the open atmosphere. Precautions need to be taken to prevent leakage of air, water vapor, and water into the chambers.

Titanium alloys also can be welded very successfully in air with the right supplemental equipment. The inert gas flowing from a conventional TIG welding torch is generally not sufficient to protect titanium during welding. Auxiliary trailing shields attached to the welding torch, or auxiliary shielding devices built into the weld tooling afford the required protection. The importance of tooling to assist in weld shielding was discussed earlier in this report in the section "Shielding". Figure 32 shows one of the commonly used combined torch-trailing-shield arrangements. Such shields are designed to supply a uniform nonturbulent flow of inert gas over the weld as it cools behind the torch. It is much easier to insure good shielding during mechanized TIG welding than in manual operations; therefore mechanized welding operations are recommended and used wherever possible in welding titanium assemblies.

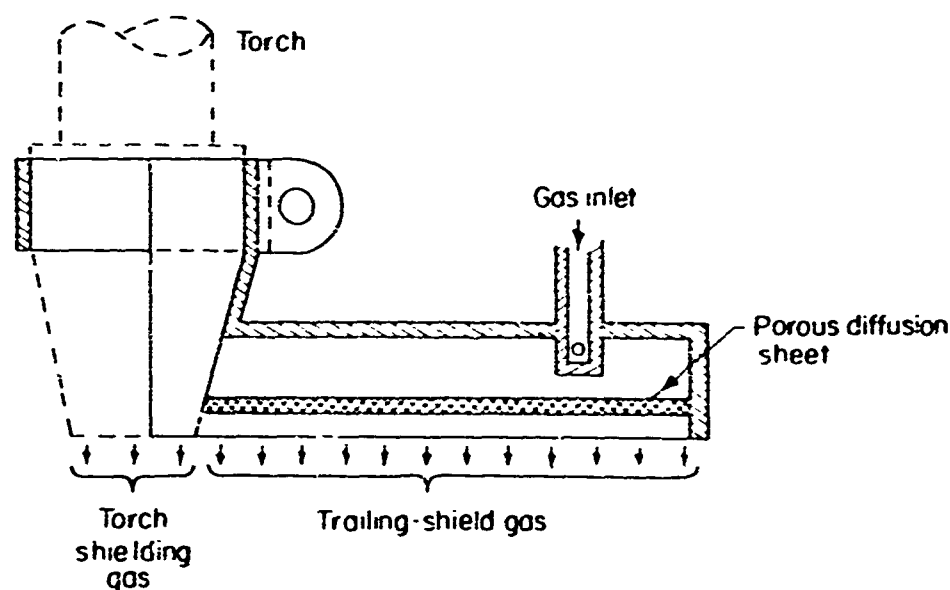


FIGURE 32. A COMBINATION TORCH-TRAILING-SHIELD ARRANGEMENT

Electrodes for TIG welding titanium and titanium alloys normally are operated on straight-polarity direct current. The electrodes are always ground either to a conical shape having a sharp point or to a rounded point. A cone height of 1.5 to 2.0 times the electrode diameter has been used by one fabricator (Ref. 36). Thoriated-tungsten electrodes are used by many fabricators (Refs. 21, 12, 36, 37). Tungsten electrodes also are used, but experience shows that weld-metal contamination by tungsten is less with the thoriated-tungsten electrodes. Tungsten inclusions are of two kinds - globular tungsten drops and tungsten oxide flakes. These inclusions are minimized by using proper welding current for the electrode size and by providing inert-gas shielding for the electrode until it cools to temperatures at which oxidation cannot occur. Chemical compositions of conventional TIG welding electrodes are given in Table III (Ref. 38). The gap between the rod and metal is critical in gages less than 0.006 inch; on 0.001-inch-thick metal a gap of 0.010 inch has been used (Ref. 39).

TABLE III. CHEMICAL COMPOSITION OF ELECTRODE MATERIALS
FOR TIG WELDING (REF. 38)

AWS-ASTM Classification	Tungsten, Minimum, per cent	Thorium, per cent	Zirconium, per cent	Total Other Elements, Maximum, per cent
EWT	99.5	--	--	0.5
EWTh-1	98.5	0.8 to 1.2	--	0.5
EWTh-2	97.5	1.7 to 2.2	--	0.5
EWZr	99.1	--	0.3 to 0.5	0.5

The equipment used to drive titanium welding wire in the TIG process should receive special attention. Filler-metal feed rates should be as uniform as possible with both manual and machine wire feeding to prevent localized irregularities that may contribute to cracking (Ref. 10). Even the best quality welding wire can be contaminated in this equipment if periodic checks are not made to be sure that oil is not present in the drive system or guide components.

Materials. Commercially pure titanium and many of its alloys can be TIG welded readily. Commercially pure titanium is the most popular filler wire, although titanium-alloy filler metals are used for some applications. Titanium and titanium-alloy filler wires

are available in continuous coils. However, cut and straightened lengths of filler wire may be used instead of continuous coils. Cut lengths are easier to clean immediately prior to welding than coiled products. In manual TIG welding, sheared strips of a base-metal sheet are sometimes used as filler wire. On rare occasions, a similar procedure is used in mechanized welding when a preplaced strip of sheet or wire is inserted in the joint to serve as a filler metal. Care is recommended when using this procedure because potential contamination problems involved.

Porosity, contamination, and embrittlement have been experienced with all of the commonly used joint designs. These problems, however, normally are eliminated by following procedures that will ensure cleanliness of the material, filler wire, and welding fixtures and protection of the parts from contamination during welding. Pre-weld cleaning is essential to the successful welding of titanium alloys.

WELDING CONDITIONS

Welding conditions are dependent on material thickness, joint design, the type of weld tooling being used, and whether manual or machine welds are made. Also, for any given thickness and joint design various combinations of amperage, voltage, welding speed, and filler-wire input speed are satisfactory. As a result, no hard-and-fast rules can be specified for welding conditions. Tables IV and V illustrate typical welding conditions that have been used in the TIG welding of titanium.

Welding conditions generally do not have to be adjusted radically to accommodate the various titanium alloys but are often adjusted as a means of controlling weld porosity. Almost any change in a welding condition that will decrease the freezing rate of the weld will produce a decrease in porosity.

As in welding other materials, starting and runoff tabs are used by some fabricators (Refs. 12, 36). The starting and runoff tabs usually are of the same material as the parent metal being welded and are placed against the parent part at each end of the weld as shown in Figure 33. The purpose of these tabs may be one or more of the following:

Starting tabs

- (1) Initiate the arc
- (2) Establish a steady arc
- (3) Allow time to adjust welding conditions
- (4) Observe irregularities in material or arc behavior

TABLE IV. CONDITIONS FOR MANUAL TIG WELDING TITANIUM AND TITANIUM ALLOYS

Joint Thickness, in	Nominal Composition (Balance Titanium), per cent	Joint Type	Current (SPCD), amperes	Arc Potential, volts	No. of Passes	Electrode Diameter and Material (Ref 18)	Filler Wire		Shielding Gas and (cm) Flow Rate			Cleaning
							Diameter, in	Material	Torch	Shield	Back-Up	
0.050	Commercially pure titanium and various alloys	--	65	9	--	--	--	--	10A	--	--	--
0.050	"	--	60-70	9	--	--	--	--	10A	10A	3A	--
0.070	"	--	90	9	--	--	--	--	15A	--	--	--
0.070	"	--	85-95	9	--	--	--	--	15A	15A	4A	--
0.070	Ti-15Mo	--	80	10	--	1/16-EWT	Parent metal strips	--	Argon-filled chamber and torch gas	--	--	2HF/40HNO ₃ aqueous
0.080	Commercially pure titanium and various alloys	--	120-130	9	--	--	--	--	15A	15A	4A	--
0.080	"	--	125	9	--	--	--	--	15A	--	--	--
0.100	"	Sq. butt	--	--	--	--	--	--	--	--	--	--
0.110	"	--	120-140	12-14	--	3/32-EWT	Th-2	3/32	Commercially pure titanium	15-20A	--	10-35A ^(a) Alcohol or acetone
0.120	"	--	--	--	--	--	--	--	--	--	--	--
0.125	Ti-4Al-4V	Corner and fillet	210	--	--	--	1/16	Commercially pure titanium	--	--	--	--
0.250	Ti-4Al-4V	Single vee, 60° in-cluding angle	200	40	4	--	3/32	Commercially pure titanium	--	--	--	--
0.500	Ti-4Al-4V	Single vee, 60° in-cluding angle	270	40	6	--	3/32	Commercially pure titanium	--	--	--	--

(a) For tacking.

(b) For closing root pass

TABLE V CONDITIONS FOR MACHINE TIG WELDING TITANIUM AND TITANIUM ALLOYS

Joint Thickness, in	Nominal Composition (Balance Titanium), per cent	Joint Type	Welding		Arc Potential, volts	Electrode Diameter, in. and Material (Ref. 18)	Filler Wire		Shielding Gas and Flow Rate (cfh)		Number of Passes
			Travel Speed, in./min	Current, amp			Material	Diameter, in.	Feed Rate, ipm	To Shielding Gas To Shield Up	
0.008	Commercially pure titanium and various alloys	--	16	10	14	--	--	--	--	--	--
0.020	"	--	8-12	27	--	--	--	0.062	1	3A-7He	--
0.030	"	--	10	30	10	--	--	--	--	--	--
0.040	"	--	14	30	20	--	--	0.062	18	15A	--
0.050(a)	"	--	7	60	9	--	--	--	--	20A	--
0.060(a)	"	--	6	60	9.4	--	--	--	--	18A	--
0.060	"	--	10	95	10	--	--	--	--	15A	--
0.080	"	--	12	125	10	--	--	0.062	22	15A	--
0.070	"	--	--	--	--	--	--	--	--	--	--
0.080	"	--	10	195	12	--	--	--	--	20A	--
0.090	"	--	12	210	12	--	--	0.062	24	20A	--
0.125	"	--	12	230	12	--	--	0.062	20	20A	--
0.125	"	--	15	180	18	--	--	--	--	Helium-filled chamber	--
0.125	"	--	8	110	18	--	--	--	--	Helium-filled chamber	--
0.125	"	--	15-25	250-260	20	--	--	0.062	200-225	50A-15He	20He
0.140	Ti-0Al-0V-2Sn	50 butt	4-6	165	11	1 B-EWT	AMS4941	0.047	26	40He	20A
0.250(a)	"	--	4-6	205	12-14	--	--	--	--	40He	--
0.250	"	--	15-25	300-320	30	--	--	0.062	300-320	50A-15He	25He
0.500	"	--	15-30	340-360	45	--	--	0.062	375-400	50A-15He	30He
0.625	"	--	15-35	350-370	45	--	--	0.062	400-425	50A-15He	30He

(a) Multipass procedures

Di
le
bu
ar
to
sepa
tu
ad
fa
vi
de
pr
we

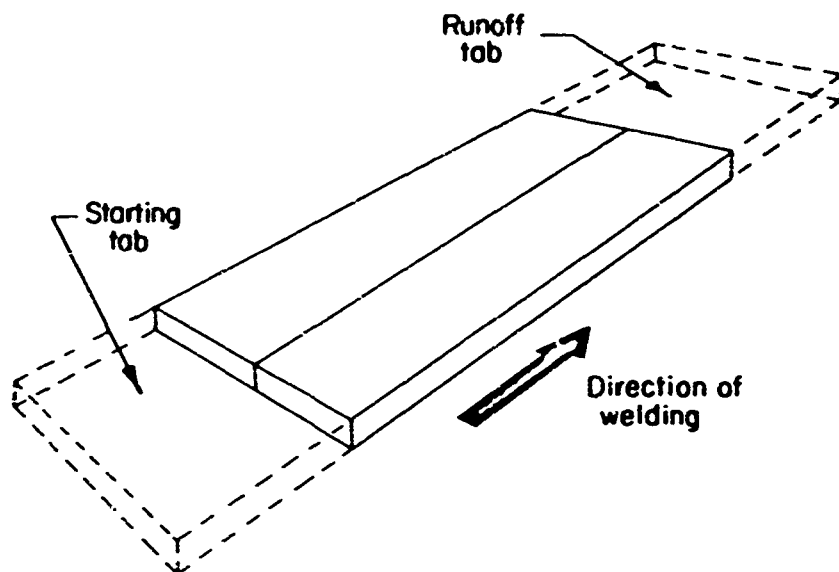


FIGURE 33. THE USE OF STARTING AND RUNOFF TABS

Runoff tabs

- (1) Extinguish the arc
- (2) Avoid crater formation within the part
- (3) Avoid the formation of crater cracks within the part
- (4) Eliminate weld stops and resultant craters from the weldment.

Difficulties have been experienced with starting and runoff tabs. Unless a good fit of the tabs to the plates to be welded is maintained, burnthrough can occur at the junction. To overcome this difficulty the arc is operated at a very low current on the starting tab and increased to weld amperage as soon as the arc crosses the part (Ref. 40). This sequence is reversed at the end of a weld.

Tack Welding. Tack welding is used to pre-position detail parts or subassemblies for final welding operations. Elaborate fixturing often can be eliminated when tack welds are used to their full advantage. Various tack-welding procedures are used by titanium fabricators but good cleaning practices and adequate shielding are provided to prevent contamination of the welds. Contamination or cracks developed in tack welds can be transferred to the finish weld. One procedure is to perform tack welding in such a way that the finished weld never crosses over a previous tack weld. To accomplish this,

sufficient filler metal is used in tack welding to completely fill the joint at a particular location. The final weld beads are blended into each end of the tack welds (Ref. 9).

Properties. A large number of joint properties have been determined for TIG welds in titanium alloys of interest. The properties measured by static tension, notch tension, bend and crack susceptibility tests compare very favorably with parent-metal properties. Axial-tension fatigue tests generally show a significant decrease in properties when compared with similar parent-metal specimens. Fracture-toughness test results on fusion weldments are not easily interpreted. Depending on the evaluation criteria selected, the data from these tests are indicative of fair to good performance. Weldment thermal-stability trends in the 6Al-4V and 8Al-1Mo-1V alloys appear to parallel parent-metal trends.

TIG weldments have been used in several structural test components. The behavior of weldments in such tests is by far the best evaluation of joint properties. Reported behavior to date is encouraging with few exceptions. Delayed cracking of weldments has been observed in some instances. In some cases, the reasons have been apparent and solutions obvious. Where the cause of such cracking is not known, a strong effort to find the cause is indicated.

Sources of detailed information on properties of TIG welded titanium and titanium alloys are given in Table VI.

Applications for TIG Welding Titanium Alloys. TIG welding is among the most widely used joining processes for titanium and titanium alloys. Some of the typical products manufactured by TIG welding are described below.

Chemical Processing Equipment. Commercially pure titanium was the preferred material for several large heat-exchanger coils for use in a calcium hypochlorite plant (Ref. 21). The coil sub-assemblies required the butt-welding of titanium tubing and pipe into lengths necessary for each complete coil as shown in Figure 34 (Ref. 21). Inlet, outlet, and dummy connections, angle supports, and other attachments also were made. All welded connections were made using manual TIG welding techniques. Since numerous joint designs and part configurations had to be welded, it was necessary to use several inert-gas-shielding techniques to make the required welds successfully. Features of the fabricating and shielding methods are described below.

TABLE VI TIG WELD PROPERTY DATA SOURCES

Base Alloy	Filler Alloy	Test Condition	Thickness, in.	Type of Tests and Test Temperatures, F	Reference
13V-11Cr-3Al Al-4V	13V-11Cr-3Al	Annealed, as welded	0.187/0.250	Static tension and bend (RT)	41
Al-4V	13V-11Cr-3Al	Annealed, as welded	0.02/0.09	Ditto	41
Al-4V	Al-4V	Annealed, as welded	0.03	Static tension, notched tension ($K_t = 3$), fracture toughness, and fatigue (-110, 75, 400, 650), bend (RT)	41
13V-11Cr-3Al Al-4V	--	Annealed, as welded	0.086	Same as above except static tension at 75 and 650 only. Add thermal stability	42
13V-11Cr-3Al Al-4V	--	Annealed, as welded	0.20	Bend (RT) Charpy V-notch impact (-40 to 65 C)	43
Commercially pure titanium and 6Al-4V	Commercially pure titanium and 6Al-4V	Aged, welded	0.125	Ditto	43
6Al-6V-2Sn 6Al-6V-2Sn	6Al-6V-2Sn Commercially pure titanium	Annealed, as welded Aged, welded Aged, welded, aged Aged, welded, aged	0.125 0.140	Static tension and bend (RT)	28
6Al-6V-2Sn 6Al-6V-2Sn	6Al-6V-2Sn 6Al-6V-2Sn	Annealed, as welded Aged, welded	0.125 0.125	Static tension and notched tension ($K_t = 8$) (-40 to 70, 200, 400) Fracture toughness, bend, biaxial stress, (RT)	28
6Al-6V-2Sn	Commercially pure titanium	Annealed, as welded Aged, welded	0.125 0.14	Static tension, notched tension ($K_t = 8$) bend, and fracture toughness (RT) Cyclic loading test (RT)	28
6Al-4V	Commercially pure titanium 13V-11Cr-3Al	Aged, welded, aged	0.18	1.710	28
6Al-6V-2Sn 6Al-6V-2Sn	6Al-6V-2Sn 6Al-6V-2Sn	Annealed, as welded (a)	0.11 0.14	Hydrostatic burst (RT) Static tension fracture toughness, cyclic loading (RT), hydrostatic burst	28
6Al-6V-2Sn	6Al-6V-2Sn	Annealed, as welded Annealed, welded, aged Aged, welded	0.1	Static tension, notched tension ($K_t = 16$), and bend (RT)	12
6Al-6V-2Sn	(b)	Aged, welded	0.04	Static tension and bend (RT)	44
Al-4V	(b)	Aged, welded, aged	0.04	Ditto	44
Al-4V	Commercially pure titanium	Aged, welded, aged Welded stress relieved	0.06	Static tension (RT)	45
Al-4V	Commercially pure titanium, Nonf	Annealed, as welded Aged, welded	0.025	Bend (RT)	46
13V-11Cr-3Al 6Al-4V, 6Al-1Mo-1V 13V-11Cr-3Al, and 6Al-6V-2Sn 13V-11Cr-3Al 13V-11Cr-3Al	-- -- -- -- --	Annealed, as welded Aged, welded Aged, welded, aged Aged, welded, aged Aged, welded, aged	0.02 0.04 0.02 to 2.0 0.032, 0.06 0.071 0.062	Static tension and thermal stability (RT 600, 800, 1000), bend (RT) Data from before 1960 Comprehensive evaluations Static tension, notched tension ($K_t = 16$) (RT, 600), thermal stability (RT, 600, 800, 1000), thermal-stress stability (RT) Static tension (-120, -110, -65, RT, 800, 1000) bend test (RT) creep stability (RT), notched tension ($K_t = 346$) (-170, -110, RT) Static tension (RT)	47 48 49

(a) After special postweld hot rolling to relieve residual stresses

(b) Nine different filler alloys were used

The fabrication procedure was designed to permit the maximum number of welds to be visually inspected, both inside and out. To permit internal inspection of the weld root, straight lengths of pipe were welded. Full root penetration was mandatory to avoid internal stress raisers and no undercut was permitted on either side of the joint. Weld-face reinforcement was kept to a minimum so that welds could pass through bending rolls. (The first coil bent revealed that even very slight reinforcement on the outside had to be dressed down to below a maximum height of 1/32 inch to avoid buckling of the pipe wall adjacent to the weld and to avoid damage to the bending rolls.)

Figure 35 shows such a butt weld being made in pipe out of position in the open atmosphere (Ref. 21). None of the welds failed during bending to a 2-1/2-foot radius. This radius was very near the bend radius of the unwelded pipe. Bending was done cold and the tube was not filled. After bending, welds were air leak tested and hydrostatically tested at 225-pounds pressure. Figure 36 shows some components that were welded in a controlled atmosphere box (Ref. 21). The elbows were fabricated to the maximum bend that permitted good visual inspection of the root side of the butt weld connecting the elbow to the coil. Angles also were fabricated from 1/4-inch by 2-1/2-inch-thick titanium bars by inside-fillet and outside-corner welding. Both welds were continuous. This welding resulted in considerable distortion but the angles were cold straightened after welding. Figure 37 illustrates the welded angle and attachment to the pipe coil.

Leak tests and visual inspection were selected in preference to X-ray, magnetic-particle, and ultrasonic examination for several reasons. These processes were considered more costly and would not provide useful information concerning root-side contamination or embrittlement. The back-side of welds was inspected visually using the bore inspection instrument to determine the physical condition of the weld root after making the root pass and again after making the cover pass. Penetration, undercut, weld concavity, and adequate back-side shielding were inspected. Only two of approximately 275 welds were cut out because of the loss of the back-side shielding when a workman tripped over the supply hose and when a welder inadvertently ran out of gas from his purging bottle.

Figure 38 shows the underbead side of a typical butt weld in pipe as seen through the bore-inspection instrument (Ref. 21). The greatest difficulty in using the bore-inspection instrument was to determine whether the bead was concave or convex. The difficulty was entirely one of depth perception through the optics and determining whether the weld surfaces were projecting inward or outward.

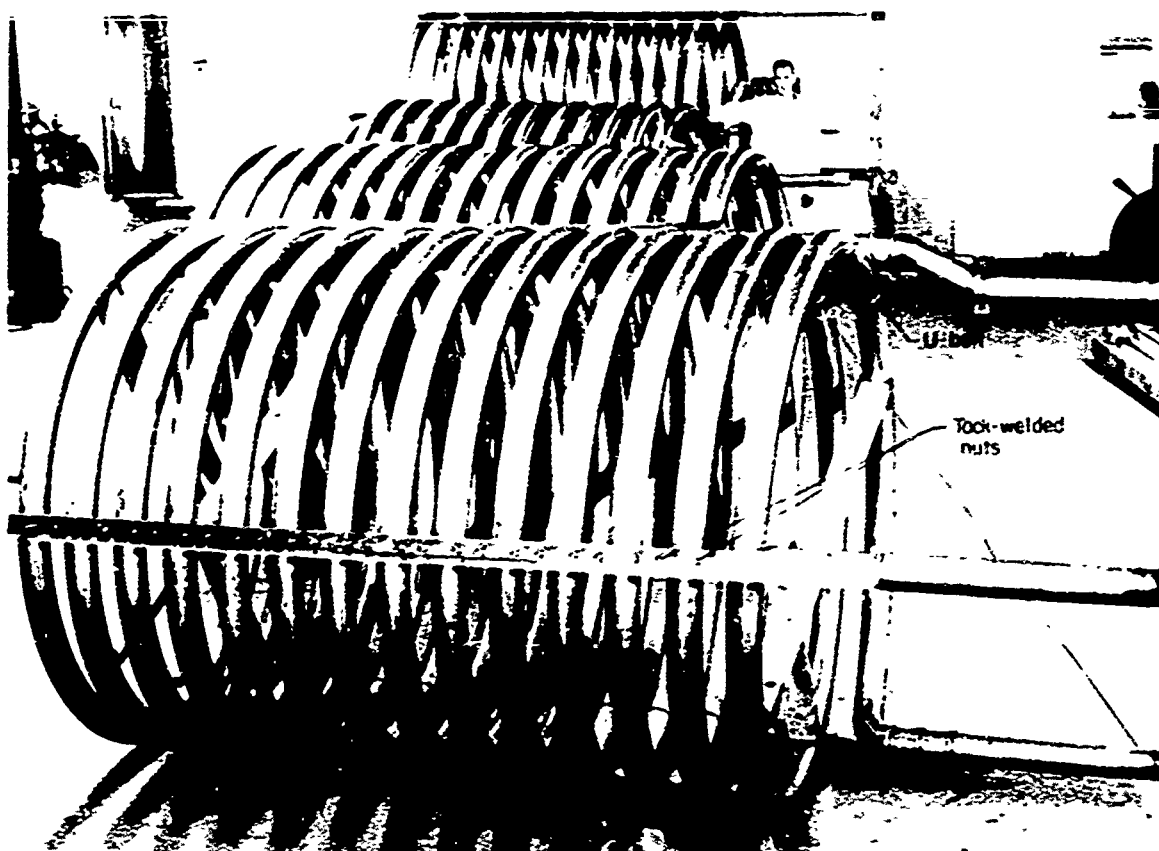


FIGURE 34. CALCIUM HYPOCHLORITE PLANT HEAT-EXCHANGER COILS MADE FROM COMMERCIAL PURE TITANIUM (REF. 21)



FIGURE 35. OUT-OF-POSITION BUTT WELD BEING MADE IN THE OPEN ATMOSPHERE USING TORCH SHIELDING COMBINED WITH SUPPLEMENTARY SHIELDING EQUIPMENT (REF. 21)

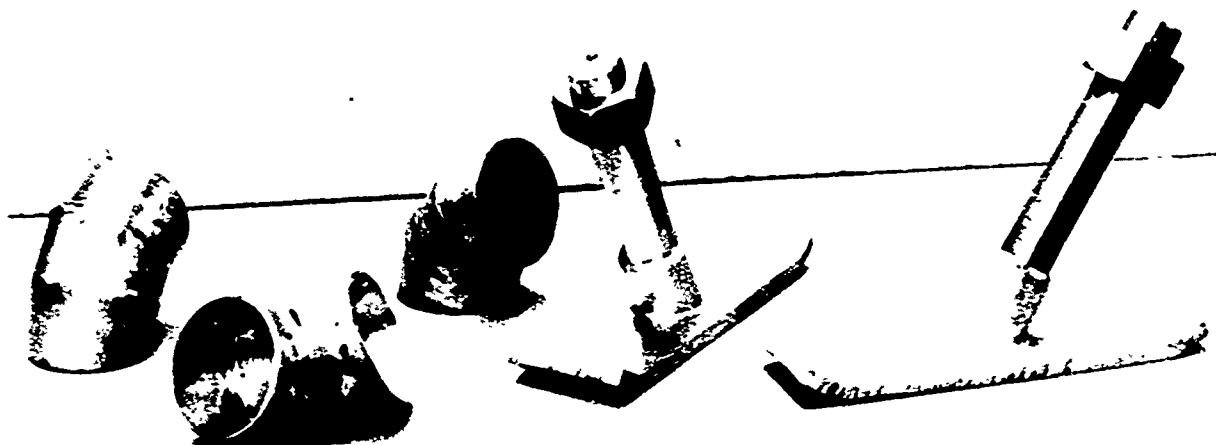


FIGURE 36. HEAT-EXCHANGER SUBASSEMBLIES WELDED IN A CONTROLLED ATMOSPHERE CHAMBER (REF. 21)



FIGURE 37. DETAIL OF THE MECHANICAL SUPPORT SHOWING THAT THE NUTS ARE TACK WELDED (REF. 21)

This is a view of the intermediate point in the coil.

After bending, two major areas of cracks originating from discontinuities on the inside of the pipe wall in the first coil were found visually. The cracks were not related to welding since the nearest weld was about 25 feet away. Air tests were used instead of water to detect leaks.

Butt welds were inspected differently from the other welds. The procedure was to make the root pass leaving approximately 1 inch of the root on the 9 to 10 o'clock side open, the side that would not be in tension when passing through the pipe bending rolls. The inside of the root pass was inspected using a small inspection instrument as shown in Figure 39 (Ref. 21). Next, the cover pass was made except at the closure area and a second bore inspection was made. The second inspection was primarily to ensure that there had been no inside purge failure when making the cover pass. Following this last bore inspection, the root side purge gas pressure was dropped and the open length of weld was closed. There were no failures in this area from bending.

Rings. In work aimed at developing high-strength, lightweight pressure vessels, the Ti-3Al-13V-11Cr alloy was studied extensively because of its inherent high strength and potential of exceeding 1,000,000 inches strength-to-density ratio and possibly reaching 1,200,000 inches (Ref. 50). The main problems involved the development of fabricating techniques to achieve consistently high strength levels along with the most economical use of material. Welding development was aimed primarily at obtaining good weld quality and fracture toughness. During development work 40-inch-diameter rings were prepared from 0.250-inch-thick plate, by TIG welding (Ref. 13). The weld joint developed for welding 1/4 by 8 by 10-inch panels was a double vee-groove joint, completed in three-passes. The first pass was a fusion pass, followed by a filler pass from the outside, and then a filler pass from the inside. Welding conditions were not reported, but radiographic weld quality appeared satisfactory.

Roll-forged rings of Ti-6Al-6V-2Sn alloy also have been evaluated for weldability using the TIG process, by making single-pass circumferential machine butt welds, using commercially pure titanium filler metal. A segmented, expanding internal copper back-up of the type shown in Figure 40 together with external stainless steel hold-down bands were used (Ref. 13). Sound welds were obtained using normal welding conditions. A small amount of porosity was the only observed weld defect. In other work, higher mechanical properties were developed by the 6Al-6V-2Sn alloy welded with commercially pure titanium welding filler than comparable welds in the 6Al-4V alloy using the same filler metal (Ref. 51). A wider range of aging temperatures for



FIGURE 38. PHOTOGRAPH TAKEN THROUGH A BORESCOPE OF A TYPICAL WELD ROOT (REF. 21)

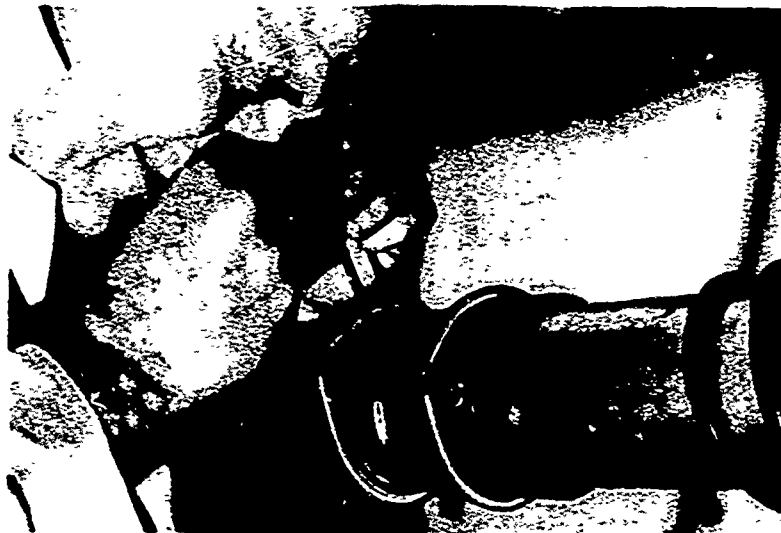


FIGURE 39. INSPECTION OF THE ROOT PASS OF THE BUTT WELD SHOWN IN FIGURE 38 (REF. 21)



FIGURE 40. SEGMENTED WELDING FLXTURE WITH SOLID COPPER BACK-UP SHOES
MOUNTED ON POSITIONER (REF. 13)

6Al-6V-2Sn alloy weldments has been shown to develop parent-metal yield strength of 130,000 or better. Welding techniques used on Minuteman were designed to produce a weld with lower strength, but greater ductility than the parent metal. The lower strength is compensated by thickened material at the weld so as to place the weld at lower stress than the parent metal. A stress-relief heat treatment is performed after welding.

No significant improvement in quality or fracture toughness was observed with electron-beam welds as compared with TIG welds (Ref. 13).

Space Vehicles. The inner shell of the Mercury capsule shown in Figure 41 is basically a pressure vessel consisting of a cone-shaped side wall with a large spherical pressure bulkhead on one end and a small pressure bulkhead on the other (Ref. 52). The side wall and the large bulkhead are both made of two thicknesses of 0.010-inch commercially pure titanium. The inner thickness is smooth, and the outer one is stamped with a pattern of strengthening beads.

Because of size limitations on the available titanium sheet, it was necessary to make each layer of the large bulkhead from three pieces welded together, and each of the sidewall cones from eight pieces. Each of the sidewall cones was fitted one inside the other so that the mating surfaces were in intimate contact all over. Further, wrinkles that might interfere with resistance-seam welding were prohibited so the forming operation is critical. A special machine trims the parts to size with a 2-1/2-inch high-speed steel saw blade. Speed was 210 rpm, and feed was 8 ipm. This combination produced a smooth edge that did not require draw filing or hand fitting for welding.

Welding the Mercury capsule starts by joining the eight segments of the smooth inner conical skins by TIG welding without filler metal. To make a good joint with this technique, the 0.010-inch titanium sheets must be spaced with a maximum gap of 0.004 inch. The length of each weld on the inner skin is about 4 feet; on the outer skin about 6 feet. The fixturing for this operation as shown in Figure 42, includes a conical support for the parts and a row of segmented clamps on each side of the joint (Ref. 52). The clamps hold the parts in precise alignment and also serve as a chill bar. To hold the proper shape, the panels are strapped down against the conical supporting fixture during each weld. Then, as additional panels are added to the assembly, each one in turn occupies the same relative area on the contour of the tool. The spherical skin assemblies are welded in much the same manner, but their shape causes an added complication.

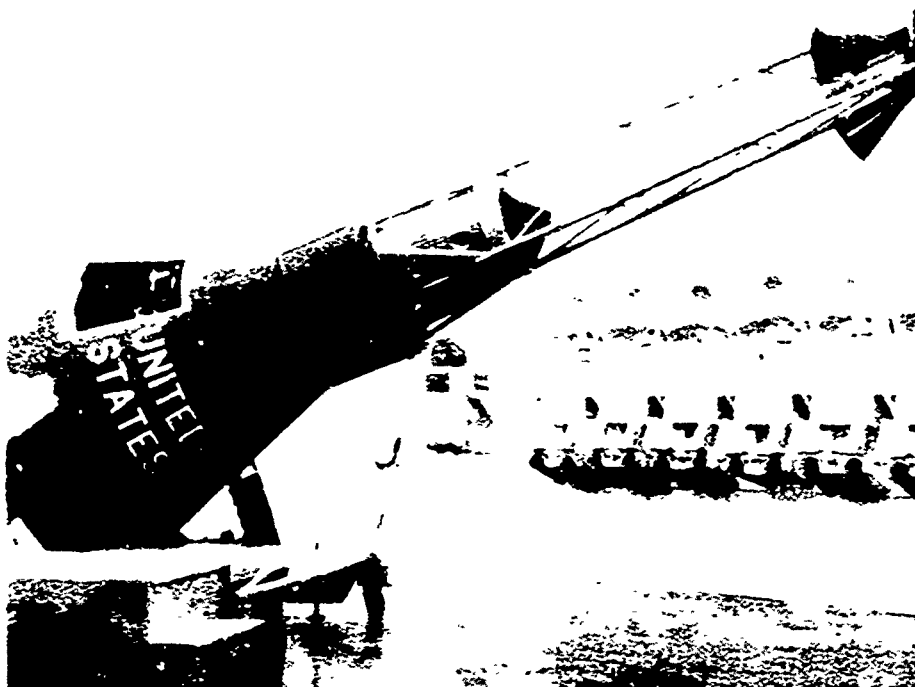


FIGURE 41. MERCURY SPACE CAPSULE (REF. 52)

Astronauts were checked out on instruments in this space capsule at the fabricator's plant. Outer shell is made of René 41 shingles. Inside is fiberglass insulation and the double-wall inner shell is made of 0.010-inch titanium.



FIGURE 42. FIXTURE HOLDS FIRST TWO PANELS OF OUTER CONICAL SKIN FOR TIG WELDING (REF. 52)

Straps keep part tight against contour of fixture.

They are made in three sections, a center piece and two pieces, so that the joint forms a curved path about 6 feet long. The fixture for this operation as shown in Figure 43, rotates the whole part so that the joint to be welded moves past a stationary torch, just the opposite of the setup for welding the cones. In both operations, however, the welding speed is 7 ipm.

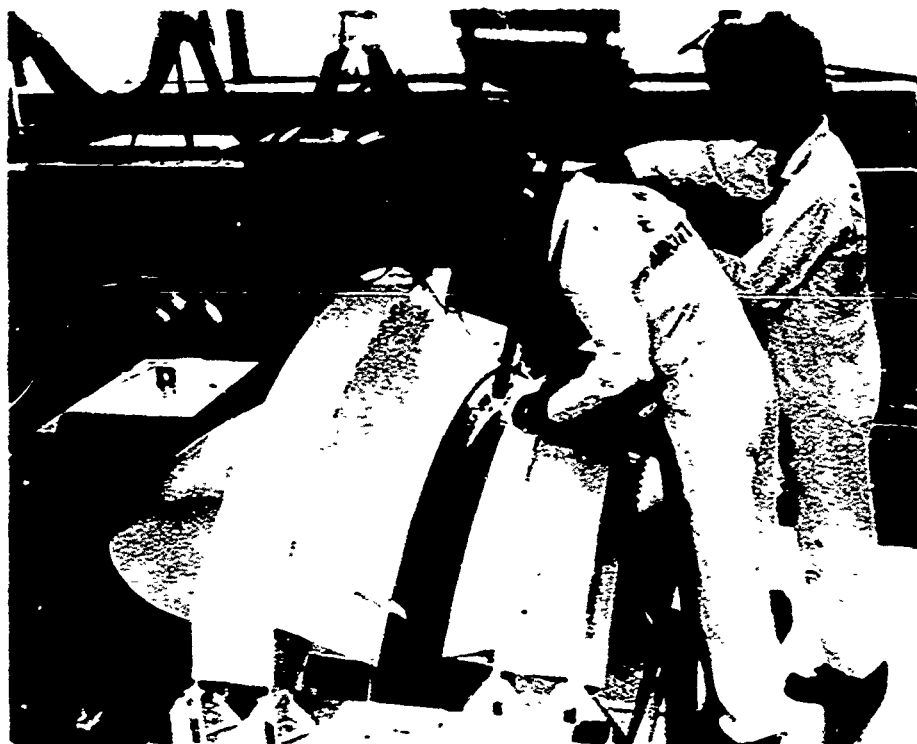


FIGURE 43. ROTATING FIXTURE MOVES THE WORK PAST STATIONARY TIG TORCH AT 7 IPM TO JOIN TWO SECTIONS OF SPHERICAL BULKHEAD (REF. 52). SEGMENTED FINGERS HOLD EDGES OF JOINT IN ALIGNMENT

Aircraft Wing Leading Edge. The Ti-5Al-2.5Sn alloy is readily weldable if atmospheric contamination is avoided. The A-5 Vigilante wing leading edge shown in Figure 44 is fabricated from this alloy using manual and mechanized TIG welding techniques (Ref. 53). Commercially pure titanium filler metal is used.

Figure 45 shows the leading-edge section and illustrates several types of weld-joint designs established to permit fabrication of thin parts. These joint designs include a simple square-butt joint,

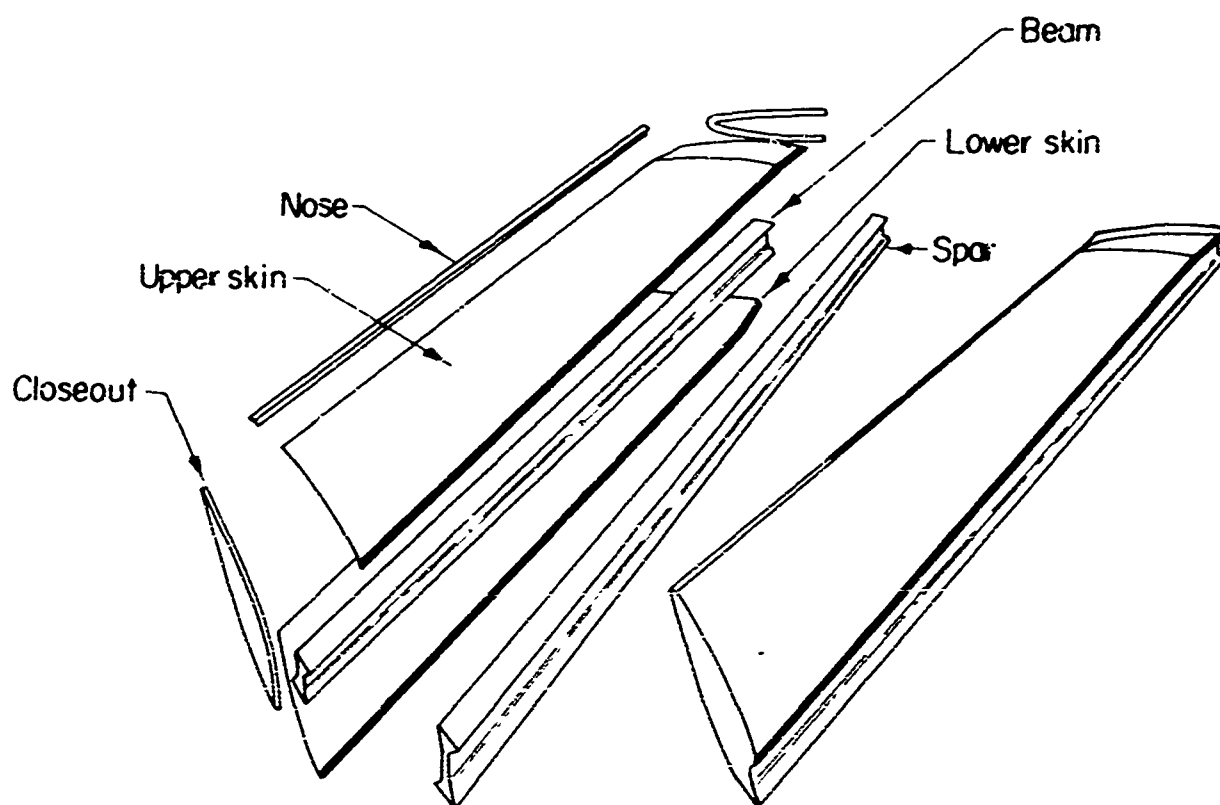


FIGURE 44. VIGILANTE WING LEADING EDGE (REF. 53)

Several welds are needed to assemble the boundary layer control wing section. Subsequent stress relieving is carried out in vacuum to prevent contamination of the structure by halogens.

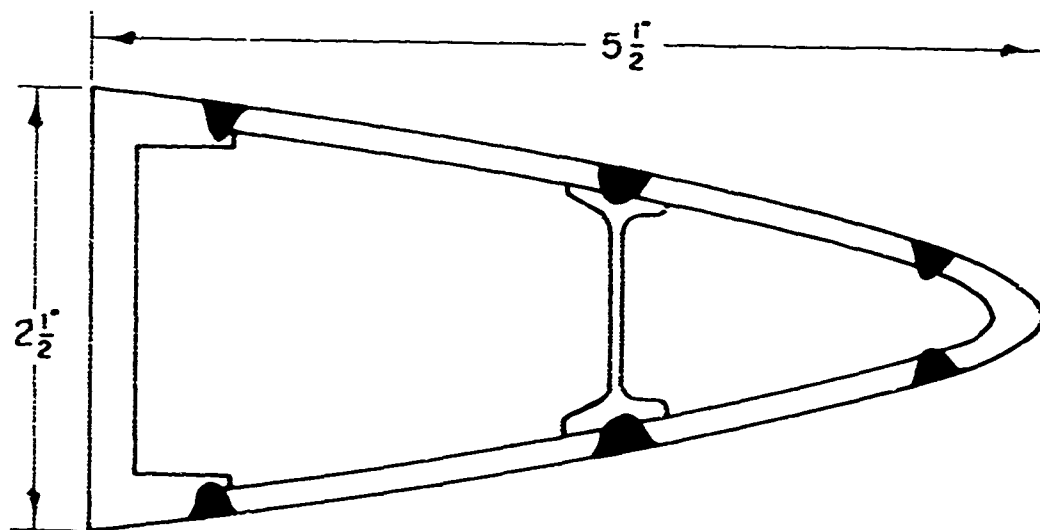


FIGURE 45. TYPICAL CROSS SECTION OF WELDED TITANIUM LEADING EDGE (REF. 53)

Figure 46a, a square-butt joint having an integral back-up, Figure 46b, and an arc-seam lap joint, Figure 46c (Ref. 2).

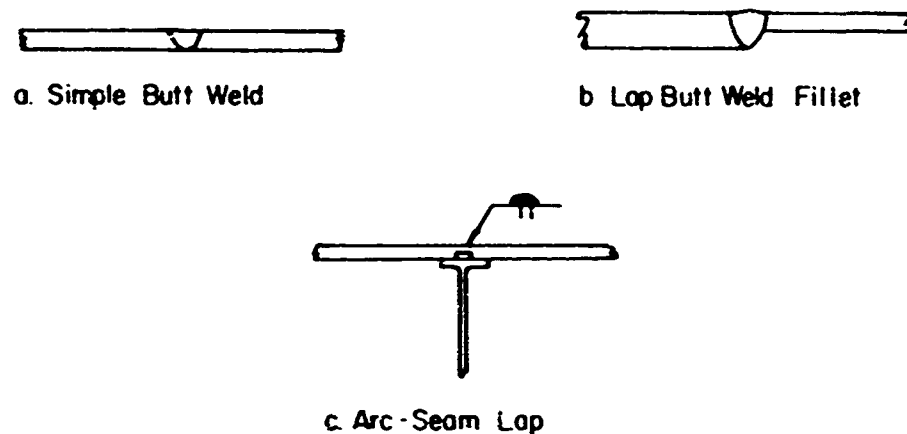


FIGURE 46. WING LEADING-EDGE JOINT DESIGNS (REF. 2)

The arc-seam lap joint originally involved melting completely through the skin member with the arc and fusing it to the edge of the rib, as shown in Figure 47 (Refs. 2, 53). Early assemblies were successfully welded in this manner, but the joint carried the constant danger of being ruined if the welding electrode was misaligned with the hidden web. Because of the alignment problem, the sheet metal web was redesigned into a flanged I-beam. The wide flange provided considerable latitude for aligning the electrode. Initial welding tests indicated that arc-seam lap welds could be made without undue difficulty. Water-cooled copper chill bars were used to control the width of the top bead and enough current was fed into the arc to melt completely through the top skin and into the I-beam flange. It was an engineering requirement that the fusion zone between the skin and the flange be at least 0.18 inch wide. Trouble was encountered when the welding current was increased to obtain the 0.18-inch width. Good arc behavior

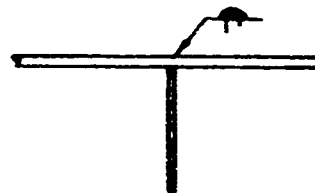


FIGURE 47. ARC-SEAM TEE WELD-JOINT DESIGN (REFS. 2, 53)

would exist for several inches of weld, and then the arc-voltage-controlled welding head would suddenly drive the welding electrode down into the puddle. Careful observation of this runaway welding-head action revealed that just as the electrode dove into the puddle, the puddle itself seemed to get much wider and the bottom of it seemed to drop. A groove was machined on the top side of the skin to reduce the current input necessary to get the proper width of fusion at the interface. This change did make it easier to melt through the skin, but did not reduce the arc problems. Additional tests were made to determine the gap that could be tolerated between the skin and the I-beam flange and still get an acceptable weld. It was found that the current needed to melt through the skin into the flange was actually much less when the skin was off the flange than when it was down tight. It was also found that the amount of gap present between the skin and the flange could vary considerably, once a few thousandths of an inch gap existed, without changing the current requirements significantly. Next, tests were made with the skin thickness reduced by means of a groove on the bottom side of the skin, against the I-beam flange. This provided a built-in gap of about one-half the thickness of the skin. The groove was made 0.18 inch wide to match the fusion-zone width requirement. The arc readily melted away the half thickness of the skin and actually formed a hole through the skin. The arc then went on down and impinged on the flange, melting its surface. As the welding operation proceeded along the joint, the arc melted the skin ahead of it, the molten metal flowed around the sides of the hole, and came together again at the back where it joined with metal from the flange that had been melted as the arc passed along the seam.

In production operations, holes are drilled completely through the skin from the groove bottom at about 10-inch intervals. These holes provide lineup cues on the top, visible portion of the skin during fitup in the weld tool. Tests have shown that the welding electrode can vary as much as 0.030 inch from the centerline of the groove without losing fusion on the sidewall farther away. After the parts are fitted up, manual tack welds are made through the holes to anchor the skin to the flange and keep it from creeping and crawling during the main welding operation. The machine weld is then made and proceeds right over the tack welds. A second pass is made to add filler wire and fill up the concavity left from the first pass.

Structural Shapes. The equipment shown in Figures 48 through 51 is used for accurate sine welding of aircraft ribs at high speeds (Ref. 54). The ribs require the welding of thin titanium corrugated sheets at right angles to rib stiffeners on both ends. Because of the difficulty in following the long continuous series of ridges and

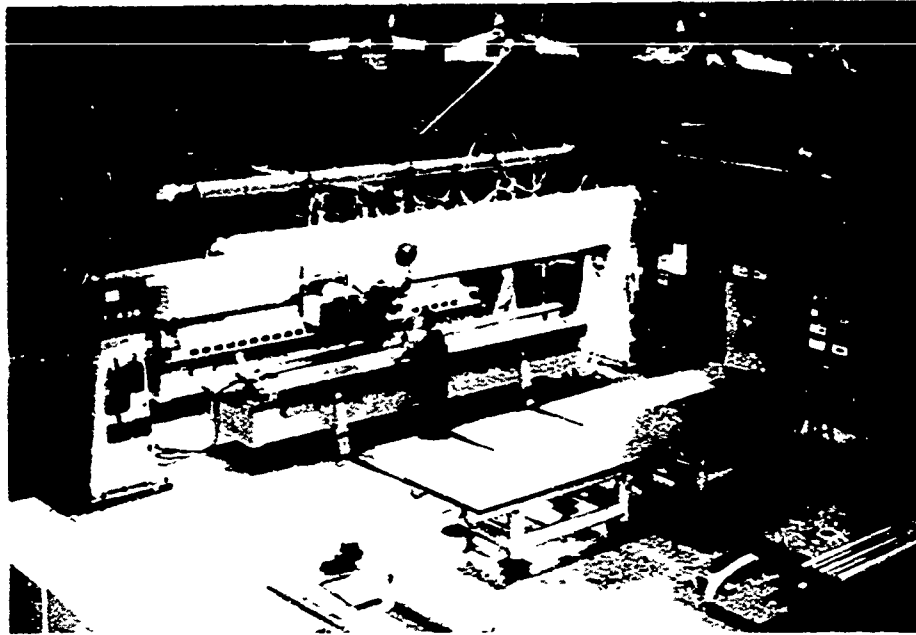


FIGURE 48. GENERAL VIEW OF THE SINE-WAVE WELDING MACHINE (REF. 54)



FIGURE 49. WELDING OF THIN CORRUGATED TITANIUM SHEET (REF. 54)



FIGURE 50. SINE-WAVE WELDING STATION AREA (REF. 54)

Adjustments are being made to the argon shielding box which follows the welding head.



FIGURE 51. COMPLETED RIB FOR THE AMERICAN RS-70 AIRCRAFT (REF. 54)

grooves in extremely thin members, manual control of the weld torch is impossible. Special machines have been developed to make sine-wave shaped welds. The sine-wave welding machine can deal with 20-foot lengths and can weld at the rate of 30 in./min. Titanium in thicknesses from 0.008 to 0.125 inch has been welded on the machine.

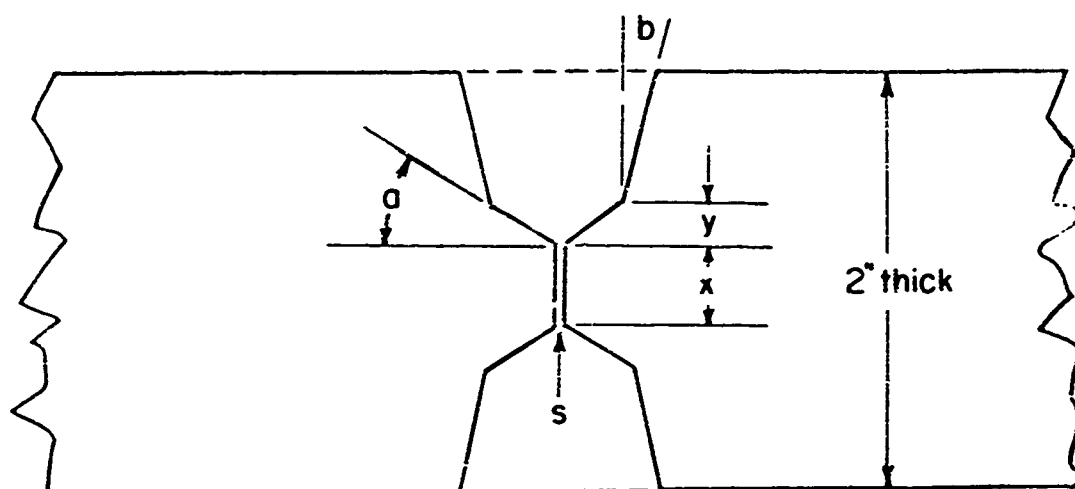
This welding setup is operated with two tables so that fixturing can be carried out on one while the ribs and beams are being welded on the other. Since each weld fixture has provisions for tracing template, the concept eliminates the need for indexing the entire length.

A trace mechanism works off a template guide to follow the sine-wave weld pattern. The welding torch is led through its path by a magnetic tracing system (Refs. 54, 55). The system includes a stylus that clings to the template by magnetic-flux attraction. Only rolling action exists between the stylus and the template. Since no pressure is applied on the stylus, hardened templates are not needed. Construction of the beam and carriage assembly is such that the torch tip center can track the seam center within ± 0.002 inch. This accuracy can be maintained over the full weld length in any direction.

By means of jog buttons that act on X and Y motions the operator brings the tracer to its starting point on the template. The tracer is then set for automatic operation. The welding torch is positioned over its starting point on the weld seam by means of micrometer adjustment. Then the wire feeder is positioned properly. A small moving boxlike shield measuring 3-1/2 by 7 in. is linked to the welding head and moves close behind it to shield the weld. The end result of the system combines high production rates with higher than normal use of both the machine and the weld technician's time (Ref. 55). Each table fixture has provisions for a tracing template. For this reason, there is no need to index the entire length of a weld path.

Special Products. Weldments designed specifically for testing purposes also often provide useful information on welding procedures and properties. The Navy Explosive Bulge Test Specimen may be included in this classification. During work to develop final welding conditions for fabricating bulge test specimens, a variety of joint designs and welding conditions were investigated (Ref. 56); these are illustrated in Tables VII and VIII. Properties obtained are reported in Table IX.

TABLE VII. VARIATIONS OF A MODIFIED DOUBLE-VEE-JOINT DESIGN USED FOR EXPERIMENTAL TIG WELDMENTS AND FOR A 2 x 30 x 30-INCH FINAL PLATE WELDMENT ON 2-INCH-THICK COMMERCIALY PURE TITANIUM PLATE (REF. 56)



Weldment Identification	Indicated Angle or Dimension				
	Land (x), in.	(y), in.	Angle (a), deg	Angle (b), deg	Gap (s), in.
1 (Experimental)	0.100	1/4	45	20	Butt
2 (Experimental)	0.100	1/4	45	20	Butt
3 (Experimental)	5/16	1/4	45	15	Butt
4 (Experimental)	1/2	1/4	30	15	0.060"
5 (Experimental)	1/2	1/4	45	15	0.070"
Final weldment (2 x 30 x 30 in.)	3/8	3/16	30	15	Butt

TABLE VIII. WELDING CONDITIONS USED IN CONJUNCTION WITH VARIATIONS IN WELD DESIGN FOR THE VARIOUS EXPERIMENTAL TIG WELDMENTS AND THE FINAL 2 x 30 x 30-INCH PLATE TIG WELDMENT ON 2-INCH-THICK COMMERCIAL PURE TITANIUM PLATE WELDED WITH COMMERCIAL PURE TITANIUM FILLER WIRE (REF. 56)

Welding Parameter	Weld 1		Weld 2		Weld 3		Weld 4		Weld 5		2 x 30 x 30-In. Weldment	
	Fusion	Filler	Fusion	Filler	Fusion	Filler	Fusion	Filler(a)	Fusion	Filler	Fusion	Filler
Electrode Diameter, inch	3/16	3/16	3/16	3/16	3/16	3/16	3/16	3/16	3/16	3/16	3/16	3/16
Electrode-Arc Gap, inch	1/8	3/16	1/8	3/16	1/8	3/16	1/8	3/16	1/8	3/16	1/8	3/16
Amperage	250	270	250	320	250	300	310	320	320	320	320	330
Volts	10	10	16	17	14	17	20	16	16	16	16	16
Carriage Travel, ipm	8	4	8	3	8	5	4	3	3	3.5	4	3
Heat Input, joules/inch		40,000		110,000		60,000		100,000		85,000		105,000
Wire Feed Rate, fpm	--	2	--	5.5	--	6	--	6	--	6	--	5
Filler Pases, number/side	--	17	--	4	--	8	--	4	--	5	--	7
Shielding Gas Flow, cfm												
Torch (A) (He)	10 A	10 A	10 He	10 He	10 He	10 He	10 He	10 He	10 He	10(b)	10 He	10(b)
Trailer (Argon)	50	50	50	50	55	55	55	55	55	55	55	55
Back-up (Argon)	10	10	10	10	30	30	30	30	30	30	30	30

(a) Some vibrations applied during solidification.

(b) 50% argon and 50% helium.

TABLE IX. BASE METAL AND WELD METAL TENSILE AND COMPRESSION TEST RESULTS ON
COMMERCIALLY PURE 2-INCH-THICK PLATE TIG WELDMENTS - WELDED WITH
COMMERCIALLY PURE TITANIUM FILLER WIRE (REF. 44)

Sample Location	YS, 0.2% Offset, ksi	TS, ksi	RA, %	Elongation, per cent in 1 inch
<u>Tensile Tests</u>				
Base Metal	77.3	90.8	45	24
(Weldment 1)				
Weld 1	69.3	86.5	38	20
Weld 2	73.3	90.7	37	17
Weld 3	46.6	47.8	8	3
Weld 4	84.6	101.8	14	7
Weld 5	73.3	92.1	37	17
Spec. Min. (RS-70 Grade)	70.0	80.0		15
<u>Compression Tests</u>				
Base Metal	84.2			
(Weldment 1)				
Weld 1	73.2			
Weld 2	97.5			
Weld 3	69.5			
Weld 4	82.5			
Weld 5	79.2			

MIG WELDING

MIG welding is a process that can provide high deposition rates and ease in welding in the "out-of-flat position". The process is being developed for joining titanium alloys and has been used to a somewhat lesser degree than TIG welding for actual production and prototype components. MIG welding can be manual, semiautomatic, or fully automatic. MIG welding is particularly well suited for the joining of thicker sections of titanium. The process is very economical for this type of work because high weld finishing rates are obtainable. However, MIG welding also can be used on light gage thicknesses.

In MIG welding, the heat required to melt the joint edges is supplied by an arc between the filler wire and the workpiece. The filler wire replaces the tungsten electrode used in TIG welding. The filler wire, therefore, is designated as the electrode in MIG welding as was the tungsten electrode in TIG welding. The MIG welding filler wire also is called "electrode wire", "consumable electrode", "consumable electrode wire", "filler metal", and "filler wire". For welding of titanium, the consumable electrode is either commercially pure titanium wire or a titanium-alloy wire. The arc and surrounding area is kept free of air by a flow of inert gas around the electrode, as is the case in TIG welding. All of the metal added to the weld joint is supplied by the consumable electrode. This metal is transferred from the electrode to the workpiece as fine droplets, a metal spray, or by short-circuit transfer. The metal being transferred across the arc may be exposed to much higher temperatures than if it were just being melted. The combination of very high temperatures and fine particle sizes represents a set of conditions ideal for the contamination of titanium. Therefore, in MIG welding, it is extremely important that the arc area be completely protected from exposure to any gases other than the inert gases.

MIG welding of titanium is normally done in the flat welding position. However, when required other welding positions can be used. For example, the Navy has developed suitable out-of-position welding techniques that could be applied to the fabrication of titanium hull structures. A check should always be made before MIG welding titanium in any position to insure that adequate gas shielding is being obtained. In general, good shielding is more difficult to provide when welding in positions other than the flat position.

Equipment. Conventional MIG welding power supplies, torches, and control systems are used effectively in welding titanium. The nature of MIG welding makes this process somewhat more

sensitive to changes in welding equipment characteristics than is the case for TIG welding. The limited published information on MIG welding (Refs. 1, 6, 57-59) indicates that constant potential power sources are being used with various types of constant wire feeders. Conventional MIG welding water-cooled torches are modified to provide the necessary supplemental gas shielding needed for titanium. Although MIG welding has been conducted in vacuum-purged weld chambers and in the open atmosphere, it is likely that most applications of this process will be set up in air. Typical MIG welding equipment arrangements are shown in Figures 52 and 53 (Refs. 7, 20).

For in-air welding with the MIG process, supplemental shielding devices described earlier should be employed. Trailing shields designed for MIG welding are usually considerably longer than those used in TIG welding. This is to insure good protection for the larger volumes of material that are heated during MIG welding and as a result cool more slowly.

Direct-current reverse polarity is normally used in MIG welding of titanium.

Wire-Feeding Equipment. For economic reasons MIG welding equipment should be kept in proper operating condition at all times. The most common causes of downtime are found in the wire-feed system. A typical wire-drive unit for constant-potential welding is shown in Figure 54. For feeding filler wire, a spool of wire is placed on a spindle threaded through a straightening device and into the grip of wire-feed rolls. From the rolls the wire is pushed through a flexible wire-feed cable through the gun and into the arc. Hoses and plumbing to supply the gun with shielding gas and cooling water, if used, are included.

The only function of the wire feeder is to move wire and shielding gas to the arc in such a manner as to provide a sound porosity-free weld deposit. It is up to the operator to move the gun and the arc along the seam to distribute the weld metal properly.

In a correctly designed wire-drive system, the wire is confined laterally so that it can move only in the desired direction. If the drive motor has sufficient power, the wire will move smoothly from spool to gun.

Often there are signals of pending wire-feeding failures. An alert operator becomes aware that the wire speed is varying, which is usually the signal that something is going to happen. Before a complete

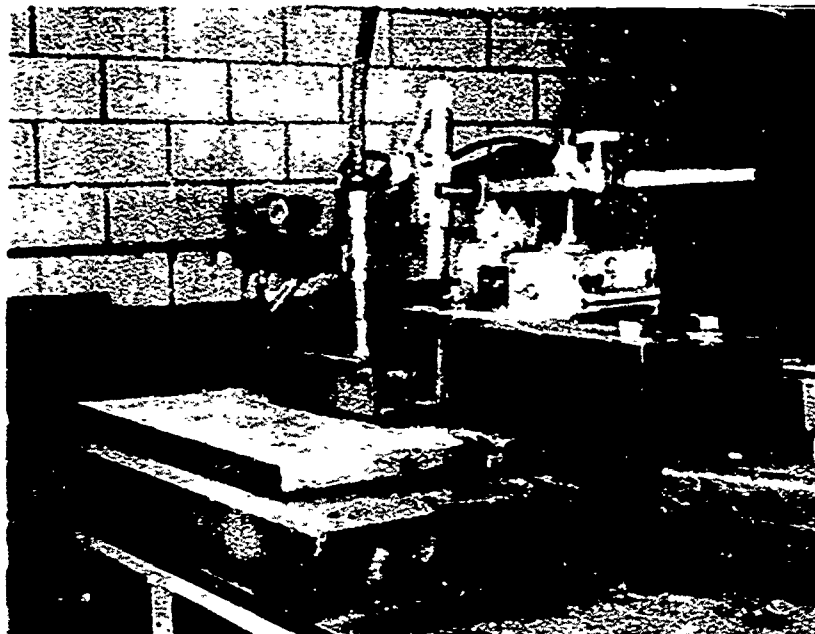


FIGURE 52. MIG WELDING-EQUIPMENT ARRANGEMENT FOR WELDING IN THE OPEN ATMOSPHERE (REF. 7)

Front clamping bars are removed.

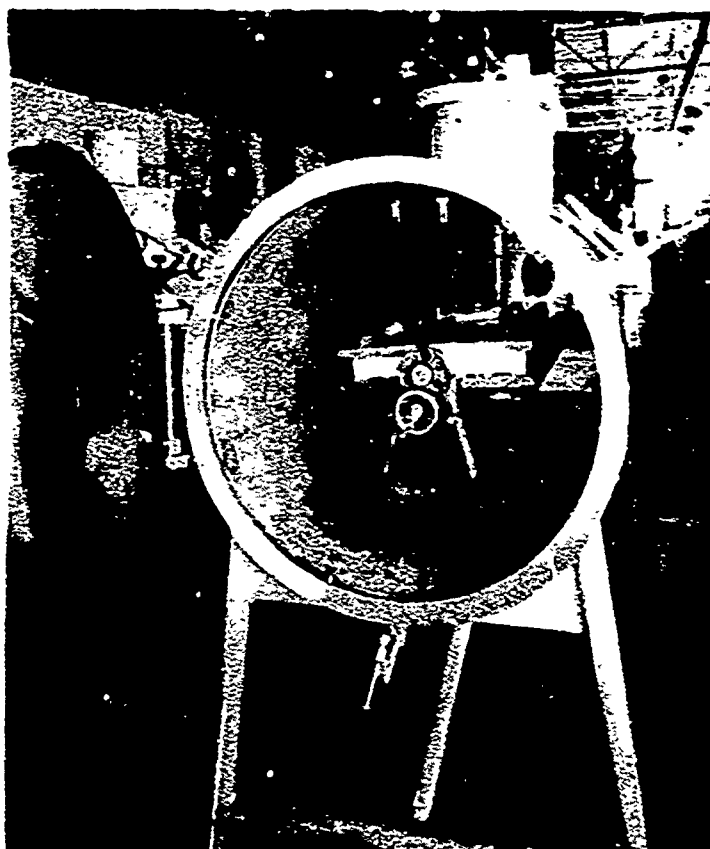


FIGURE 53. MIG WELDING ARRANGEMENT IN A CONTROLLED ATMOSPHERE WELDING CHAMBER (REF. 20)

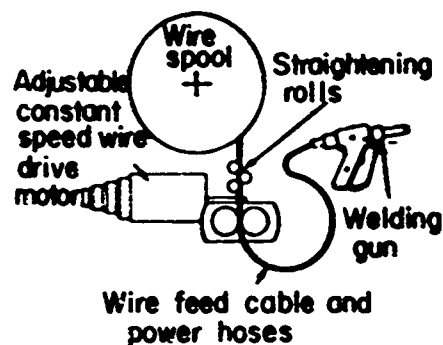


FIGURE 54. (REF. 60)

stoppage occurs, a quick step-by-step inspection of the equipment will usually locate the trouble. Precautions that should be taken with wire-feeding apparatus are well known and are reviewed below (Refs. 5-7, 60):

- (1) Check the wire on the spool or coil. If it is not wrapped snugly and if loops have slipped down over the wire as it is drawn off the spool, the effect is the same as pulling the wire through a knot. This situation can occur if the spool is mounted horizontally and the friction device allows it to coast when the arc is stopped. When wire is fed from a barrel, rolling the barrel will also cause the wire to tangle. The effect of an entanglement is usually gradual, but it can eventually stop the movement of wire entirely.
- (2) Check the adjustment of the wire-straightening rolls. Very little bending is required to remove the "cast" from the wire, and excessive bending as shown in Figure 55 will give it an opposite cast. This increases the load on the drive motor and causes overheating.

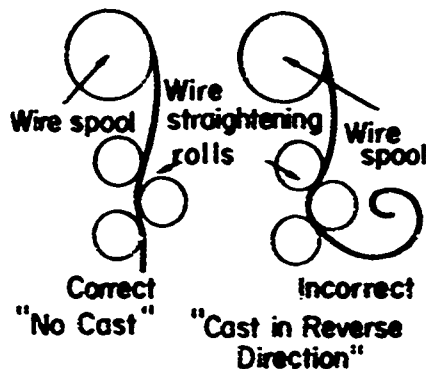


FIGURE 55. (REF. 60)

- (3) Check the distance from the point where the wire leaves the feed rolls to where it enters the wire-feed cable, see Figure 56. This is possibly the most critical link in the whole system because the wire is unsupported and is also subjected to maximum thrust. If this distance is adjustable make sure the unsupported wire is as short as possible. If it is not adjustable, make sure the various parts are in perfect condition; parts showing any wear should be replaced.

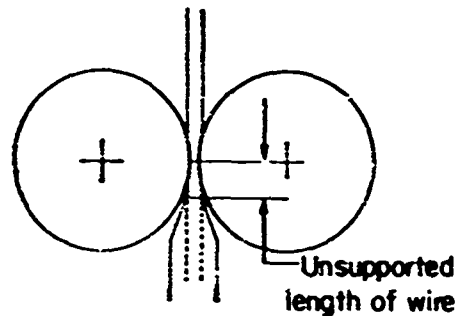


FIGURE 56. (REF. 60)

- (4) Make sure the wire enters at the proper location on the drive rolls. If it approaches the rolls at an angle, it tends to climb out of the groove. Then the rolls tend to separate, loosening traction on the wire and allowing it to slip, Figure 57.

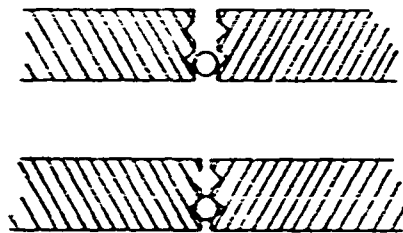


FIGURE 57. (REF. 60)

- (5) Make sure the drive-roll clamping pressure is as recommended by the manufacturer. Too light a pressure will allow slippage, and too heavy will flatten the wire to the point where it will not go through the contact tube in the gun, Figure 58.

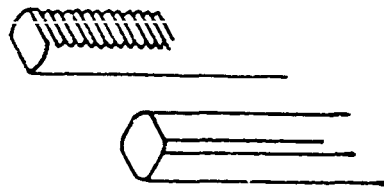


FIGURE 58. (REF. 60)

- (6) Make sure the wire-feed cable is clean and free of kinks. Steel welding wires are usually copper stained, and the copper tends to flake as it passes through the drive rolls, especially knurled drive rolls. Some of the flakes are then scraped off inside the wire-feed cable, Figure 59.

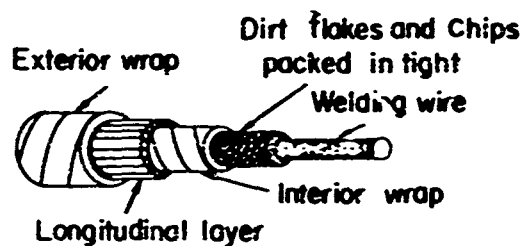


FIGURE 59. (REF. 60)

If the wire-feed cable is not cleaned out often enough, dirt, copper flakes, or other foreign material can accumulate and jam the wire so tight that it cannot be moved either way, even with tools. However, the gun and cable can usually be cleaned out (with the wire removed) by placing an air-hose nozzle on the exit end of the contact tube and blowing the chips out. When the wire-feed cable is not free of kinks, a condition known as "wire whip" can occur (Ref. 57). This term describes a condition when the electrode wire upon emerging from the contact tube, surges erratically toward the joint faces. An analysis of one equipment setup revealed that the wire, after leaving the straighteners, had passed through one 90-deg turn and two 180-deg turns before entry into the welding gun. This series of turns induced an irregular curvature in the wire that eventually resulted in wire whip. The problem was alleviated by mechanically supporting the

wire-carrying cable from an overhead roller device. Figures 60 and 61 illustrate the change made to overcome the wire-whip problem. It is a good general rule to clean the cable every time a new spool of wire is installed, at least until a cleaning program based on experience is established.

- (7) Make sure the correct wire-feed cable and/or liner for the job is used. A cable with too small a bore will cause excess friction when bent, and too large a bore will let the wire deflect laterally and possibly collapse.

The first and final test for a wire-feed system is the ease of wire movement. With drive-roll clamping pressure removed, and with the hoses and cables relatively straight, the wire should be free to move in either direction without too much effort.

MIG Gun. Although the gun or torch is the last link in the wire-feed chain, it usually does not cause gradual failure of wire feed as the others do. Instead, its function and its possible failings are more concerned with electric power and shielding gas.

One of its functions is to transfer the welding power to the wire, preferably at the exit end of the contact tube. Its other major function is to direct a gas shield over the weld zone so as to exclude the adjacent atmosphere, which would otherwise cause porosity in the completed weld.

The gun is without question the most abused part of the system, and yet, it absolutely must be kept in good condition to produce good welds. Bent, worn, or broken parts should be replaced.

Contact Tube. Particular attention should be given to the contact tube. These tubes are usually made of copper or some special copper alloy, and they are subject to a number of ills. They become spattered, they wear out, and they are occasionally melted when the wire burns back to the tip as a result of wire-feed failure.

Burn backs are generally caused by arcing in the contact tube. This makes the wire stick, and then the open-circuit voltage burns the wire back to the tube.

Worn contact tubes contribute to burn backs because, as the bore size increases, the transfer of electric power to the wire becomes



FIGURE 60. MIG WELDING SETUP SHOWS SHARP BENDS IN WIRE-FEED CABLE (REF. 5, 6)

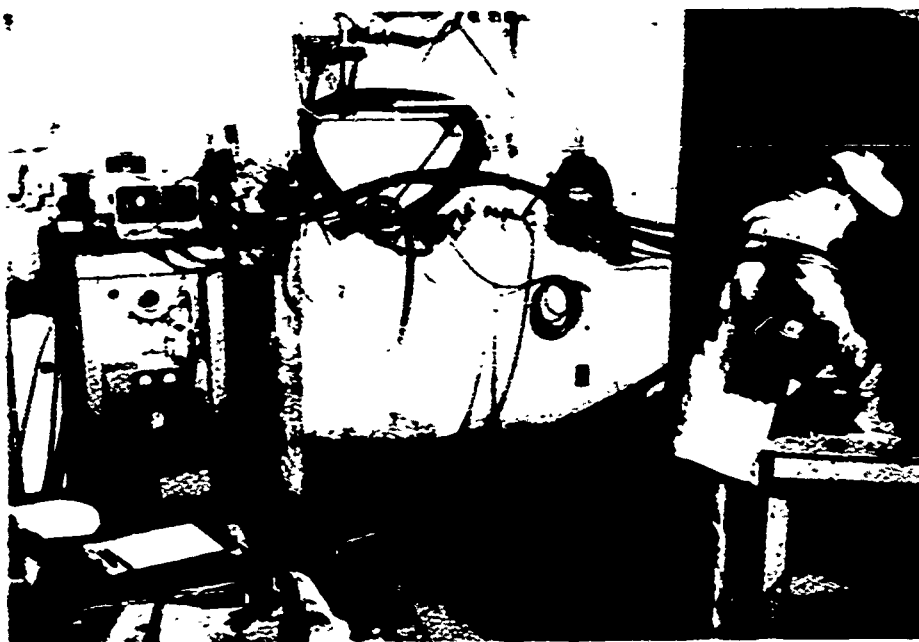


FIGURE 61. HOSE-AND-CABLE SUPPORT ARRANGEMENT EMPLOYED TO ELIMINATE WIRE WHIP DURING MIG WELDING (REF. 5, 6)

erratic. For this reason, reaming out the bores with gas-torch tip cleaners is not recommended.

Burn backs are not too much of a problem with CO₂ shielding gas used with steel because of the short arc length per volt. When welding titanium, inert gases can amplify the burn-back problem. In arc-spot welding applications where argon or argon mixtures are necessary, the burn-back problem can be handled very well with burn-back timers.

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

Gas leaks or cooling-water leaks can also cause porosity in titanium welds. Bending, plugging or mis-installation of parts should be corrected.

Materials. A limited number of titanium alloys have been welded with the MIG process. The alloys that have been MIG welded to date include:

- Commercially pure titanium (Ref. 5)
- Ti-5Al-2.5Sn (Ref. 5)
- Ti-3Al-13V-11Cr
- Ti-4Al-4V (CP titanium filler wire) (Ref. 9)
- Ti-6Al-4V (CP titanium and Ti-6Al-4V filler wire) (Refs. 5, 6)
- Ti-7Al-2Cb-1Ta (similar or lower aluminum content filler wire).

It is expected that the MIG process will be adapted for welding other titanium alloys in the not-too-distant future.

The most important material in MIG welding is the welding electrode or filler wire. Commercially pure titanium or titanium alloy filler wires that match the base-metals composition are normally used. MIG welding makes use of wire provided in coil form. Other methods of supplying wire are impractical for MIG welding. The quality requirements for MIG welding wire are perhaps even more

stringent than comparable requirements for TIG wire. One reason for this is that welding current must be transferred from the contact or guide tube to the wire. Also, the wire-feed speeds employed in MIG welding are much higher than those employed in TIG welding. Therefore, any wire characteristic that tends to impede the flow of wire through the welding torch may cause undesirable variations in welding conditions or even an equipment malfunction. Such undesirable characteristics as kinks, soft spots, and rough surfaces are not tolerable in MIG welding wire.

Cleanliness of the welding filler wire is extremely important, and good cleaning practices must be used to minimize contamination. Fabricators have experienced unacceptable variations in weld quality that have been attributed to inadequate control of filler-wire preparation.

One fabricator found a "waxlike" surface coating at regular intervals along the length of Ti-6Al-4V filler wires (Ref. 6). The nature of this coating could not be identified. Since cleanliness is extremely important in welding titanium, it is believed that coatings of this type can contribute to porosity. Attempts to remove the surface coating by passing the wire through a tube filled with abrasive fibers were not totally effective. However, periodic inspections showed definite evidence of residues on the abrasive fibers.

Electrochemical surface finishing techniques have been developed for inspection of incoming filler-wire quality (Ref. 61). The chem-milling technique discloses seams, laps, and some other defects that are difficult to find by other means.

Titanium welding wire is supplied by all of the major titanium companies and by several companies specializing in processing high-quality metals and alloys. Filler metals that are cleaned and packaged in sealed containers are available.

Gases for shielding the weld pool, underbead side of the weld, and hot weld metal include the welding grades of argon, helium, and argon-helium mixtures. Inert gases containing oxygen additions should not be used.

Tooling and Fixtures. Backing for MIG welding titanium alloys has been varied depending on joint design, quality requirements, and fabricator. Backing bars are used to provide root-side shielding and to facilitate control of the weld puddle, root reinforcement, and heat effects of welding. Backing bars also are used to minimize

distortion by promoting more rapid solidification and cooling of weld metal. In some instances, the more rapid solidification of weld metal is reflected in higher ductility and toughness (Ref. 9).

Copper is the most popular material for back-up bars used for MIG welding. Solid-copper back-up bars were used for fabricating tank-cupola prototypes (Ref. 41) while water-cooled copper back-ups combined with inert-gas shielding devices were used in development work on thick-plate cross sections (Refs. 5, 6). Contamination of titanium welds by the back-up materials can occur and precautions must be taken to avoid excessive heating or puddling.

Welding Conditions. The welding conditions employed in MIG welding are dependent on two separate groups of factors. These groups include those that affect (1) welding arc characteristics and (2) welding conditions.

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

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

Table X illustrates some of the combinations that have been used by various investigators in the MIG welding of butt joints in titanium and its alloys. Table XI illustrates welding conditions used for other types of weld joints. Insufficient work has been reported on MIG welding to allow any comment on the most suitable conditions of those that have been investigated. Because of difficulties with crater cracking and control of penetration, starting and runoff tabs are recommended (Ref. 9).

PROPERTIES

Information on properties of MIG welds in titanium and titanium alloys is scarce due to the limited use of MIG welding for titanium alloys.

The mechanical properties of the weld metal are related to its compositions. Weld-metal composition, in turn, depends on the composition of the filler metal that is used to deposit the weld, the composition of the base metal, and the welding conditions that affect the ratio between the amount of filler wire and base metal melted in making the weld. Therefore, weld-metal properties can be varied through filler-metal selection and to a lesser extent through changes in welding conditions. Weld-metal properties for typical material combinations are given in Table XII. Weldment properties are given in Table XIII.

Only unnotched and notched tension and Charpy vee-notch impact data are available. Satisfactory properties are generally obtained in alpha or alpha-beta alloys. Very low impact properties are obtained in the beta alloy. Low impact values may result from foreign material or deposits (Ref. 9) on the welding wire.

Weld-cracking problems have been encountered at locations where weld passes cross one another and in multipass welds. Accordingly, procedures have been devised by one fabricator to use single-pass welding as much as possible and to minimize the number of locations at which two different welds come into contact (Ref. 9). In particular, crossover welding, which permitted one weld deposit to cross another, was avoided. Cracking was detected in 2-inch-thick Ti-6Al-4V weldments made with ten passes of Ti-6Al-4V filler wire when no preheat was used. A similar specimen made using 125 F preheat for the first and second passes, and a 175 F interpass temperature for the remaining passes showed no radiographic evidence of cracks (Ref. 5). These weldments also contained porosity that tended to concentrate at the ends of the joints. Sources of additional properties information are listed in Table XIV.

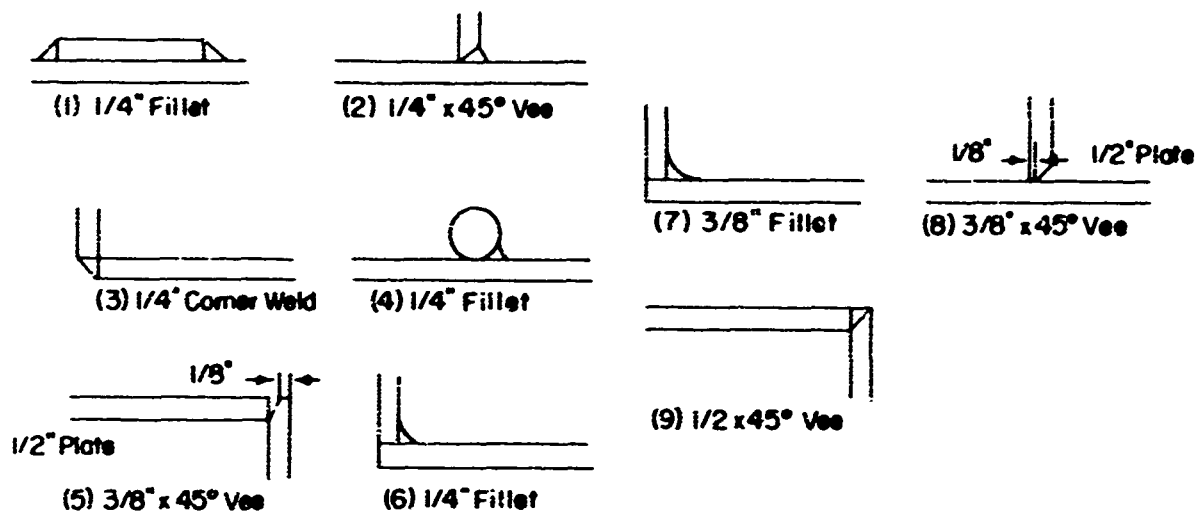
TABLE X. MIG WELDING CONDITIONS FOR VARIOUS TITANIUM ALLOYS (REF. 9)

Material Thickness, in.	Travel Speed, ipm	Current (DCRP), amp	Arc Potential, volts	Electrode		Tip to Work Distance, in.	Torch Shielding Flow Rate (CFM) and Gas	Reference
				Distance, in.	Speed, ipm			
0.125	15/25	250/260	26	0.062	200/225	--	50A-15He	8
0.250	15/25	300/320	30	0.062	300/320	--	50A-15He	8
0.250	27	385/395	36/38	0.062	100	--	10A-100He	63
0.375	25	350/360	33	0.045	865	0.6(b)	20A-100He	Boeing
0.500	15/30	340/360	40	0.062	375/400	--	50A-15He	8
0.625	15/35	350/370	45	0.062	400/425	--	50A-15He	8
0.625(a)	Manual	300/320	38	0.062	--	--	36A-10He	5, 6
1.0(a)	20	320/330	37	0.062	380	1.2	70A	--
1.0(a)	23	340/350	36	0.062	380	1.2	70A	5, 6
2.0(a)	Manual	300/320	38	0.062	--	--	36A-10He	5, 6
2.0(a)	20	330/340	33	0.062	450	0.750/1.12	Chamber A	Battelle
2.0(a)	27	315/325	33	0.062	450	0.875	Chamber A	Battelle

(a) Multipass procedures.

(b) 8-degree leading angle.

TABLE XI. GAS METAL-ARC WELDING CONDITIONS FOR FABRICATION OF Ti-4Al-4V
TITANIUM TANK CUPOLA (REF. 9)



Type of Joint	Plate Thickness, in.	CP Titanium Filler Metal Diam, in.	Volts	Amp	Wire Feed Rate, ipm
1	1/4	1/32	38	250	1470
2	1/4	1/32	38	250	1470
		1/16	39	400	350
3	1/4	1/32	38	250	1470
4	1/4 plate 1/4 diam round	1/32	38	250	1470
5	1/2	1/16	40	400	350
6	1/2	1/16	39	380	330
7	1/2	1/16	40	400	350
8	1/2	1/16	40	400	350
9	1/2	1/16	40	400	350

TABLE XII. TENSILE PROPERTIES OF MIG WELD METALS IN TITANIUM ALLOYS

Filler Metal		0.2 Per Cent Offset Yield Strength, ksi	Ultimate Strength, ksi	Elongation, per cent in 2 in.	Reduction in Area, per cent	Reference
Nominal Composition	Size, in.					
<u>Ti-5Al-4V Parent Metal</u>						
Parent metal	--	115	132	11	21	63
CP titanium	0.062	83	93	18	39	63
CP titanium	0.062	85	100	31	25	63
5Al-2.5Sn	0.062	123	133	25	25	63
5Al-2.5Sn	0.062	131	139	11	19	63
6Al-4V	0.062	128	144	6	9	63
6Al-4V	0.062	129	143	15	13	63
6Al-4V	0.062	139	151	8	8	63
6Al-4V	0.062	143	151	4	5.3	5
CP titanium	0.062	57	72	24	49	5
Parent metal	--	115	132	11	21	65
6Al-4V	0.062	--	135	--	--	
<u>Ti-5Al-2.5Sn Parent Metal</u>						
Parent metal	--	129	135	13	25	63
CP titanium	0.062	77	87	21	34	63
5Al-2.5Sn	0.062	125	138	8	12	63
5Al-2.5Sn	0.052	--	137	--	--	64
6Al-4V	--	127	141	11	16	63

TABLE XIII. TRANSVERSE TENSILE PROPERTIES OF MIG WELDMENTS IN TITANIUM AND TITANIUM ALLOYS

Filler Metal		Offset yield Strength ^(a) , ksi	Ultimate Tensile Strength, ksi	Elongation, per cent in 2 in.	Reduction of Area, per cent	Location of Failure ^(b)	Reference
Nominal Composition	Size, in.						
<u>Commercially Pure Ti</u>							
CP titanium (parent metal)	0.62	97(0.1)	107	22.0	49.2	--	9
CP titanium(c)		99(0.1)	110	15.0	53.7	HAZ	9
<u>Ti-4Al-4V Alloy</u>							
4Al-4V (parent metal)	0.62	115	127	14	44	--	62
4Al-4V ^(c)		113	115	12.9	52.5	HAZ	62
CP titanium		114	122	--	25	W	
<u>Ti-5Al-2.5Sn Alloy</u>							
5Al-2.5Sn (parent metal)	--	133	138	20	43	--	62
5Al-2.5Sn		132	142	--	38	--	62
CP titanium		124	130	--	34	--	62
<u>Ti-6Al-4V Alloy</u>							
6Al-4V (parent metal)	--	135	148	16	42	--	62
6Al-4V		138	152	--	44	--	62
CP titanium		126	134	--	30	--	62

(a) 0.2 per cent unless otherwise noted.

(b) HAZ = heat-affected zone; W = weld metal.

(c) Filler metal deposited at 365 amp and 45 v; side-bend samples bent 180 deg without cracking.

(d) Filler metal deposited at 400 amp and 46 v; side-bend tests fractured at 55 and 80 deg.

TABLE XIV. MIG WELD PROPERTY DATA SOURCES

Base Alloy (a)	Filler Alloy	Thickness, in.	Properties Reported and Temperature Range				Reference
			Static Tension(b)	Notched Tension(b)	Charpy V Notch	Other	
CP titanium, 6Al-4V, and 5Al-2.5Sn(c)	Various	--	--	--	--	--	1
CP titanium	CP titanium and 6Al-4V	2	RT	--	-80 to +80	--	57
CP titanium	CP titanium, 6Al-4V, and 5Al-2.5Sn	2	RT	--	-80 to +80	--	57
13V-11Cr-3Al	13V-11Cr-3Al	2	RT	--	-80 to +80	--	57
6Al-4V	CP titanium and 6Al-4V	2	RT	--	-80 to +80	--	57
6Al-4V	CP titanium, 6Al-4V, and 5Al-2.5Sn	1	RT	RT ($K_t = 3.9$)	-300 to 150	Flat tension	58
6Al-4V	CP titanium and 6Al-4V	2	RT	--	--	--	6

(a) Annealed, as welded.
 (b) 0.505 round specimens.
 (c) Data from before 1960.

ha
ni
ap

fal
we
bil

fac
19
lis
tit
ni
de
el
Fa
re
a
su
te
li
we
an
de

el
pl
co
th
m
ho
ad
jo
m
to
W
th
er

tit

Applications for MIG Welding Titanium Alloys. MIG welding has been used to manufacture a variety of complex shapes from titanium and for welding thick titanium plates. Some good examples of applications for the process are described in the following.

Armored Vehicles. Armored tank cupola components fabricated from Ti-4Al-4V alloy are shown in Figure 62 (Ref. 9). MIG welding was used extensively throughout to demonstrate the fabricability of complex titanium shapes by MIG welding.

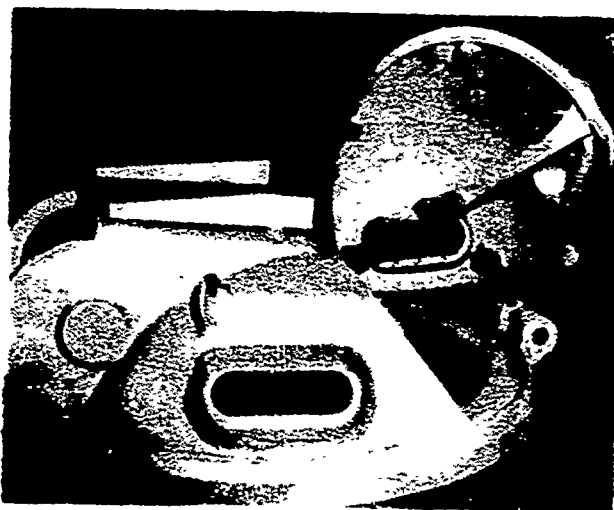
Thick Titanium Plates. Independent and Government facilities have been welding thick plates of titanium alloys since about 1952. In one program (Ref. 6) the objective was to develop and establish procedures for welding 2-inch and 5/8-inch annealed Ti-6Al-4V titanium alloy H-plates and corner joints with commercially pure titanium and Ti-6Al-4V filler metals. The procedures for welding were developed using the inert-gas-shielded metal-arc consumable-electrode process using crack-susceptibility plates and I-plates. Fabrication of the joints with unalloyed filler metal was accomplished readily; however, with the alloyed filler metal it was necessary to use a 175 F preheat and a 170 F interpass temperature for crack-susceptibility test plates, and a 175 F preheat and a 200 F interpass temperature for fabricating H-plates. Two-inch-thick plates of Ti-8Mn alloy also have been welded in early titanium alloy armor-welding development programs (Ref. 62). Due to weld-metal cracking and the development of newer, more readily weldable alloys, welding development work with the Ti-8Mn alloy was terminated.

For welding 2-inch-thick titanium plates, automatic consumable-electrode equipment was set up in a chamber for welding 2-inch-thick plate (Ref. 20). The plates were clamped in a welding fixture that could be rotated inside the chamber for weld passes on either side of the double-vee joint. This welding fixture was attached to a traversing mechanism that moved the plates under the welding torch mounted on a horizontal plate at the top of the welding chamber. The torch could be adjusted vertically or horizontally to position it with respect to the joint. Adjustments in wire-feed speed and welding travel speed were made from outside the welding chamber. Water cooling was supplied to the welding torch and to the entire shell of the welding chamber. Water cooling the chamber will be advantageous in removing some of the heat generated during welding. A constant-potential welding generator was used in welding tests.

A typical joint design and a back-up bar for welding thick-plate titanium alloys are shown in Figure 63.



a. Completed Welded Titanium Cupolas



b. View of the Dome and Hatch Assemblies in Process



c. Nose-Piece Subassembly in Position for Welding to the Cradle

FIGURE 2. ILLUSTRATION OF TANK-CUPOLA COMPONENTS FABRICATED USING THE MIG WELDING PROCESS (REF. 9)

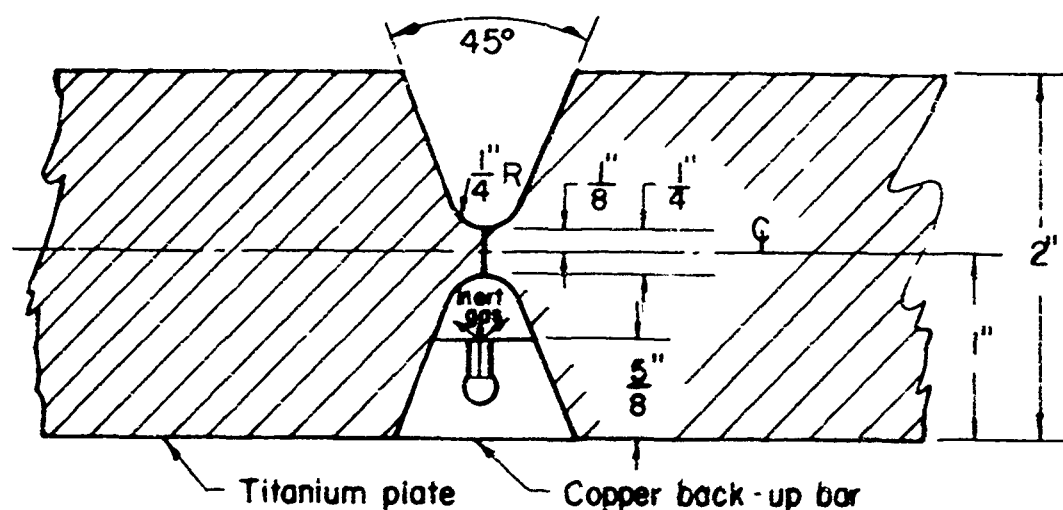


FIGURE 63. TYPICAL JOINT DIMENSIONS FOR WELDS IN 2-INCH-THICK Ti-13V-11Cr-3Al TITANIUM ALLOY PLATE (REF. 20)

ARC SPOT WELDING

Arc spot welding is being developed for joining titanium alloys in applications where resistance spot welding cannot be used or as an alternate to the resistance-spot-welding process. Arc spot welding can employ either the basic TIG or MIG welding process and is a semi-automatic or fully automatic technique. Arc spot welding can be used to join thickness combinations which are not suitable for resistance spot welding and in joints that are accessible from one side only.

The major difference between arc spot welding and either conventional TIG or MIG welding is that there is no relative lateral movement between the welding torch and the parts being joined. Starting and stopping cycles for the welding process are extremely important in arc spot welding. The total welding time generally is quite short so that it is necessary to automatically program welding parameters to insure a smooth start and stop of the process. The shielding of arc spot welds is somewhat simpler than for conventional TIG or MIG welds. Simple cylindrical auxiliary shields placed around the welding torch are sufficient to prevent contamination from the top surface of the weld. Shielding of the underside of the joint also may be required.

Equipment. The equipment required for arc spot welding is generally similar to conventional TIG or MIG welding equipment. However, the arc-spot-welding nozzle is a complete down-to-the-surface shield and it is a locator for arc length or contact-tube-to-work distance. Also, some means of programming appropriate welding parameters to obtain desired starting and stopping cycles is used.

Materials. The materials used in arc spot welding usually are the same as those used in either TIG or MIG welding. Earlier sections should be consulted for comments on materials.

Welding Conditions. The welding conditions employed in arc spot welding are generally similar to the TIG or MIG welding conditions used in joining comparable thicknesses of the outer materials. Arc spot welding can be used for joining similar and dissimilar metal thickness combinations. The arc spot is always made through a relatively thin member of the part being fabricated. The backing member may be thin or thick. There are indications that the top layer that can be penetrated by TIG spot welding is limited to 0.060 to 0.070-inch-thick titanium. However, detailed welding conditions for arc spot welding of titanium have not been reported.

ELECTRON-BEAM WELDING

Electron-beam welding is an extremely attractive process for use in joining titanium and other highly reactive materials. The process is applicable to a wide range of thicknesses from about 0.0015 inch to over 2 inches. One major advantage of the process is that all welding is performed in a high-vacuum chamber. Contamination of the weldment from external sources is essentially nonexistent. All electron-beam welding is done using mechanized equipment. Electron-beam welds made with high-power-density type equipment exhibit a characteristic high depth-to-width ratio of the weld metal and heat-affected zone. This characteristic is advantageous from the standpoint of minimizing the distortion that normally accompanies welding. It may also result in welds whose properties are not altered significantly from those of the base material.

The electron beam can concentrate a large amount of energy in a spot diameter of about 0.010 inch or less (Ref. 60). Energy densities range from about 5,000 to 40,000 kw per square inch, compared with about 100 kw per square inch for tungsten-arc welding.

In electron-beam welding, the heat required to melt the joint edges is supplied by a focused electron beam generated in an electron

gun. This beam is focused and accelerated so that it strikes the joint line parallel to the existing interface. Electron-beam welds are usually made without the addition of any filler wire.

Equipment. Electron-beam welding equipment is classified in two divisions. High-voltage welding is performed in the 75,000 to 150,000-volt range while low-voltage welding is performed in the 15,000 to 30,000-volt range. Normally, the high-voltage equipment produces much narrower heat-affected zones than low-voltage equipment.(Ref. 66). Low-voltage equipment provides a wider weld and is used very effectively in special can-sealing operations. Acceptable welds can be made with either type of equipment. A schematic diagram of an electron-beam welding machine is shown in Figure 64 (Refs. 67, 68). Special electron-beam units using either clamp-on-type chambers of special electron-gun assemblies designed to allow the electron beam to be projected into the air have not seen much use on titanium. Clamp-on-type chambers may be quite useful in the joining of long lengths of special shapes fabricated from titanium.

Fixturing is needed to hold the parts in position, but the fixturing need not be as heavy as for other welding methods (Ref. 69). Copper chill bars can be used to restrict the width of the heat-affected zone and to confine and control the fusion-zone geometry (Ref. 66).

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

There are no known applications where filler metal is used for electron-beam welding of titanium alloys.

Welding Conditions. Welding conditions 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

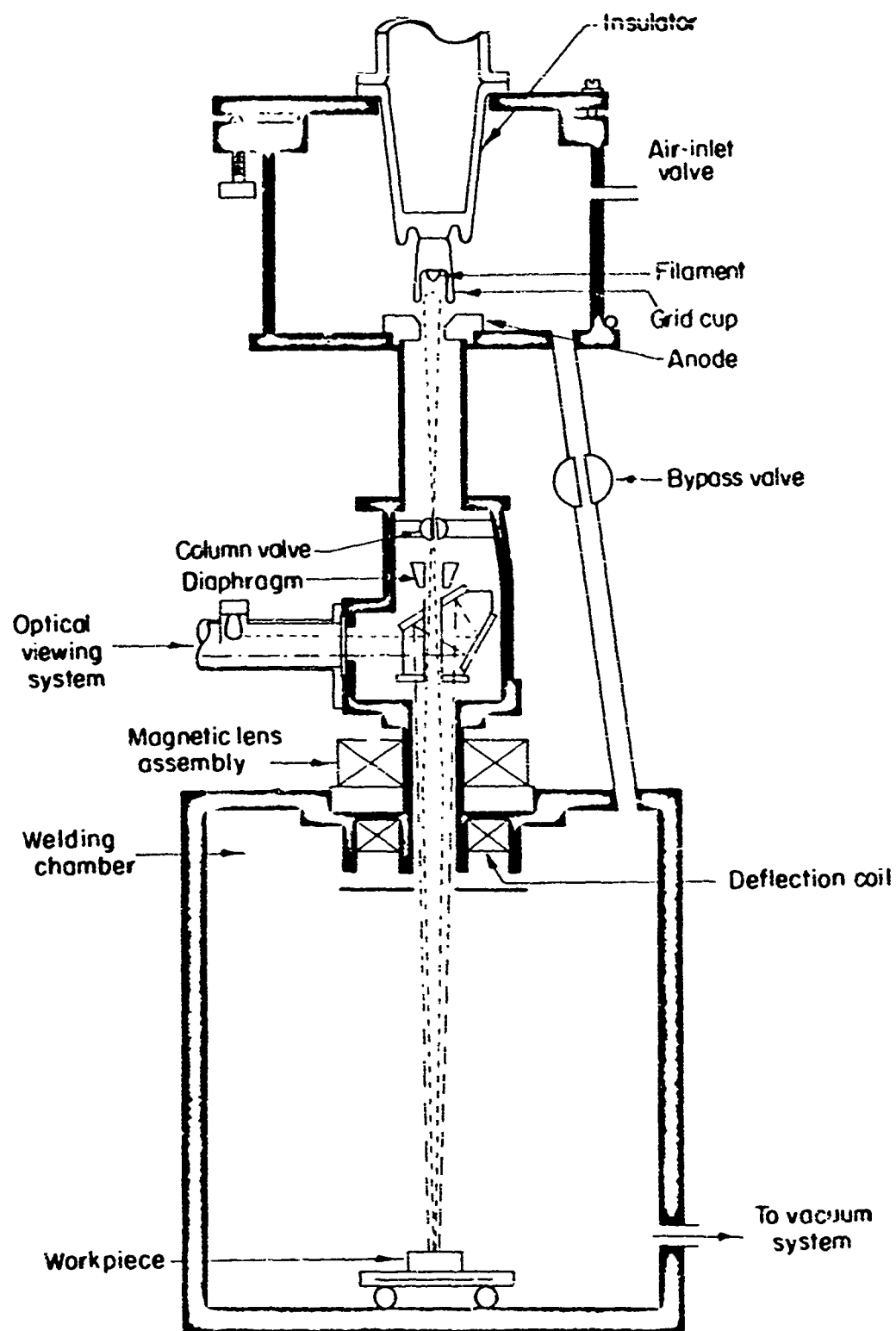


FIGURE 64. SCHEMATIC DIAGRAM OF AN ELECTRON-BEAM WELDING MACHINE (REF 68)

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 eliminated by a second weld pass made at somewhat lower energy levels with a slightly defocused beam. However, undercutting has been largely reduced by making minor adjustments in travel rate (Ref. 66). The underside of electron-beam welds also may exhibit an undesirable contour. Some type of metal-removal operation is generally required to produce an acceptable underside contour.

The flat welding position is used in electron-beam welding. The welding positions that can be used are limited by the versatility of the available welding equipment. Table XV shows some of the welding conditions that have been used in the electron-beam welding of titanium and its alloys.

Properties. Sources of property data on electron-beam welds are shown in Table XVI. In general, the properties obtained in electron-beam welds are similar to those obtained in TIG welds. Strengths up to 140,000 psi can be obtained depending on the welding conditions used (Ref. 70). Postweld aging of electron-beam welds in 1-inch-thick Ti-6Al-4V alloy increased the tensile properties 2 to 3 per cent (Ref. 71).

Applications for Electron-Beam Welding Titanium Alloys. Normally used for the production welding of precision assemblies, electron-beam welding has been used for fabricating pressure vessel spheres as shown in Figure 65 (Ref. 72). Electron-beam repair welding has saved tens of thousands of dollars by its ability to make repairs on close-tolerance parts that might otherwise have to be scrapped. Electron-beam welding enabled one fabricator (Ref. 65) to salvage many parts that formerly could not be repaired because of tolerance, configuration and/or material problems. Repairs consisted essentially of patching, plugging, joining, and similar welding-type operations. Typical applications included: adding a block of material to an area where too much stock had been machined off; plugging unwanted holes; adding tabs, bosses, and other fittings to a machined part; filling porosity or voids in machined castings; and

TABLE XV. ELECTRON-BEAM WELDING CONDITIONS

Base Alloy	Thickness, in.	Acc. Voltage, kv	Beam Current, ma	Travel Speed, ipm	Beam Diameter, in.	Reference
5Al-4V	0.05	85	4	60	0.006	42
Ditto	0.2	125	8	18	0.01	42
"	0.191	28.2	170	98	--	--
Several alloys	0.084/0.125	14	250	8 to 10	--	66
5Al-2.5Sn	0.09	90	4.8	18	--	69
13V-11Cr-3Al	0.125	135	6.5	28	--	69
Ditto	0.125	20	95	30	--	
"	0.03	30	26	89	--	40
8Al-1Mo-1V	0.05	110	2	45	0.005	40
CP titanium	0.05	95	1.8	30	--	--
Ditto	0.125	125	6	30	--	--
"	0.250	138	10	25	--	--
"	0.340	150	15	60	--	--

TABLE XVI. ELECTRON-BEAM WELD PROPERTY DATA SOURCES

Base Alloy	Test Condition	Thickness, in.	Type of Tests and Test Temperatures	Reference
6Al-4V, 8Al-1Mo-1V	Annealed, as welded	0.05 and 0.20	Static tension, notched tension ($K_t = 3$), fracture toughness, (RT), and fatigue (75 and 650)	42
13V-11Cr-3Al	Aged, welded	0.05, 0.1, 0.15	Static tension, notched tension ($K_t = 8$), bend and fracture toughness (RT); cyclic loading test (RT)	28
13V-11Cr-3Al	Annealed, as welded Annealed, welded, aged	0.125	Static tension (RT)	69
13V-11Cr-3Al	Annealed, welded, aged	0.125	Static tension (RT)	68
6Al-4V, 5Al-2.5Sn, 13V-11Cr-3Al		0.125	Static tension (RT), sheet impact (-200 to +300)	66
6Al-4V, 5Al-2.5Sn	Annealed, as welded	2	Static tension (RT)	73
6Al-4V	Aged, welded Aged, welded, aged	1	Static tension and fracture toughness (RT)	71



FIGURE 65. ELECTRON-BEAM WELDED TITANIUM
PRESSURE-VESSEL SPHERE

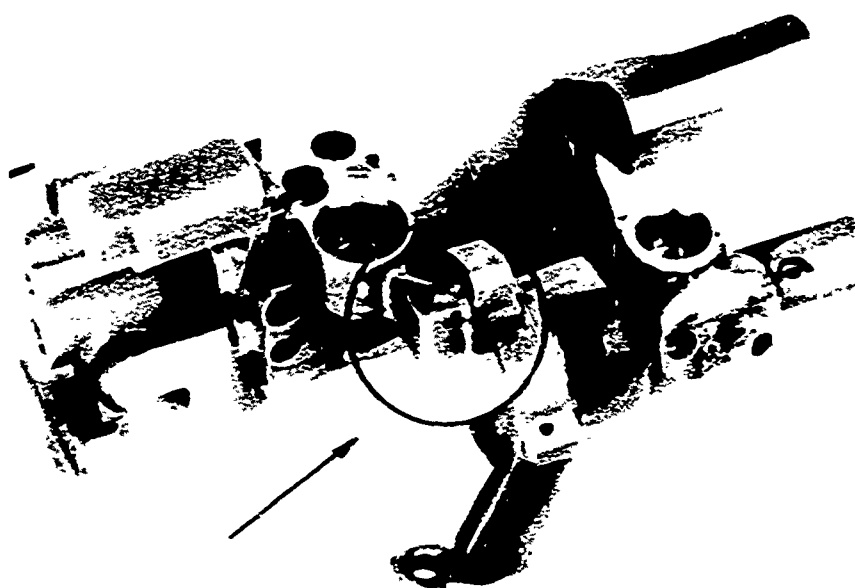
patching cracks in precision fixtures. Examples of electron-beam weld repairs are shown in Figure 66 (Ref. 65).

PLASMA-ARC WELDING (Refs. 74, 75)

Plasma-arc welding is an inert-gas welding method utilizing a transferred constricted arc. The process is now used as an alternative process for TIG welding for a limited number of industrial applications where greater welding speeds, better weld quality, and less sensitivity to process variables are obtained.

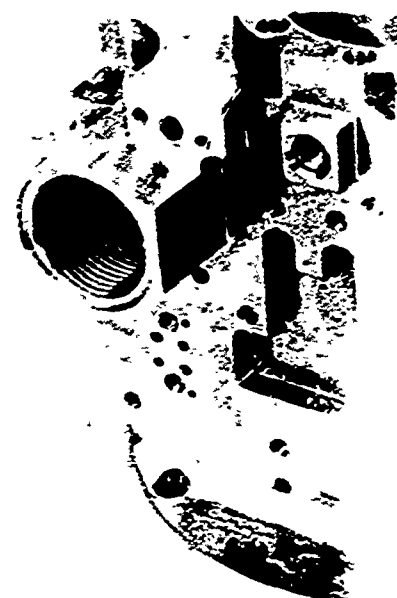
The general characteristics and electrical circuit used for plasma-arc welding are shown schematically in Figure 67. The arc plasma or orifice gas indicated in Figure 67 is supplied through the torch at a flow rate of 1 to 15 cfh. Suitable gases are argon, and mixtures of argon and helium. Argon-hydrogen mixtures also are used for some materials, depending on the application. The gas flowing through the arc-constricting nozzle protects the electrode from contamination and provides the desired composition in the plasma jet.

Relatively low plasma-gas flow rates are used to avoid turbulence and undesirable displacement of the molten metal in the weld puddle. Since the low gas-flow rates are not adequate for shielding the puddle,



a. Boss Added

Precisely-machined AMS 5616 control-spider housings were saved from the scrap pile when an engineering change called for the addition of a wedge-shaped boss (in circle). The critical nature of the part dictated a maximum distortion of 0.00025 inch at the weld area. The boss was welded at a speed of 27 ipm. Welding time was about 1 second. Small spot size, fast travel, and precise beam control permitted concentrating the heat at the vertical interface between the boss and housing. Inspection of the welded parts could detect no measurable distortion.

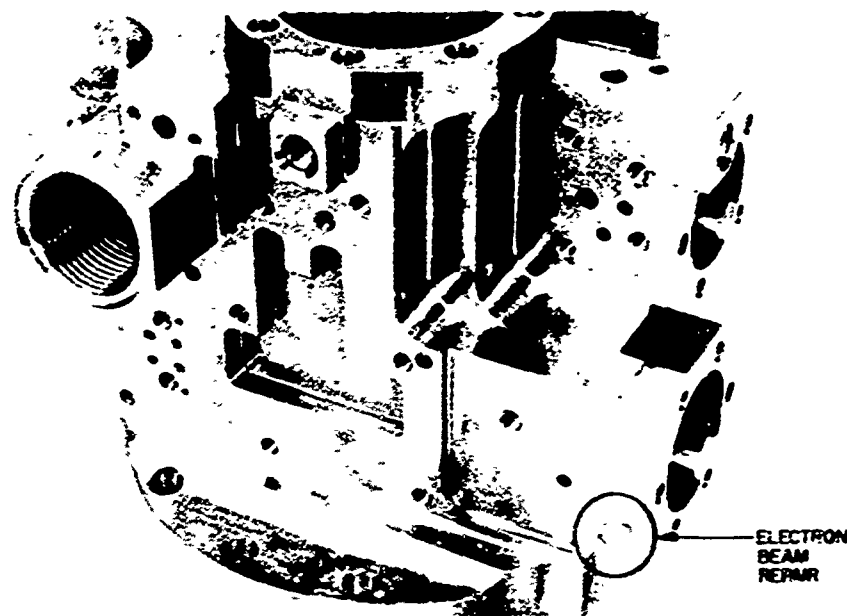


b.

Electron-beam welding saved the part. An unwanted hole was filled by directing the beam parallel to the hole. Minimum heat requirements allowed the pair not only saved the costly part but also saved the cost of fabricating a replacement.

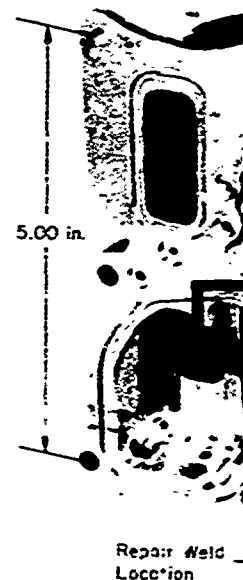
FIGURE 66. EXAMPLES OF ELECTRON-BEAM WELDING

A



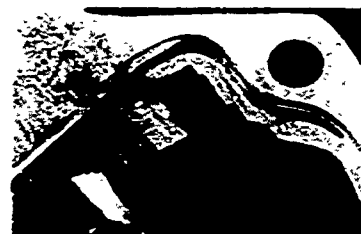
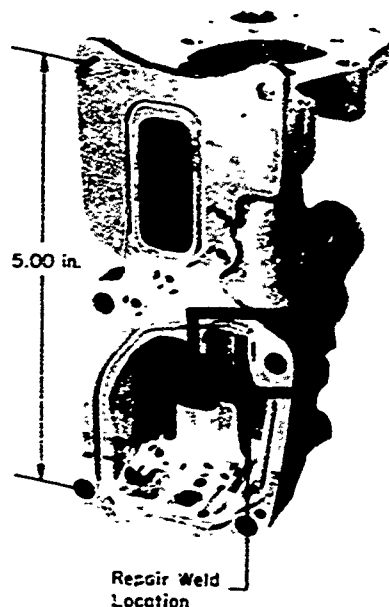
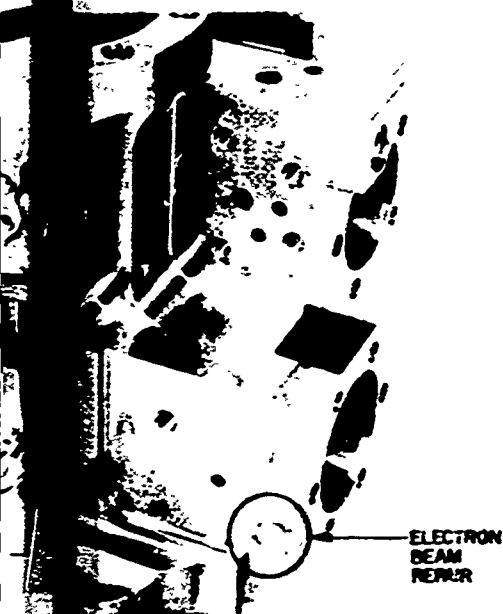
b. Hole Plugged

Electron-beam welding salvaged this machined titanium housing. An unwanted hole was filled by welding a titanium plug in place. By directing the beam parallel to the hole axis, the weld was made with minimum heat requirements and without distortion or cracking. The repair not only saved the costly part, but also avoided a 3-month delay for fabricating a replacement.



Housings were saved from being scrapped. An interior slot from which a small block of material was removed to provide a repair area was then remachined for the application. The setting of 125 kv and 5 in less than 1 second of

FIGURE 66. EXAMPLES OF ELECTRON-BEAM WELDING FOR SALVAGE OF COSTLY, PRECISION PARTS (REF. 65)



c. Slot Narrowed

Housings were saved by using electron-beam welding to correct an interior slot from which an excessive amount of stock had been machined away. A small block of the same alloy, AMS 4214, was welded onto the slot wall to provide an additional thickness of metal. The built-up area was then remachined to bring the slot back to the required width for the application. The tab was welded at 27 ipm, using a power setting of 125 kv and 5 ma. The full-penetration welds were made in less than 1 second of actual welding time.

FOR SALVAGE OF COSTLY, PRECISION PARTS (REF. 65)

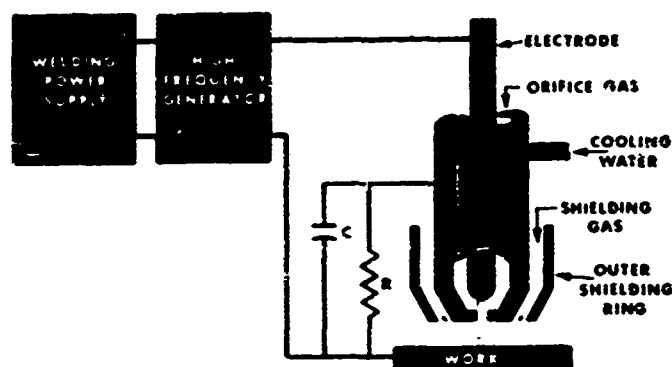


FIGURE 67. SCHEMATIC REPRESENTATION OF PLASMA-ARC WELDING OPERATION (REF. 74)

supplementary shielding gas is provided through an outer gas cup. The type and flow rate of supplemental shielding gas are determined by the welding application. Typical arc and shielding gas flow rates are 4 and 35 cfh, respectively.

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

Keyholing can be obtained on most metals in the thickness range of 3/32 inch to 1/4 inch, and is one of the chief differences between the plasma-arc and gas tungsten-arc processes. Presence of the keyhole, which can be observed during welding, gives a positive indication of complete penetration.

Equipment. A mechanized plasma-arc welding torch is shown in Figure 68. This torch can be operated with either straight or reverse polarity connections at arc currents up to 450 amp. Water-cooled power cables are connected at the top of the torch to supply power and cooling water to the electrode. Fittings are provided on the lower torch body for the plasma-gas hose, the shielding-gas hose, and the cooling water for the nozzle.

The two types of electrodes used in the plasma-arc torch are shown in Figure 69. The tungsten electrode shown on the left is used for straight-polarity operation and is available in 1/16-, 3/32-, and 1/8-inch diameters, depending on the current to be used. A

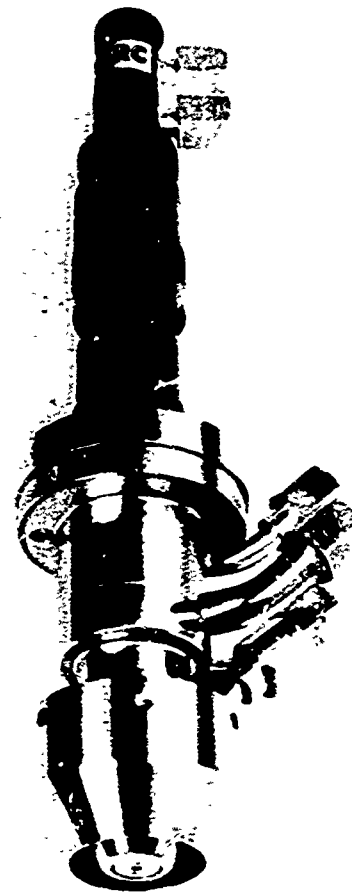


FIGURE 68. MECHANIZED PLASMA-ARC WELDING TORCH (REF. 74)

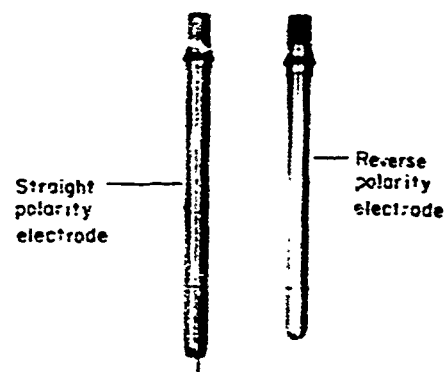


FIGURE 69. TUNGSTEN AND COPPER ELECTRODES USED FOR STRAIGHT AND REVERSE POLARITY OPERATION, RESPECTIVELY (REF. 75)

water-cooled copper electrode shown on the right side of Figure 6^o is used for reverse-polarity operation.

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

Welding Conditions. Typical welding conditions for square butt joints in titanium are shown in Table XVII. Often, conditions determined for joining various thicknesses of stainless steel can be used as starting-point conditions for welding the same thicknesses of other materials. The data in Table XVII were obtained with the electrode set back 1/8 inch from the face of the torch nozzle. Electrode setback is accomplished by rotating a collar on the upper torch body, and the distance is gaged with a probe on a setback tool. Nominal torch-to-work distance is 3/16 inch.

TABLE XVII. PLASMA-ARC WELDING CONDITIONS FOR SQUARE BUTT JOINTS IN TITANIUM

Plate Thickness, in.	Welding Speed, ipm	Arc Current, amp (d.c.s.p)	Arc Voltage, v	Gas Flow Rate, cfh	
				Nozzle	Shielding
1/8	20	185	21	8	30
3/16	15	190	26	12	45

Pure argon is used to weld reactive materials that have a strong affinity for hydrogen, such as zirconium and titanium. Use of argon as the nozzle gas and CO₂ as the auxiliary shield has increased speeds on certain mild-steel welding applications but CO₂ is not to be used for welding titanium or its alloys. When making the second or cap pass on a joint requiring two passes, helium can be used for the plasma and shielding gases. The helium effluent does not have the momentum required to produce a keyhole, but this is not necessary on the cap pass.

There is no information on properties of plasma-welded titanium alloys available in the published literature at this time. However, since several organizations are using the process in development work, properties data probably will be available in the near future.

Applications. Plasma-arc welding has proven commercially important advantages in several specific areas of application. These include the welding of stainless steel tubing, making circumferential joints on copper-nickel and stainless steel pipe, and the welding of reactive-metal compacts to form furnace electrodes. Development activities are under way on other promising applications including missile cases.

Aerospace Applications. Development work is in progress on the plasma-arc welding of missile casings of titanium, 18 per cent nickel maraging steel, D6AC steel, Type 410 stainless steel, and 4130 steel. The plasma-arc welds on thicknesses where keyholing is obtained, have strength, elongation, and notch-toughness properties equivalent to those of TIG welded joints. In addition, welding speed is increased and greater uniformity is obtained. For example, longitudinal and circumferential joints in 3/16-inch-thick titanium tankage are welded in one-fourth the time required for the TIG process. The overall time saving is even greater, because the plasma-arc welds are made on square butt joints while prepared joint designs were required for TIG welding.

Titanium Sponge. Production of ingots of reactive metals such as titanium and zirconium starts with the pressing of small chips of the metal and alloying elements into a mold to form a sponge compact or briquette. The compacts are then welded together to form a primary electrode which in turn is melted into ingot form in a vacuum electric furnace. The welding of the metal compacts is another commercial application for plasma-arc welding.

Use of TIG welding is not permitted in the production of reactor-grade zirconium because of the possibility of tungsten inclusions in the base metal. Since TIG welding is ruled out, MIG welding (or consumable electrode welding) was generally used to join the compacts. However, MIG is an expensive process for this application because of the price of zirconium welding wire (about \$17.00 per lb). Occasional burn backs of the guide tubes in MIG torches resulted in excessive copper deposits in the primary melt electrodes which sometimes caused the copper content of the finished ingot to exceed the specification. Similar difficulties would be expected with titanium made by this method.

In plasma-arc welding of titanium and zirconium sponge, the torch uses a nonconsumable water-cooled electrode operating on reverse polarity without filler-wire addition. There is no tungsten present which eliminates the possibility of tungsten inclusions. The cost of the

welding wire is also eliminated. Plasma-arc welding of sponge compacts is performed both in the atmosphere and in inert-gas chambers. When the compacts are loaded into a chamber, the air is evacuated and the space is back filled with argon. The plasma-argon issuing through the torch nozzle keeps the chamber under positive pressure. When compacts are being welded in the open atmosphere, a trailing shield is attached to the torch to blanket the weld puddle with inert gas to prevent contamination.

Laboratory tests and production experience indicate that transfer of copper from the water-cooled copper electrodes used in this process is essentially zero. In one plant, the plasma torch is taken out of service after each 60 hours arc time to clean accumulated spatter from the electrode and nozzle. In another plant, downtime per torch varies from 5 to 7 hours per month, with production time scheduled for 550 hours per torch.

In one installation, the savings realized by eliminating the use of welding wire paid back the investment in plasma-arc welding equipment in fifteen 8-hour shifts.

RESISTANCE SPOT WELDING

Resistance spot welding has been used more than any other resistance-welding process for joining titanium and its alloys. Spot welding has been used to join titanium in thicknesses ranging from a little under 0.01 inch up to pile-up thicknesses totaling 2-1/2 inches. The thickness that can be welded in any given application is limited only by the power and force capacity of the available equipment.

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. The electrode tips are held against the workpieces with considerable force, so that good electrical contact is maintained throughout the assembly. Resistance-spot-welding techniques can also be used to make joints in which no melting is involved. Such joints can be called diffusion welded, diffusion bonded, yield-point diffusion bonded, or solid-state bonded. Joints of this type are very similar to conventional resistance welds with the exception that no molten metal is formed during the joining process. Titanium normally is welded using the conventional technique involving melting. The diffusion-bonding technique has been used only experimentally. Even conventional spot welds in titanium contain an area around the molten nugget

that is diffusion bonded. The bond in this area is generally strong enough to make a significant contribution to the load-carrying ability of the spot weld.

Titanium is spot welded in much the same manner as other metals. In many respects, titanium is an easy material to resistance spot weld (Ref. 11). The configurations involved in spot welding and the relatively short time periods used with the process tend to preclude any contamination from the atmosphere. As a result, there appears to be little need to consider auxiliary shielding of titanium during resistance spot welding. The relatively low thermal and electrical conductivities of titanium are definite advantages for the spot-welding process. As a result, titanium is often considered to be more readily spot welded than aluminum and many of the carbon and low-alloy steels. Titanium and stainless steel alloys are similar in thermal and electrical conductivity and strength at elevated temperatures. These similarities have simplified the spot welding of titanium. A titanium alloy of a given thickness can be spot welded with the settings that are satisfactory for a similar gage of stainless steel. The recommended spot-welding machine settings developed for titanium by various investigators substantiate this to a degree which is generally as accurate as the ability to incorporate any recommended data into the settings from one production machine to another. In fact, the differences of control-panel settings from machine to machine probably exceed the differences in recommended settings between titanium and stainless steel (Ref. 11).

EQUIPMENT

Titanium has been successfully welded on almost all types of available conventional resistance-spot-welding equipment.

Figure 70 (Ref. 11) illustrates a conventional spot-welding operation. Spot-welding machines used for welding titanium should provide accurate control over the four basic spot-welding parameters: welding current, duration of welding current, force applied to the welding electrodes, and electrode geometry. Various data indicate that each of these parameters may vary to a certain degree without appreciably reducing weld quality. But once the optimum settings are obtained for a given application, it is desirable to have enough control over the parameters to obtain reproducible results. Light gage sheet (less than 0.040 inch) can be welded with most of the 30 kva, 60-cycle, single-phase, rocker-arm-type machines. Because of the higher currents and electrode forces required for heavier gage sheet, the larger press-type machines are more suitable for gages above about 0.040 inch.



FIGURE 70. CONVENTIONAL RESISTANCE-SPOT-WELDING EQUIPMENT

Press-type, 600 kva, 60-cycle single-phase spot-welding machine with control unit, for welding sheets in thicknesses of 0.062, 0.070, and 0.093 inch (Ref. 11).

Various auxiliary controls such as up slope or down slope, or postweld heat controls have not demonstrated any advantages when used in welding titanium.

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. Future developments may show such a preference when weld properties are evaluated more thoroughly on the basis of properties, such as fatigue, or the reduction in residual-welding stresses.

Electrode Types. The most satisfactory electrodes are the spherical-faced, copper-alloy types. They allow a wide range of current settings from the point of no weld up to the point of metal expulsion. Also, higher weld strengths can be obtained with larger weld nuggets, better control of penetration, less electrode indentation, and

less sheet separation for a given set of welding conditions in comparison with other types of electrodes. The truncated-cone electrodes have been satisfactory for some cases but often produce nonuniform sheet separation and excessive electrode indentation. A comparison between weld strengths obtained when using spherical-faced and truncated-cone electrodes for spot welding 0.093-inch Ti-6Al-4V is shown in Figure 71 (Ref. 11). The figure indicates that higher strengths for a given set of weld conditions can be obtained with spherical-faced electrodes. Also, metal expulsion occurs at significantly higher current settings. Resistance Welder Manufacturers Association Class 2 copper alloy was used for both electrode configurations. RWMA Class 3 copper alloy electrodes may also be used and will result in a longer tip life where production rates are high. Electrodes for resistance spot and seam welding may be water cooled externally. Welding conditions and weld properties obtained with external water cooling are not available.

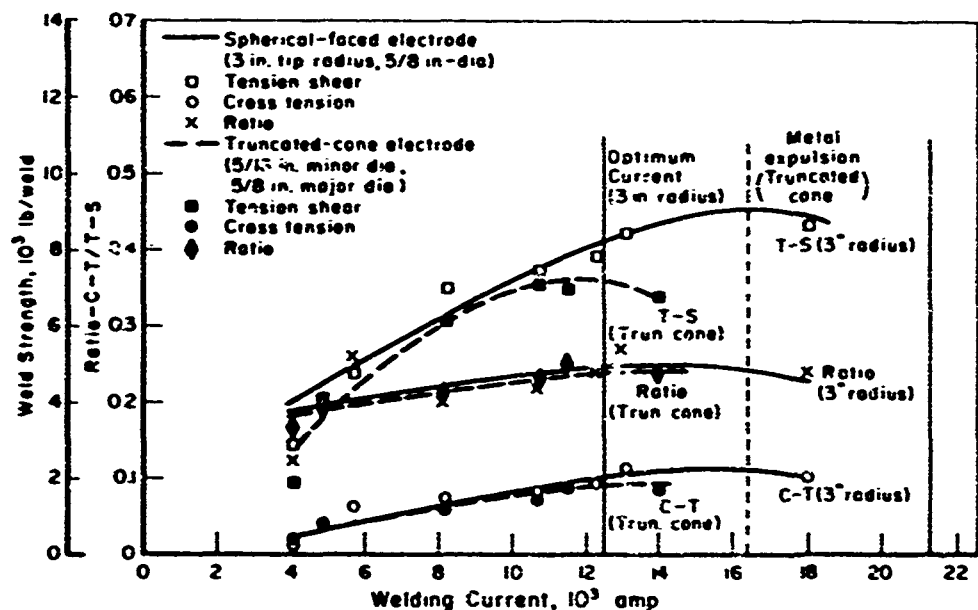


FIGURE 71. SPOT-WELD STRENGTH VERSUS WELDING CURRENT FOR SPHERICAL-FACED AND TRUNCATED-CONE ELECTRODES (REF. 11)

As welded with 2400 lb electrode force, 16 cycles weld time, Class 2 electrodes.

Joint Design Considerations.

Minimum Joint Overlap. When spot welding overlapped sheet joints, it is important to maintain a minimum joint overlap great enough to avoid end tearing of the sheet in tension-shear loading. Insufficient overlap will result in metal expulsion and a very weak spot using the weld settings ordinarily considered to be optimum with proper joint overlap. An illustration of the type of tension-shear failures obtained with varying overlaps at the optimum weld settings is shown in Figure 71 (Ref. 11). For the 0.062-inch sheet, an overlap of 1/4 inch resulted in metal expulsion and end tearing; end tearing is evident with the 1/2-inch overlap, while at overlaps of 3/4 inch and above the tension-shear failures occurred by nugget pullout which is typical of the strongest tension-shear ruptures in titanium. For this 0.062-inch sheet, a minimum overlap of 5/8 inch was selected as the optimum. The 0.070-inch specimen in Figure 72 (Ref. 11) illustrates the occurrence of metal expulsion caused by too little overlap. Here, overlap was only 3/8 inch, while the optimum for this gage was fixed at 5/8 inch.

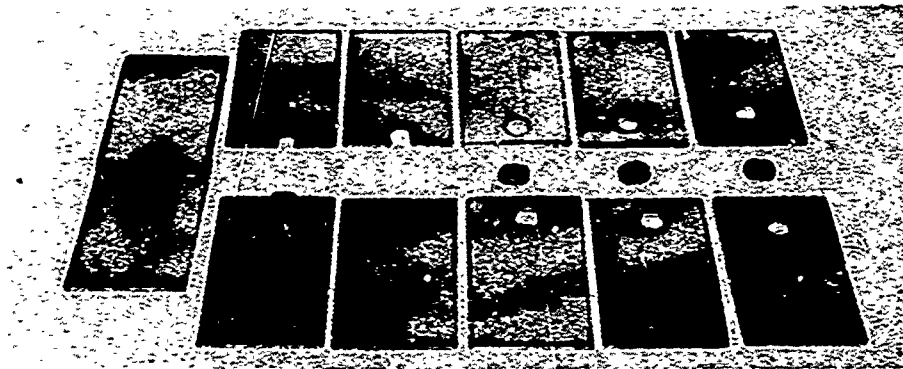


FIGURE 72. THE EFFECT OF MINIMUM CONTACTING OVERLAP ON THE TYPE OF RESULTING FAILURE FOR TENSION-SHEAR SPECIMENS (REF. 11)

The specimen at the left is 0.070-in. sheet with 3/8-in. overlap. Overlap distances for 0.062-in. specimens from left to right are: 1/4, 1/2, 3/4, 1, and 1-1/2 inches, respectively. A decrease in overlap changes failure from button pullout to end tearing.

Minimum Spot-Weld Spacing. In most materials, when spot welds are placed too close together, a portion of the current required for the second weld is shunted through the preceding weld. This, of course, means that the actual weld current is somewhat below the optimum and the resultant weld may be weak because of low heat, even though the machine is set at the optimum weld current.

Current shunting is not as critical a factor as with most other materials due to the high electrical resistance of titanium and weld strengths are not appreciably reduced until spacings are small enough to produce spot overlap. Figure 73 shows that the weld nugget size remains about the same with various spacings up to the point of spot overlap.

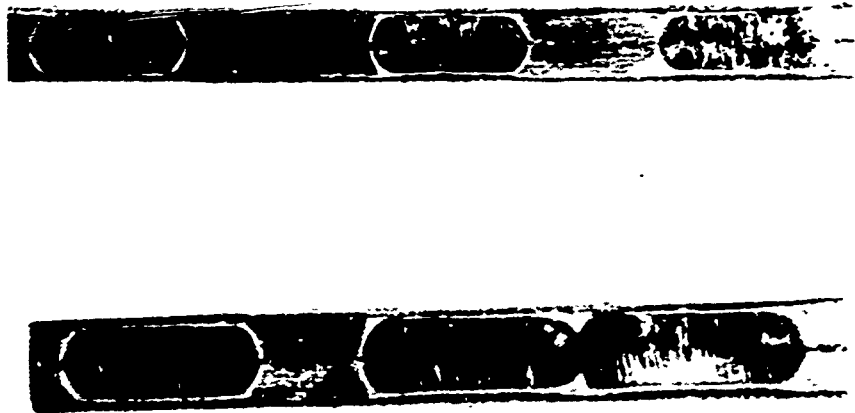


FIGURE 73. THE EFFECT OF SPOT SPACING ON WELD GEOMETRY (REF. 11)

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 pile up, various combinations of welding current, time, and applied force may produce similar welds. Other variables such as electrode size and

shape are important in controlling such characteristics as metal expulsion, sheet indentation, and sheet separation. The use of slope controls such as preheat, postheat, and additional weld forging cycles have not been found necessary in the early welding of titanium alloys.

Establishing Machine Settings. It is recommended that for each sheet thickness of titanium alloy the initial values for electrode force and weld time be obtained from the Resistance Welding Manual (Ref. 76) for comparable thicknesses of stainless steel (Ref. 11). Then optimum settings for welding current for titanium alloys can be determined.

In a recent investigation to check the spot-welding settings listed in the Resistance Welding Manual, many tests were conducted on Ti-6Al-4V using electrode forces and weld times recommended for stainless steel. The RWMA recommended conditions for spot welding stainless steels are given in Table XVIII. These settings were found to produce good spot welds with no advantage gained by varying any of the settings. When using electrode forces lower than those recommended, the welds were weaker in both tension and shear. Higher electrode forces than those recommended produced higher shear strengths but lower cross-tension strengths, the result being much lower cross-tension/tension-shear ratios. Higher electrode forces also caused metal extrusion to occur at lower current settings, thus increasing the per cent of sheet separation at the optimum current setting.

Establishing Welding Current. After selecting the recommended electrode force and welding time for a given sheet thickness, the optimum weld current must be established. This is the most important spot-welding variable and determination of the optimum current setting is best accomplished by welding some test specimens and choosing the weld current on the basis of weld strength, sheet separation, electrode indentation, weld diameter, and per cent penetration. Figure 74 (Ref. 11) illustrates the variation in some of the weld-quality parameters obtained by using welding currents below and above those selected as optimum for the various gages. If some of the parameters such as sheet separation, etc., are of no concern higher weld currents (up to the point of metal expulsion) may be used to obtain stronger welds. There is a definite decrease in weld strength and sheet separation at the point of metal expulsion.

Establishing Squeeze Time and Hold Time. Electrode force is applied to the sheets being welded for a period longer than the time that welding current flows. The total time that electrode force is

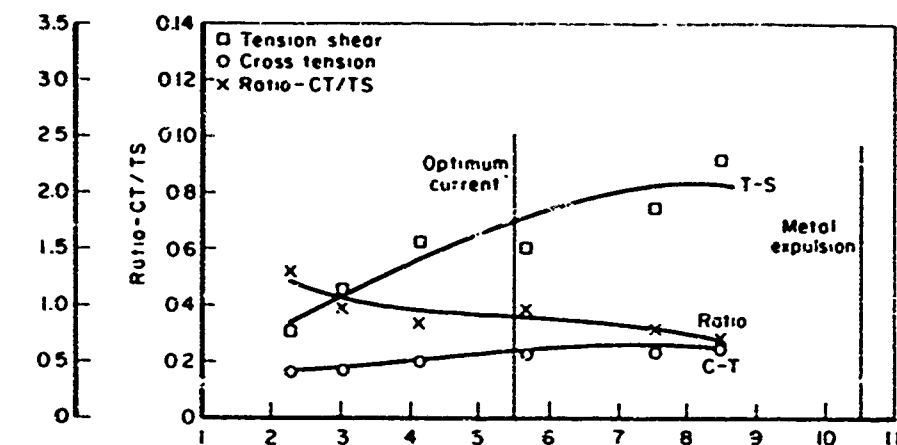
TABLE XVIII. RECOMMENDED PRACTICES FOR SPOT WELDING STAINLESS STEELS (REF. 16)

Thickness "T" of Thinnest Outside Piece, in.	Electrode Diameter and Shape D, in., d, in., min. max.		Net Electrode Force, lb	Weld Time (Single Impulse), cycles (60 per sec)	Welding Current (Approx.), amps			Minimum Contacting Overlap, in.	Minimum Weld Spacing, in.	Diameter of Fused Zone (Approx.), in.	Minimum Shear Strength, lb			Thickness "T" of Thinnest Outside Piece, in.
					Tensile Strength Below 150,000 psi and Higher	Tensile Strength 150,000 psi and Higher	Tensile Strength up to 90,000 psi				Ultimate Tensile Strength of Metal			
											up to 90,000 psi	150,000 and Higher		
0.006	3/16	3/32	180	2	2,000	2,000	3/16	3/16	0.045	60	70	85	0.006	
0.008	3/16	3/32	200	3	2,000	2,000	3/16	3/16	0.055	100	130	145	0.008	
0.010	3/16	1/8	230	3	2,000	2,000	3/16	3/16	0.065	150	170	210	0.010	
0.012	1/4	1/8	260	3	2,100	2,000	1/4	1/4	0.076	185	210	250	0.012	
0.014	1/4	1/8	300	4	2,500	2,200	1/4	1/4	0.082	240	250	320	0.014	
0.016	1/4	1/8	330	4	3,000	2,500	1/4	5/16	0.088	280	300	380	0.016	
0.018	1/4	1/8	380	4	3,500	2,800	1/4	5/16	0.092	320	360	470	0.018	
0.021	1/4	5/32	400	4	4,000	3,200	5/16	5/16	0.100	370	470	500	0.021	
0.025	3/8	5/32	520	5	5,000	4,100	3/8	7/16	0.120	500	600	680	0.025	
0.031	3/8	3/16	650	5	6,000	4,800	3/8	1/2	0.130	680	800	930	0.031	
0.034	3/8	3/16	750	6	7,000	5,500	7/16	9/16	0.150	800	920	1100	0.034	
0.040	3/8	3/16	900	6	7,800	6,300	7/16	5/8	0.160	1000	1270	1400	0.040	
0.044	3/8	3/16	1000	8	8,700	7,000	7/16	11/16	0.180	1200	1450	1700	0.044	
0.050	1/2	1/4	1200	8	9,500	7,500	1/2	3/4	0.170	1450	1700	2000	0.050	
0.056	1/2	1/4	1350	10	10,300	8,300	9/16	7/8	0.210	1700	2000	2450	0.056	
0.062	1/2	1/4	1500	10	11,000	9,000	5/8	1	0.220	1950	2400	2900	0.062	
0.070	5/8	1/4	1700	12	12,300	10,000	5/8	1-1/8	0.250	2400	2800	3550	0.070	
0.078	5/8	5/16	1900	14	14,000	11,000	11/16	1-1/4	0.275	2700	3400	4000	0.078	
0.094	5/8	5/16	2400	16	15,700	12,700	3/4	1-3/8	0.285	3550	4200	5300	0.094	
0.109	3/4	3/8	2800	18	17,700	14,000	13/16	1-1/2	0.290	4200	5000	6400	0.109	
0.125	3/4	3/8	3300	20	18,000	15,500	7/8	2	0.300	5000	6000	7600	0.125	

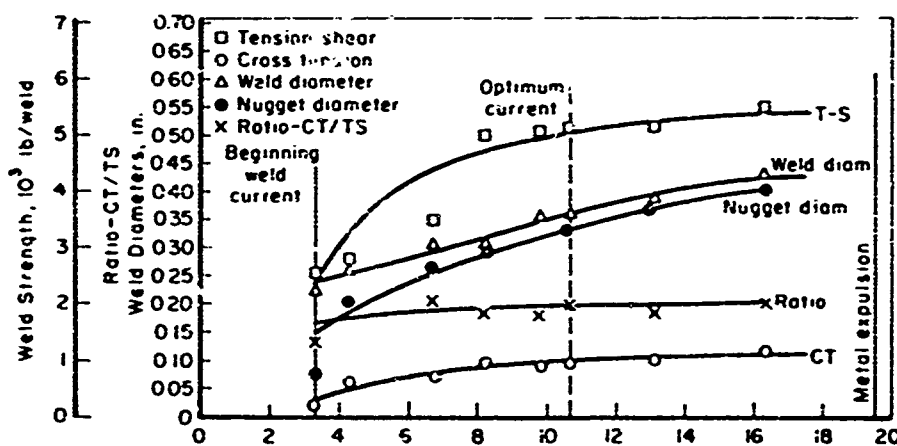
Notes:

- (1) Types of steel - 301, 302, 303, 304, 308, 309, 310, 316, 317, 321, 347 and 349.
- (2) Material should be free from scale, oxides, paint, grease and oil.
- (3) Welding conditions determined by thickness of thinnest outside piece, "T".
- (4) Data for total thickness of pile-up not exceeding 4 "T" maximum ratio between two thicknesses 3 to 1.
- (5) Electrode material:

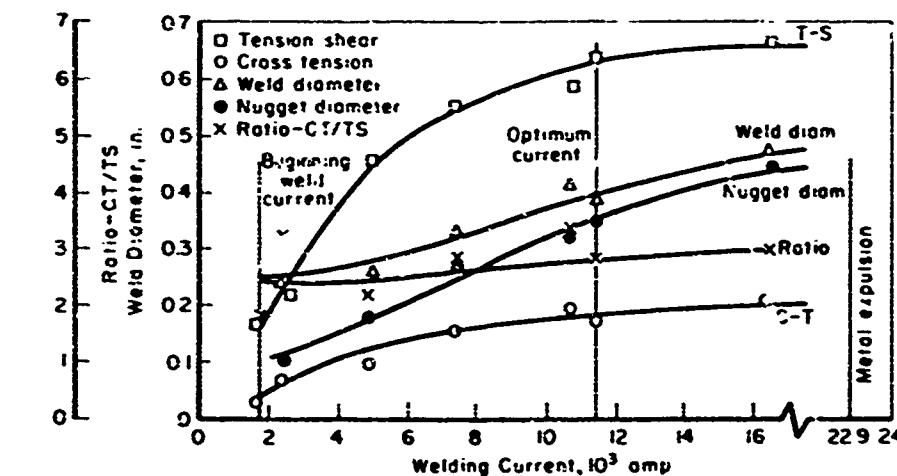
	Class 2	Class 3	Class 11
Minimum conductivity, %	75	45	30 of copper
Minimum hardness (Rockwell B)	75	95	98
- (6) Minimum weld spacing is that spacing for two pieces for which no special precautions need be taken to compensate for shunted current effect of adjacent welds. For three pieces increase spacing 30 per cent



a. 0.035-Inch Ti-6Al-4V
As welded with 600-lb electrode force, 7 cycles weld time, 3-in. spherical radius, Class 2 electrodes.



b. 0.062-Inch Ti-6Al-4V
As welded with 1500 lb electrode force, 10 cycles weld time, 3-in. spherical radius, Class 2 electrodes.



c. 0.070-Inch Ti-6Al-4V
As welded with 1700-lb electrode force, 12 cycles weld time, 3-in. spherical radius, Class 2 electrodes.

FIGURE 74. INFLUENCE OF SPOT-WELDING CURRENT ON STRENGTH AND TENSION/SHEAR RATIO FOR 0.035-, 0.062-, AND 0.070-INCH-THICK Ti-6Al-4V ALLOY (REF. 11)

applied consists of squeeze time, weld time, and hold time. Squeeze time is the time that the electrodes hold the material together at the required force before the weld current is actuated. Weld time is the time of actual current flow. Hold time is the interval during which the electrodes are in contact with the material after the current flow has stopped. Solidification of the weld nugget takes place during the hold time. Both the squeeze and hold times are generally set at about 20 cycles duration, but can be varied according to the sheet gage. In light gage sheet, the weld nugget is solidified in less than 20 cycles hold time and adjustments in these machine settings can be made in accordance with production requirements.

Spot-welding conditions used in industry for titanium alloys are given in Table XIX.

Properties. The quality of spot welds is determined by several testing methods. In addition to cross-tension and tension-shear strengths, many specifications, such as the military specification MIL-W-6858B (Ref. 8), place certain restrictions on weld penetration, sheet separation, electrode indentation, and weld diameter. These limits were originally set for stainless steel spot welds, but because of the similarity between the spot-welding characteristics of stainless steel and titanium, most of the quality parameters for stainless are applied to titanium.

Many of the properties and characteristics of resistance spot welds in titanium alloys have been determined. The properties usually determined for various titanium alloy spot weldments are given in Table XX. In many instances, complex testing procedures are required to determine the behavior of titanium spot welds under special conditions. Sources for additional information obtained from these special tests are given in Table XXI. Some of the conventional spot-weld evaluation methods are described in the following.

Tension-Shear and Cross-Tension Strength. A tension-shear test on a spot-welded specimen gives some indication of ductility since stress gradients and concentrations are set up by the nonaxiality of the specimen, the attendant bending stresses, and the stress concentration at the end of the spot weld.

A cross-tension specimen undergoes even more severe loading and, therefore, is a still better evaluation of ductility. However, spot welds in service are practically never subjected to this type of loading. Presumably, if extremely brittle zones exist in the region of a spot weld, the specimen will have low resistance to the cross-tension type

TABLE XIX. RESISTANCE SPOT WELDING CONDITIONS FOR SEVERAL TITANIUM BASE ALLOYS

Base Material		Electrode		Machine		Weld Heat		Weld Current		Nugget Dia., in.	Reference
Type	Thickness, in.	Dia., in.	Radius, in.	Force, lb	Type	KVA	Cycles	Impulses	Amperes	Phase Shift, %	
6Al-4V	0.02	0.5	10	1200	--	--	5	--	--	--	1
6Al-4V	0.02	0.375	3	795	1:	75	7	2	--	60	--
6Al-4V	0.032	0.375	3	720	3:	75	2	2	--	55	--
6Al-4V	0.035	0.625	3	600	1:	30	7	1	5,500	--	(1)
6Al-4V	0.04	0.375	3	695	1:	75	4	2	--	10	--
6Al-4V	0.05	0.625	5	1100	3:	150	4	2	--	63	--
6Al-4V	0.062	0.625	3	1500	1:	600	10	1	10,600	--	11
6Al-4V	0.065	0.90	10	1500	--	--	12	--	--	--	1
6Al-4V	0.07	0.625	3	1700	1:	600	12	1	11,500	--	1,11
6Al-4V	0.09	0.625	10	1100	3:	150	4	4	--	35	--
6Al-4V	0.095	0.625	5	2400	1:	600	16	1	12,500	--	1,11
6Al-4V	0.125	0.5	10	2300	--	--	14	--	--	--	1
8Al-1Mo-1V	0.02	0.175	3	720	3:	75	3	1	--	59	79
8Al-1Mo-1V	0.022	0.625	4	900	3:	150	3	--	--	35	--
8Al-1Mo-1V	0.039	0.625	4	1000	3:	150	6	--	--	40	77
8Al-1Mo-1V	0.040	0.375	3	750	1:	200	2	3	--	35	--
8Al-1Mo-1V	0.040	0.375	3	1050	3:	75	1	4	--	40	--
8Al-1Mo-1V	0.05	0.625	3	1100	3:	150	4	4	--	50	--
8Al-1Mo-1V	0.05	0.375	10	600	3:	75	2	4	--	90	--
8Al-1Mo-1V	0.062	0.625	4	1200	3:	150	7	--	--	45	77
8Al-1Mo-1V	0.071	0.375	3	1810	3:	75	2	4	--	60	--
8Al-1Mo-1V	0.09	0.625	10	1100	3:	150	3	3	--	35	--
CP titanium	0.04	0.625	3	760	3:	200	4	--	8,300	60	--
											0.20

(a) Weld diameter.

TABLE XX. ROOM TEMPERATURE PROPERTIES OF SPOT WELDS IN SEVERAL TITANIUM-BASE ALLOYS

Alloy	Material Condition	Thickness, in.	Weld Dia, in.	Nugget Dia, in.	Weld Penetration, %	Electrode Indentation, %	Gross Tension Strength, lb	Tension / Shear Strength, lb	Tension / Shear Ratio	Reference
6Al-4V	--	0.035/0.035	0.255	--	--	--	600	1720	0.35	11
Ditto	--	0.062/0.062	0.359	0.331	87.3	3.1	1000	5000	0.20	11
"	--	0.070/0.070	0.391	--	--	--	1850	6350	0.29	11
"	--	0.093/0.093	0.431	--	--	--	2100	8400	0.25	11
8Al-1Mo-1V	As received	0.020/0.020	--	--	--	--	245	920	0.27	77
Ditto	Ditto	0.022/0.002	--	--	--	--	--	1389	--	77
"	"	0.039/0.039	--	--	--	--	597	1967	0.30	77
"	"	0.062/0.062	--	--	--	--	1171	3117	0.34	77
7Al-12Zr	As received	0.020/0.020	--	--	--	--	188	935	0.20	77
Ditto	Ditto	0.036/0.036	--	--	--	--	404	1918	0.21	77
"	"	0.056/0.056	--	--	--	--	597	2978	0.20	77
13V-11Cr-3Al	Solution treated	0.020	--	--	--	--	657	1271	0.516	19
Ditto	Ditto	0.040	--	--	--	--	1794	2653	0.653	19
"	"	0.060	--	--	--	--	1944	3500	0.498	19

TABLE XXI. SPOT-WELD PROPERTY DATA SOURCES

Base Alloy	Total Thickness of Test Plate, in.	Type of Tests and Test Temperature, F	Reference
6Al-4V	0.04-0.180	Tensile shear (RT), penetration, and nugget diameter	41
8Al-1Mo-1V	0.04-0.175	Ditto	41
6Al-4V, 8Al-1Mo-1V	0.1	Tensile shear ^(a) , cross tension ^(a) , and fracture toughness (-110, 75, 400, 650); thermal stability, and multispot shear (RT)	12
6Al-4V, 8Al-1Mo-1V	0.180	Tensile shear ^(a) , and cross tension ^(a) , (-110, 75, 400, 650); multispot shear (RT)	12
8Al-1Mo-1V	0.044, 0.078, 0.124	Tensile shear, cross tension, and multi- spot fatigue (RT); tensile shear (200, 400, 600, 800, 1000, and 1200); thermal stability (RT)	77
6Al-4V	0.070-0.186	Tensile shear (RT, 600, 800, and 1000); cross tension, thermal stability, and thermal-stress stability	78
6Al-4V	0.05, 0.1	Tensile shear, cross tension, and fatigue (RT)	79
CP titanium, 6Al-4V	0.05	Tensile shear, cross tension, and fatigue (RT)	80
CP titanium, 6Al-4V, 5Al-2.5Sn			
6Al-4V, 5Al-2.5Sn			
8Al-1Mo-1V	0.04, 0.08	Tensile shear, cross tension, and thermal stability (RT, 600, 800, 1000)	47
13V-11Cr-3Al	0.128	Fatigue (RT and ET)	81
13V-11Cr-3Al	--	Airframe structures - static and repeated load (RT)	82
CP titanium	0.08	Tensile shear, cross tension, and fatigue (RT)	83
		Pre-1960 data summarized	1
5Al-2.5Sn	0.05, 0.064, 0.08	Tensile shear (RT, 200, 400, 600, 800, 1000); fatigue (RT)	84
8Al-1Mo-1V	0.04-1.5	Various (RT to 650) including all simple tests plus thermal stability, thermal- stress stability, and structures evaluation	--
5Al-2.5Sn	0.02, 0.040, 0.063, 0.100, 0.125	Effects of peel loading	85
2.5Al-16V	0.040, 0.063, 0.090	Tensile shear	86

(a) About one-half of these tests made after exposure to 1000 F for 10 hours, all others as welded.

of loading, cross-tension strength will be low, and the commonly used ratio of cross-tension strength/tension-shear strength will be low.

The properties measured by tension-shear tests are excellent. Cross-tension values also are good. Cross-tension/tension-shear ratios are somewhat low (0.20 to 0.35) except in the Ti-13V-11Cr-3Al alloy. Examples of tension-shear and cross-tension specimens are shown in Figures 75 and 76 (Ref. 11). The tension-shear specimens are pulled in a tensile testing machine employing grip jaws. A commonly used jig for pulling cross-tension specimens is shown schematically in Figure 77 (Ref. 11). In both cases, the maximum load prior to failure is recorded in pounds.

Fatigue and Fracture Toughness. The fatigue properties of spot welds are low, but this behavior is characteristic more of the joint type than of titanium alloys. Spot-weld thermal stability studies indicate some loss in room-temperature properties from exposure at 650, 1000, and 1200 F. Similar exposure at 800 F did not lower the room-temperature properties. A reason for this apparent inconsistency is not apparent. Fracture toughness tests of spot weldments exhibit properties inferior to comparable TIG fusion weldments. Spot welding has been used in a number of structural test components. Such tests provide the best evidence of expected weldment performance. Data from such tests have not been available for review.

Penetration. Spot-weld penetration is a measure of the distance that the weld nugget extends through the thickness of the sheets that were spot welded. It is normally expressed as a percentage of the sheet thickness with equal penetration in each of two similar sheet thicknesses.

$$P_t = P_b = \frac{d_t}{t_t} \times 100 = \frac{d_b}{t_b} \times 100$$

Penetration is a function of weld current but can be affected, or controlled, by such factors as the cooling effect of the electrodes, the material thicknesses and thermal and electrical conductivity. When dissimilar sheet thicknesses, electrodes, materials, or welding conditions on the two sides of the sheet exist, penetration of the weld nugget in each of two sheets can be quite different values. When proper welding conditions are used, spot-weld penetration usually is less than 100 per cent. Most specifications limit weld penetration to a minimum of 20 per cent and a maximum of 90 per cent for high quality spot, roll spot, and seam welds (Ref. 87).

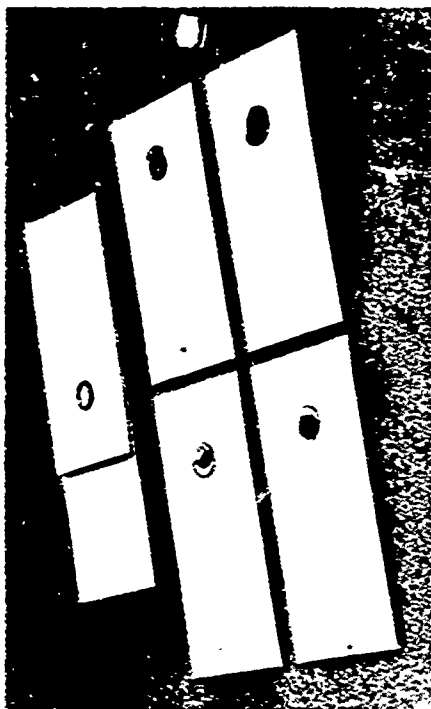


FIGURE 75. TENSION-SHEAR SPOT-WELDED SPECIMEN BEFORE AND AFTER STRENGTH TESTING (REF. 11)

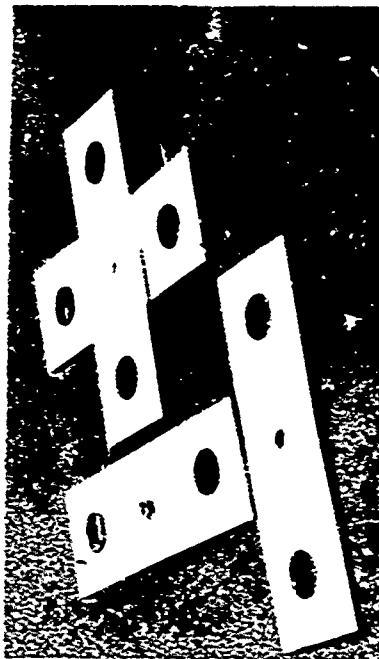


FIGURE 76. CROSS-TENSION SPOT-WELDED SPECIMEN BEFORE AND AFTER STRENGTH TESTING (REF. 11)

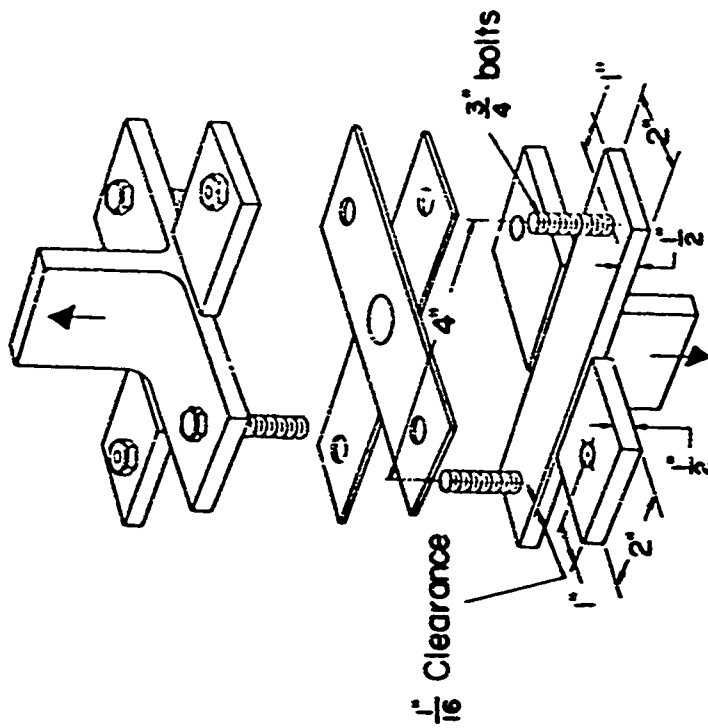


FIGURE 17. JIG FOR CROSS-TENSION TEST (REF. 11)

Sheet Separation. Sheet separation occurs as a result of the electrode force tending to extrude the plastic phase of the weld nugget out between the adjacent surfaces of the weld joint. This separation in actual practice is generally measured away from the edge of the weld at a distance equal to half the diameter of the electrode indentation. It is common practice to specify a maximum acceptable separation of 10 per cent of the sheet thickness joined, or 0.006 inch, whichever is larger (Ref. 87).

One should be careful about sacrificing weld strength for low sheet separation. It is possible to have very low separation with lower than optimum weld current. Higher than optimum weld currents also produce low sheet separation, but at the expense of excessive weld-metal expulsion. In either case, the weld strength would be somewhat less than optimum, and it would be more advisable to select an electrode with a larger spherical tip radius. It is also possible to reduce sheet separation through proper selection and control of the welding variables.

Electrode Indentation. Electrode indentation is a measure of the depth of the indentations produced in the outer sheet surfaces contacted by the electrodes. It is caused by a combination of electrode force, weld current, weld time, and upsetting and shrinkage of the heated metal. Most specifications restrict electrode indentation to 10 per cent of the sheet thickness.

Weld Diameter and Weld-Nugget Diameter. The weld diameter includes the weld nugget and heat-affected zone (assuming no metal expulsion). This can be controlled, for the most part, by the radii of the electrode tips. Weld-nugget diameter is a measure of the diameter of the fused or cast metal. These diameters are expressed in inches or in terms of sheet thickness. It was shown in Figure 73c that as the weld current increases, the weld nugget diameter and the overall weld diameter approach each other.

Extrusion. The only apparent difficulty with the actual making of titanium resistance spot welds is a problem with metal extrusion between the faying surfaces of the overlapping sheets. With thinner gages of material, extrusion does not appear to be a significant problem. However, as the gage thickness is increased there appears to be a much greater tendency for extrusion to occur. Proper welding conditions and close control of welding variables are required to minimize or eliminate extrusion.

Applications. Applications requiring the use of resistance spot welding range from small aircraft components to spacecraft. Representative examples of the use of spot welding for fabricating titanium alloys are given in the following.

Spacecraft. Spot welding has been used for many joints in Mercury and Gemini spacecraft. Many combinations of material thicknesses are encountered in resistance welding stiffeners to doublers and to skins. Spot welds have been made through as many as seven layers and more than 300 thickness combinations have been welded successfully. Gemini spacecraft involved over 25,000 spot welds.

Figure 78 shows the arrangement of the parts and equipment for spot welding stiffeners to the side wall of a Mercury capsule (Ref. 52). Spot welding fixtures are moved manually but the path of travel is established by the fixture. Typical applications of resistance spot welding to the fabrication of various spacecraft sections are shown in Figure 79 (Ref. 88).

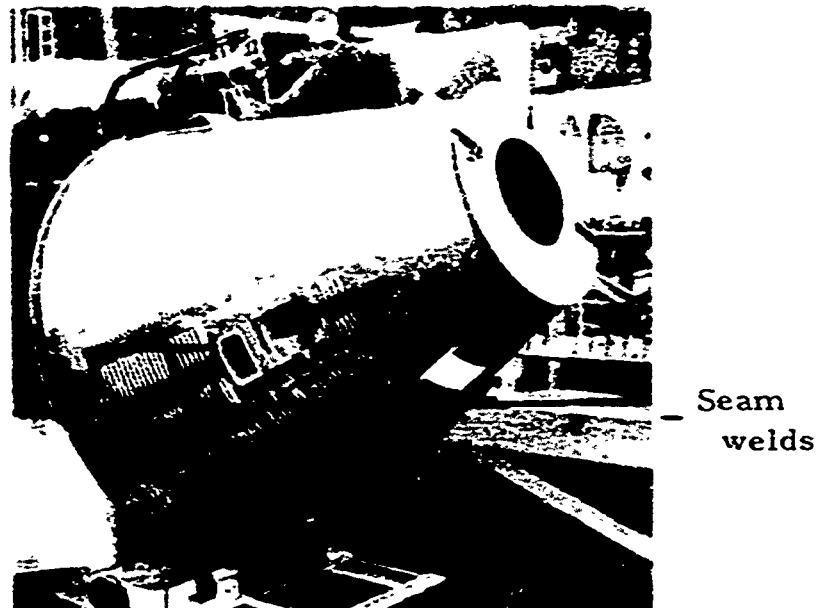
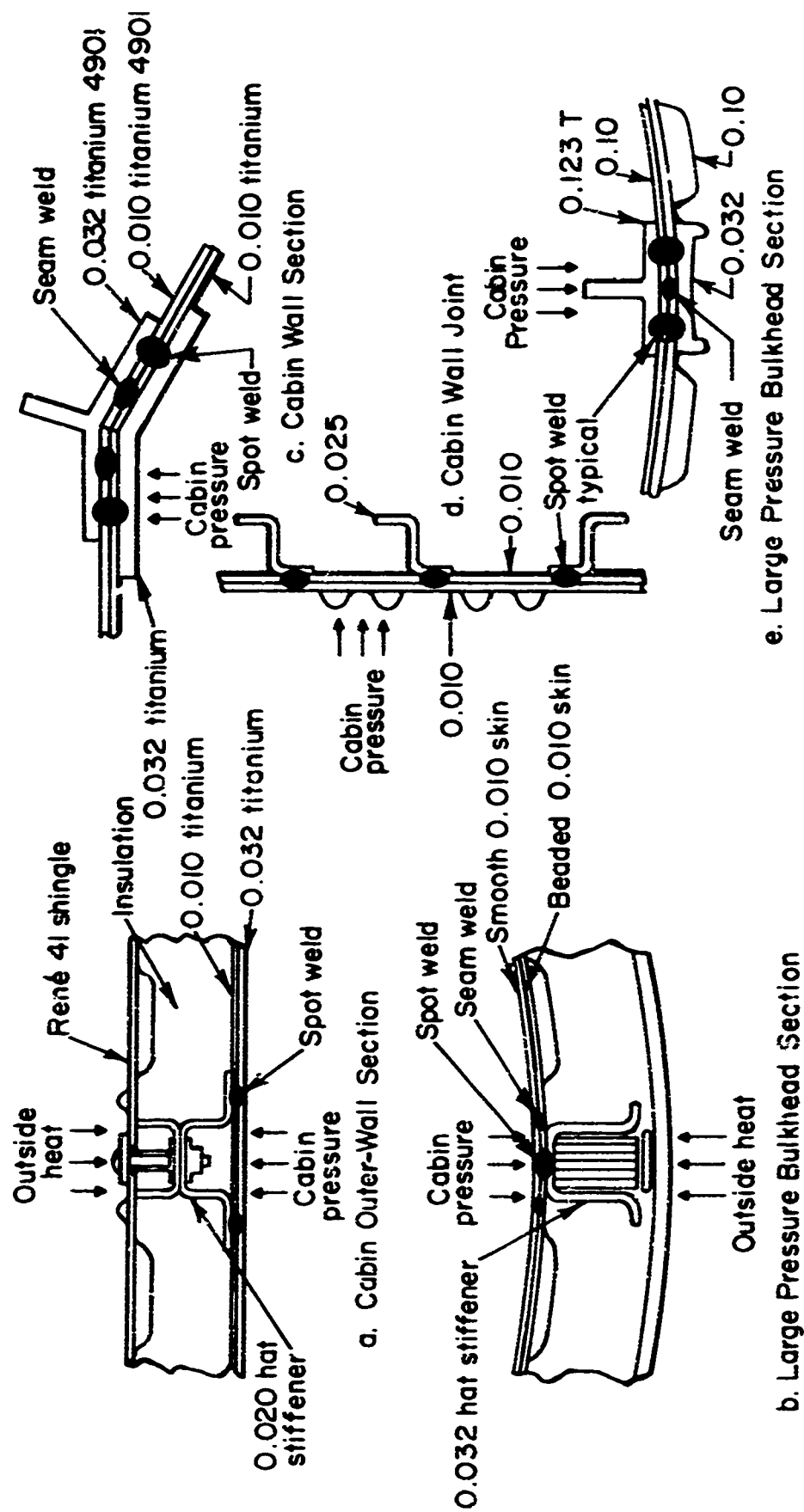


FIGURE 78. SPOT WELDING ATTACHES STIFFENERS TO SIDEWALL SKIN ASSEMBLY OF THE MERCURY CAPSULE (REF. 52)

Stiffened Titanium Sheet Panels. A statically strong, spot-welded titanium skin structure is highly practical for use in high-speed transport, according to tests conducted by one aircraft manufacturer (Ref. 87). Tests have been made on Z-stiffened sheet panels for application in the empennage section of the transport. Three panels,



All Welded Parts Shown are Titanium

FIGURE 79. TYPICAL RESISTANCE-WELDING APPLICATIONS IN VARIOUS SPACECRAFT SECTIONS (REF. 23)

18 by 18 inches, were made from Ti-8Al-1Mo-1V with five equally spaced Z-stiffeners. All material was 0.060 inch thick, and welds were spaced at 1.05, 2.10, and 3.15 inches. Equipment used was a 100-kva, single-phase spot-welding machine. Spacing at 2.10 inches, center to center, was found to be best for resisting inter-spot-weld kling, yet wide enough to avoid residual-stress interaction between spots. An average lap-shear strength of 4500 pounds was produced on individual spots, along with an average normal tensile strength of 1000 pounds.

Aircraft Structures. Several steps in the fabrication of a left-hand horizontal-stabilizer test component from Ti-4Al-3Mo-1V using spot welding to establish fabricability are shown in Figures 79 to 83 (Ref. 90). The subassembly fabrication consisted of spot welding doublers and angles to flanged ribs, Figures 80, 81, and 82; these details then were welded to the upper external skin, Figure 83. The spot-welding machine and fixture used for spot welding are shown in Figure 84.

ROLL SPOT WELDING

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

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

Roll spot welding of titanium alloys has been performed by at least one aircraft manufacturer. Welding conditions for roll spot welding of titanium have not been found in the literature, but they are expected to be very similar to conventional spot-welding conditions. Equipment



FIGURE 80. TYPICAL RIB SUBASSEMBLY WITH HOUR-GLASS-SHAPED DOUBLER SPOT WELDED TO RIB (REF. 85)

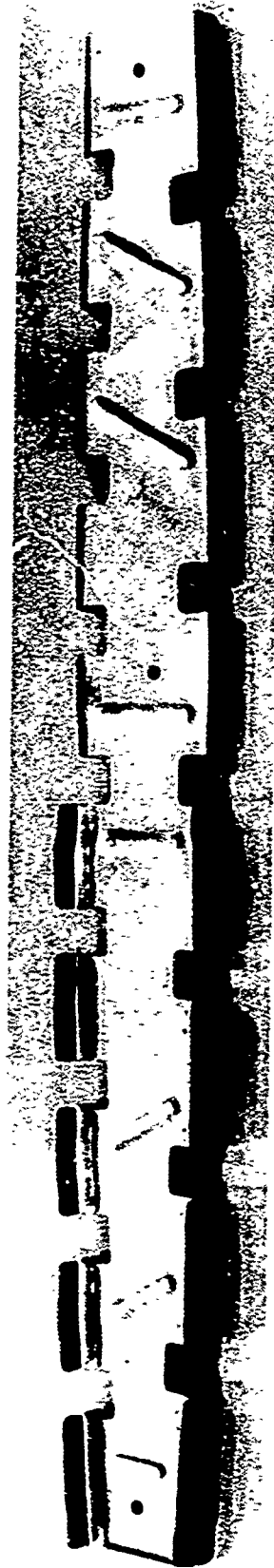


FIGURE 81. TYPICAL RIB SUBASSEMBLY WITH SHORT-ANGLE STIFFENERS SPOT WELDED TO THE RIB (REF. 85)

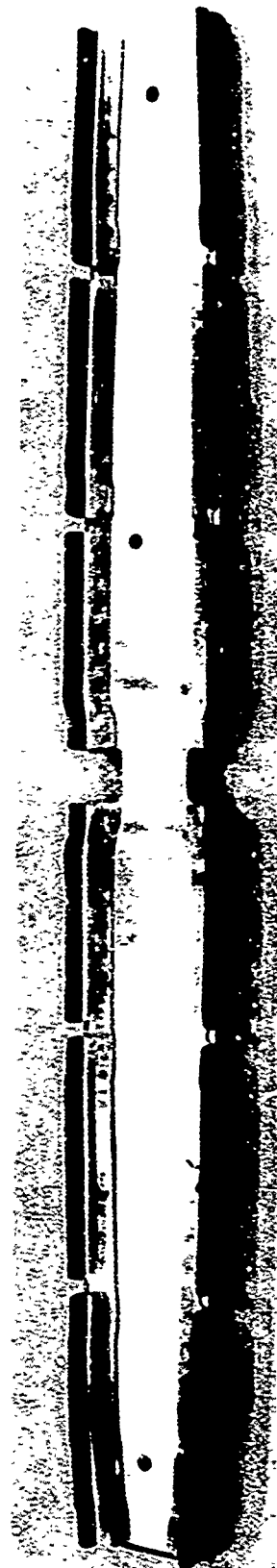


FIGURE 82. TYPICAL RIB SUBASSEMBLY WITH LONG-ANGLE STIFFENERS SPOT WELDED TO THE RIB (REF. 90)



FIGURE 83. PANEL READY FOR RESISTANCE SPOT WELDING OF STIFFENERS (REF. 90)

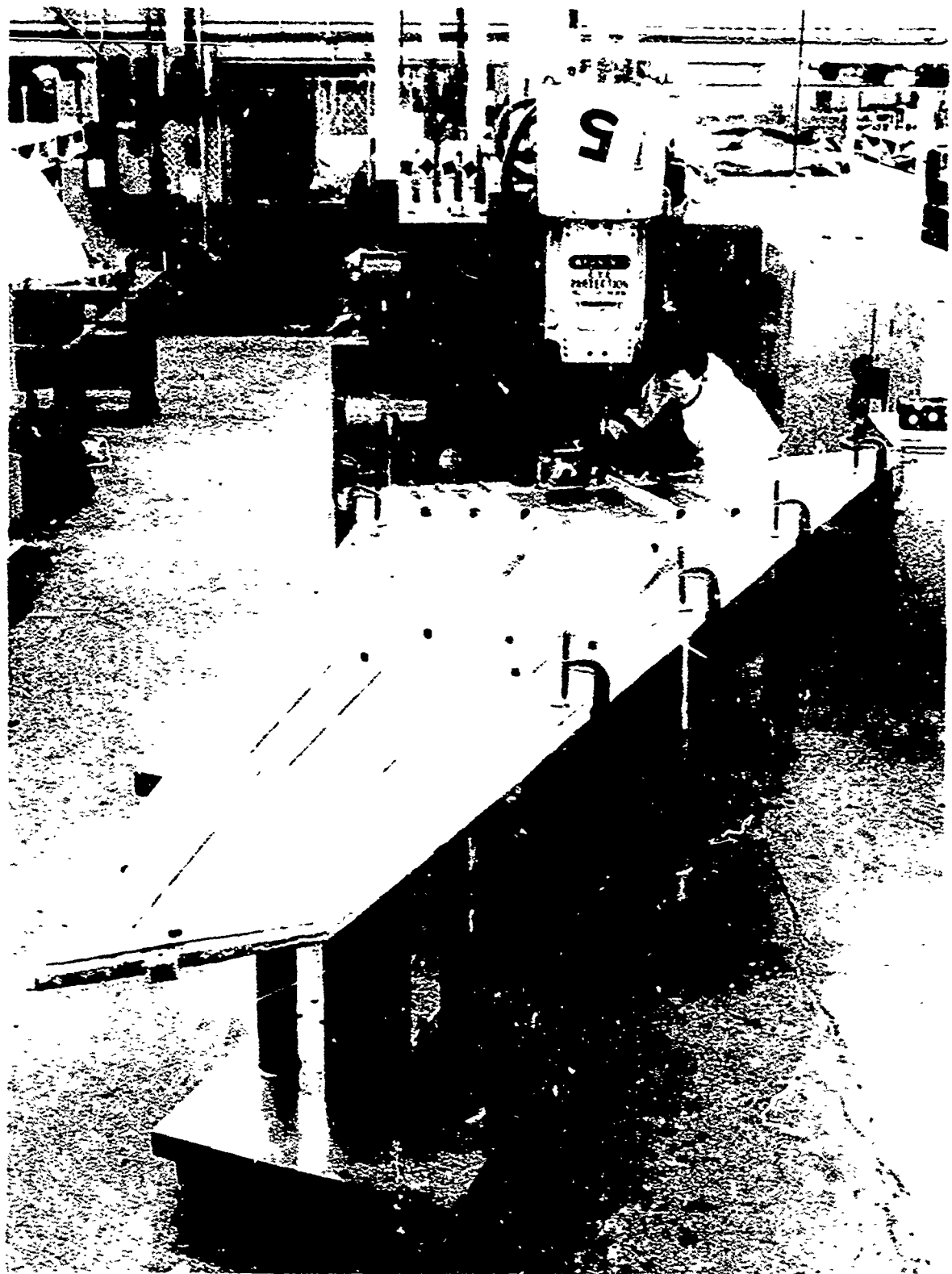


FIGURE 84. A SPOT-WELDING OPERATION ON THE UPPER SKIN SUBASSEMBLY (RET. 90)

Skin is clamped in the contoured spot-welded assembly jig.

for roll spot welding is essentially the same as equipment for resistance seam welding as shown in Figure 85 (Ref. 91).

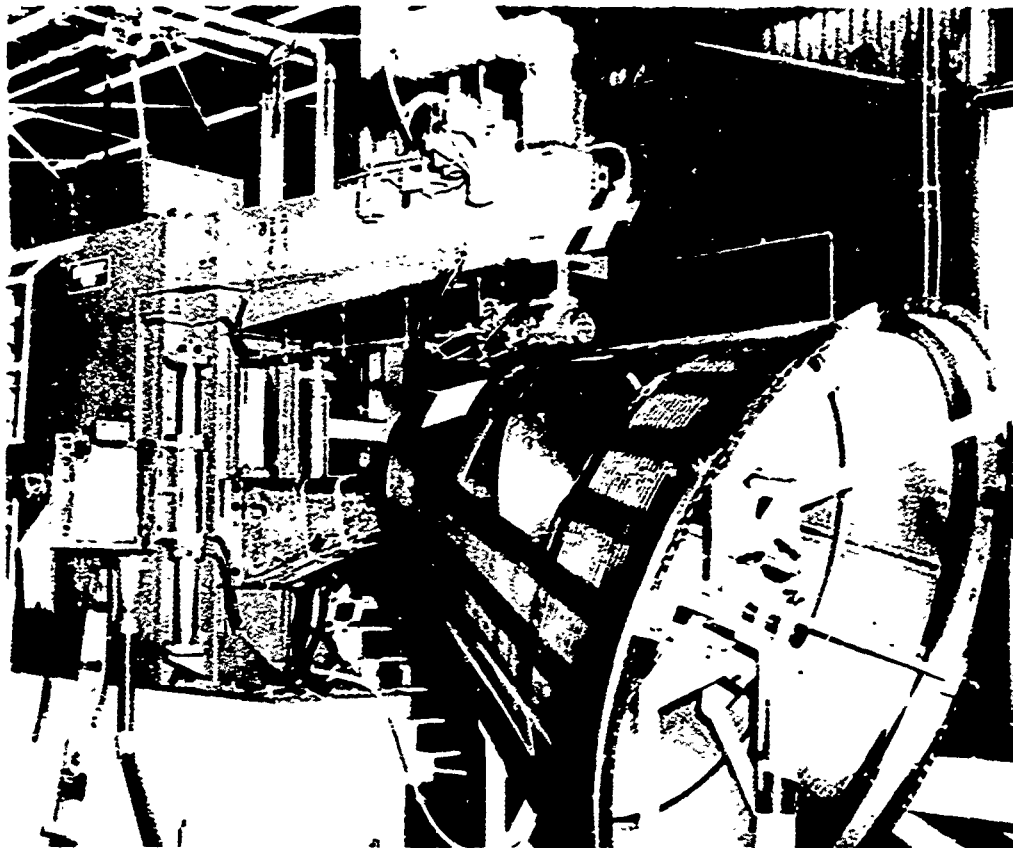


FIGURE 85. PROJECT MERCURY SPACECRAFT, BUILT OF TITANIUM, REQUIRED 20,500 INCHES OF SPOT WELD PER CAPSULE (REF. 91)

SEAM WELDING

Seam welding also is similar to spot and roll spot welding. In seam welding wheels are used in place of spot-welding electrodes. Individual overlapping spots are created by coordinating the welding current flow, time, and wheel rotation. Seam welds often are made with conventional spot-welding techniques. However, it is much more common to use equipment designed specifically for seam welding and available commercially. 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. 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.

Selected data on seam-welding conditions and properties of seam-welded joints are given in Table XXII. These data include room-temperature static tensile strength. Static tensile properties are comparable in efficiency to the parent metal for most of the titanium alloys for which seam-welding data are available.

Applications. Resistance seam welding is of interest for many applications where titanium alloys are used in sheet form. Representative applications of the process for fabricating various products are described in the following.

Aircraft and Spacecraft. For the Mercury capsule skin assemblies the inner and outer skins of each section are joined together by an intricate pattern of resistance seam welds, as shown in Figure 86 (Ref. 91). The size of the two cones is extremely important. Because of the seam-welding operation, they must fit together in intimate contact. In the cone section, the total length of these circumferential and longitudinal seam welds is about 22,000 inches. The result is hundreds of small, separately sealed pockets, which means that a crack anywhere will stop instantly. Special handling fixtures at the welding machines move the work radially or longitudinally, depending on the machine, with the electrode providing the driving force. The carriage-mounted fixture for seam welding is shown in Figure 87 (Ref. 91). Several additional applications of seam welding for spacecraft fabrication were shown earlier in Figure 78.

The use of seam welding to apply fuel-cell insulation for the F4B/C aircraft is shown in Figure 88 (Ref. 11).

Commercially pure titanium in the form of rigidized sheet also has been resistance seam welded successfully for an engine-cooling shroud assembly (Ref. 93). The original thickness of the embossed sheets was 0.012 inch. The ridges in the embossed sheets offered no difficulty to seam welding and lap joints had 100 per cent joint efficiency in static tension-shear tests.

TABLE XXII. SEAM-WELDING CONDITIONS AND ROOM-TEMPERATURE PROPERTIES
OF RESISTANCE SEAM-WELDED JOINTS IN TITANIUM

Alloy	Thickness, in.	Machine Type	KVA	Electrode		Heat Time, cycles	Cool Time, cycles	Welds Per Inch	Heat Setting	Ultimate Load, lb/in	Ultimate Stress, psi	Failure Location	Reference		
				Class	Radius, in.										
CP titanium	0.010	50	150	1	--	2	200	2	5.5	19	71.8	984/1046	--	Base metal	92
CP titanium	0.012	--	--	--	--	--	--	--	--	--	--	87 000	Base metal	1	
CP titanium	0.024	--	--	--	--	--	--	--	--	--	--	100,000	Base metal		
CP titanium	0.025	--	--	--	--	--	--	--	--	--	--	103,000	Base metal	1	
CP titanium	0.069	--	--	--	--	--	--	--	--	--	--	100,000	Base metal	1	

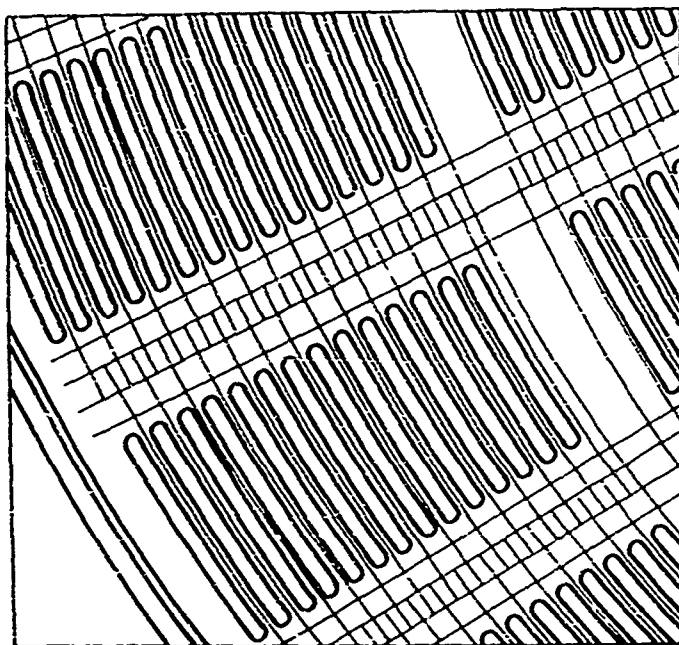


FIGURE 86. SCHEMATIC OF SEAM WELDS USED IN MERCURY CAPSULE (REF. 91)

Detail shows offset rows of reinforcing beads and intricate pattern of longitudinal and circumferential seam welds that hold the two 0.010-inch-thick mercury capsule titanium skins together.



FIGURE 87. INNER AND OUTER MERCURY CAPSULE SKINS ARE SEAM WELDED (REF. 91)

Carriage-mounted fixture holds work for intermittent seams.

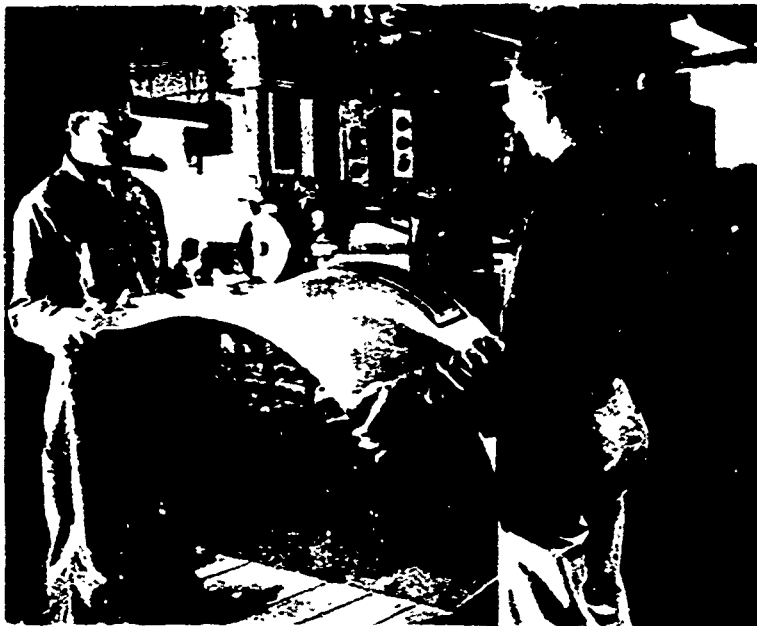


FIGURE 88. THREE-PHASE, 200 KVA, SEAM-WELDING MACHINE JOINING TITANIUM PANELS
0.002 INCH THICK TO BASE SHEET
0.020 INCH THICK (REF. 11)

End unit is for fuel-cell insulation in F4B/C aircraft.

FLASH WELDING

Flash welding is used almost exclusively to weld titanium rings for jet engines. In addition, it has been used to weld many prototype and experimental assemblies, including propeller blades and other complex assemblies.

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 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. Welding speeds are very rapid, heavy sections can be joined, and high production rates can be achieved. Filler metal is not added. 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. Good quality welds can be obtained with the process.

Equipment. The machine capacity required to weld titanium and titanium alloys does not differ greatly from that required for steel. This is especially true for transformer capacity. The upset-pressure capacity for making titanium (Ref. 94) weldments is not so high as that required for steel. Figures 89 and 90 (Ref. 94) show the transformer and upset capacity required for welds of different cross-sectional area. Also of importance, however, 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 welds also are similar to those used for other metals. Flat edges are satisfactory for welding sheet and plate up to about 1/4 inch thick. For thicker sections, the edges are sometimes beveled slightly. Figure 91 (Ref. 94) shows the metal allowances used in making titanium flash welds. The allowances include the metal lost in the flashing and upsetting operations.

Inert-Gas Shielding. For joints with solid cross sections, inert-gas shielding is not necessary (Ref. 95) but may be used. When used, Fiberglas enclosures are placed around the joints, and inert gas is introduced into the enclosure. For joints in tubing or assemblies with hollow cross sections, inert gas is introduced into the assemblies.

Conditions. 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, fast flashing speeds and short flashing times are used to weld titanium and titanium alloys. These conditions are desirable for minimizing weld contamination and are possible because of the low electrical and thermal conductivities of these metals. 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. Low-to-intermediate (7,000 to 20,000 psi) upset pressures are used (Ref. 94).

Although flash-welding variables vary from machine to machine and application to application, some conditions that proved satisfactory for two titanium alloys are listed in Table XXIII (Ref. 96). Welding current is not given, but welding current and arc voltage depend on the transformer tap that is used.

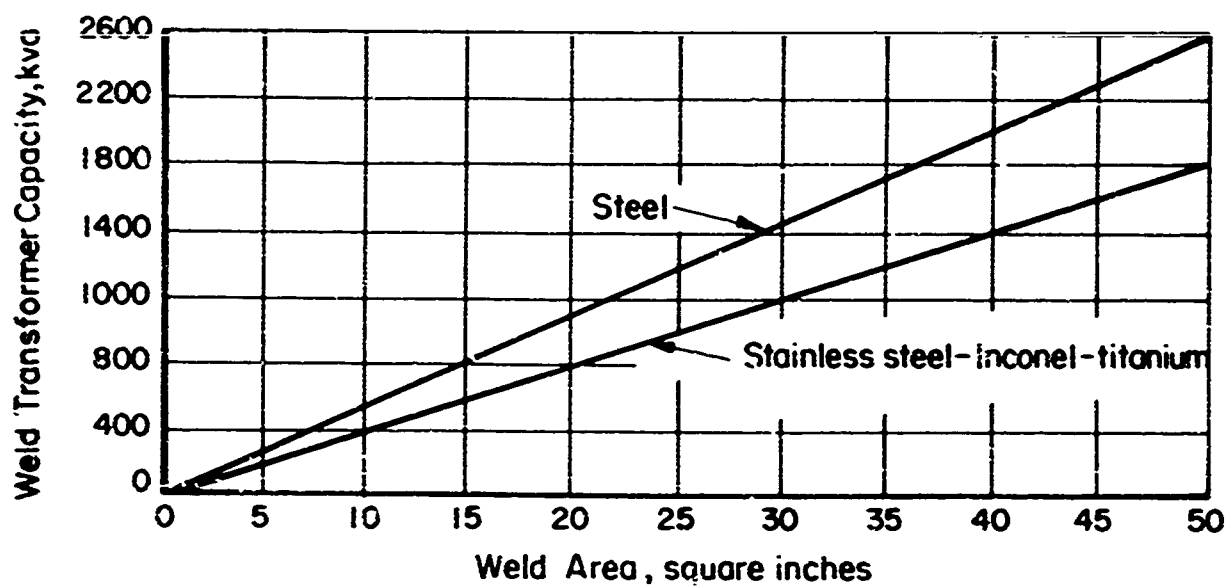


FIGURE 89. TRANSFORMER CAPACITY VERSUS WELD AREA (REF. 94)

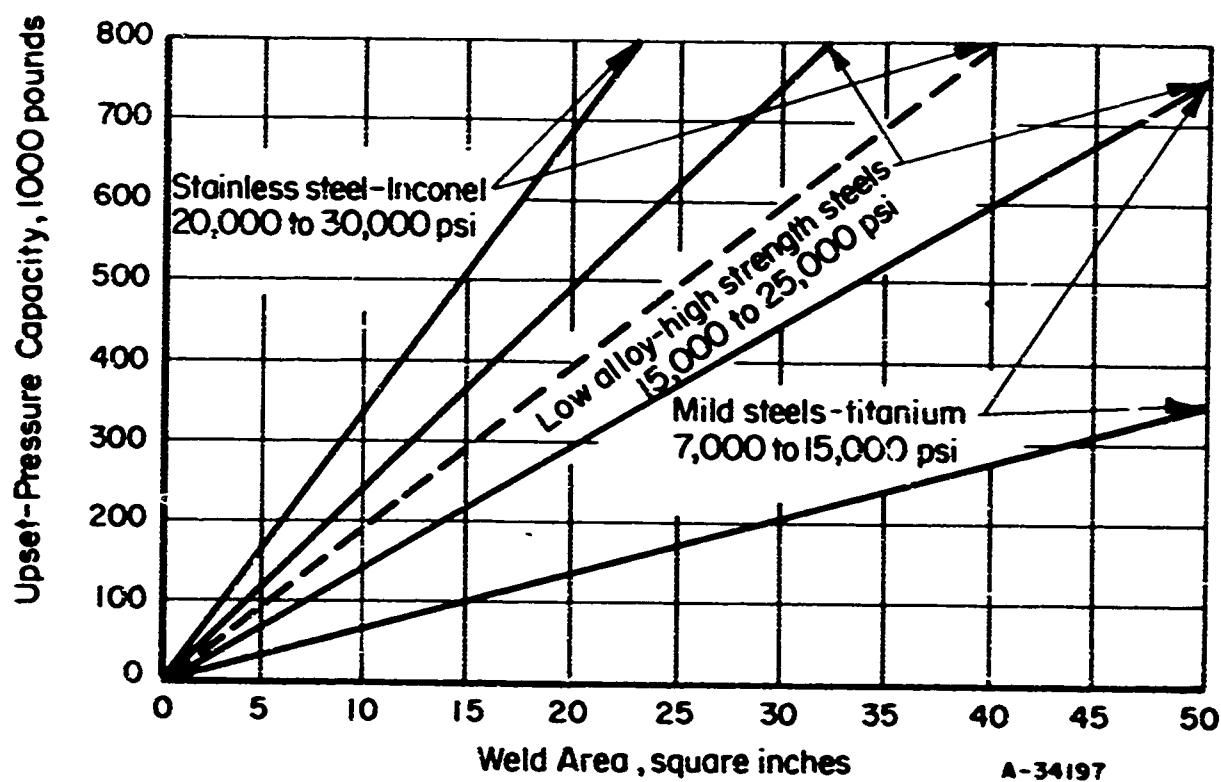


FIGURE 90. MAXIMUM MACHINE UPSET-PRESSURE REQUIREMENTS VERSUS WELD AREA (REF. 94)

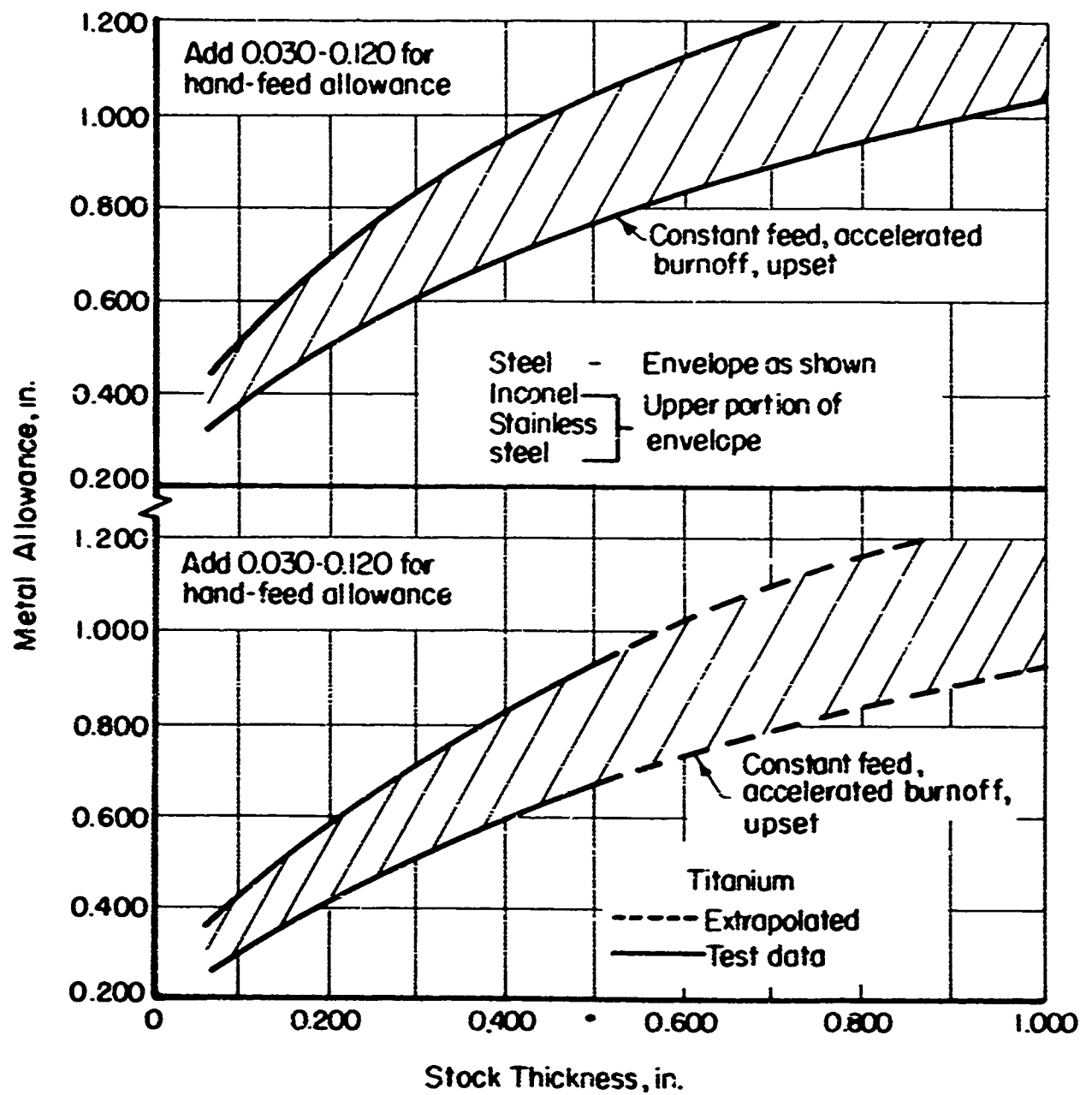


FIGURE 91. TOTAL METAL ALLOWANCE VERSUS STOCK THICKNESS (REF. 94)

TABLE XXIII. FLASH-WELDING CONDITIONS (REF. 1)

Material Configuration	Ti-4Al-4Mn, 3-1/2-Inch Round	Ti-6Al-4V, 3-1/2-Inch Round	Ti-6Al-4V, 1/4-Inch Plate
Flashing Voltage, volts	5.0	5.0	4.5
Total Metal Allowance, inch	0.617-0.940	0.617-0.940	0.700-0.800
Upset, inch	0.200-0.500	0.200-0.500	0.225-0.275
Current Cutoff, inch	0.150-0.400	0.150-0.400	0.205-0.255
Upset Pressure, ksi	15	15	18
Sheet Height, inch	1.10	1.10	0.63
Atmosphere	Argon	Argon	Argon

Properties. Flash welds that have mechanical properties approaching those of the base metals are being regularly produced in conventional machines.

The static-tension-test properties of flash-welded joints are summarized in Table XXIV (Refs. 94, 95, 96). The bend ductility and fatigue strengths of the flash-welded joints are summarized in Table XXV (Refs. 95, 96).

The static and fatigue properties of flash-welded joints are good. Most tension specimens fail away from the weld center line with strengths that are almost equal to or exceed those of the base metals. In fatigue tests, more failures at the weld center line are observed than in tension tests, but the incidence of center-line failures is not high.

Application. Flash welding has been used for fabricating components ranging from light sections such as jet-engine rings to heavy sections such as aircraft landing gear. Steps in the fabrication of several components illustrating the use of flash welding are described in the following.

Airframe Structural Components. In a program to develop new methods and techniques for titanium airframe structural components, an aluminum stabilizer yoke for the F11F-1 supersonic fighter airplane was redesigned and manufactured from Ti-5Al-2.5Sn (Ref. 98). The original yoke was made from numerous aluminum alloy pieces bolted and riveted together as shown in Figure 92. The titanium yoke for flash welding, Figure 93, consisted of three box-type sub-assemblies and two end-fitting subassemblies. One of the subassemblies is shown before and after flash welding in Figures 94 and 95, respectively.

TABLE XXIV. ROOM-TEMPERATURE TENSILE PROPERTIES OF FLASH-WELDED JOINTS (REF. 1)

Nominal Composition, weight per cent	Condition of Base Metal	Postweld Heat Treatment	Ultimate Tensile Strength, ksi	Elongation in 2 Inches, per cent
Commercially pure titanium	Annealed	Not welded	117	21-23
	Annealed	1000 F. 1 hour, air cool	114-118	19-23
5Al-2.5Sn	Annealed	Not welded	133-134	14-31
	Annealed	1200 F. 2 hours, air cool	127-136	11-28
Ti-4Mn-4Al	Annealed	Not welded ^(a)	130-141	15-19
	Annealed	1400 F. 2-3 hours, furnace cool	127-138	11-17
Ti-4Mn-4Al	1450 F. 3 hours, water quench;	Not welded	155-160	10-12
	100 F. 8 hours, air cool	1450 F. 3 hours, water quench; 1000 F. 8 hours, air cool	153-162	1 ^(b) -10
Ti-3Cr-3Al	Annealed	Not welded	142	15
	Annealed	--	142	12
Ti-6Al-4V	Annealed	Not welded	133-137	12-19
	Annealed	1300 F. 2 hours, air cool	130-145	10-15
Ti-6Al-4V	1550 F. 1 hour, water quench;	Not welded	144-148	9-10
	950 F. 24 hours air cool	1500 F. 1 hour, water quench; 1000 F. 24 hours, air cool	142-143	8-10

(a) Some specimens furnace cooled to 1000 F and then air cooled.

(b) Failed on weld center line.

TABLE XXV. BEND DUCTILITY AND FATIGUE STRENGTH
OF FLASH-WELDED JOINTS (REF. 75)

Nominal Composition, weight per cent	Condition of Base Metal	Postweld Heat Treatment	Minimum Bend Radius, T	Fatigue Strength ^(a) , ksi
Ti-5Al-2.5Sn	Annealed	Not welded	2-4	--
	Annealed	Annealed	4	--
Ti-4Al-4Mn	Annealed	Not welded	3	56-72
	Annealed	1400 F, 2 hours, furnace cool to 1000 F, air cool	3-4	35-79
Ti-4Al-4Mn	1450 F, 3 hours, water quench; 1000 F, 8 hours, air cool	Not welded	3-4	70-89
		1450 F, 3 hours, water quench; 1000 F, 8 hours, air cool	5->5	53-87
Ti-5Cr-3Al	Annealed	Not welded	2-3	84
		Annealed	2-3	70
Ti-6Al-4V	Annealed ^(b)	Not welded	3	80-91
		1300 F, 2 hours, air cool	4	44-87

(a) Rotary beam specimens, Prot method used. Most specimens failed away from the weld center line but some failed on the weld center line.

(b) Fatigue data on another heat obtained, but was very low because of impurities.



FIGURE 92. PRODUCTION YOKE WITH STABILIZER PANELS ATTACHED (REF. 98)

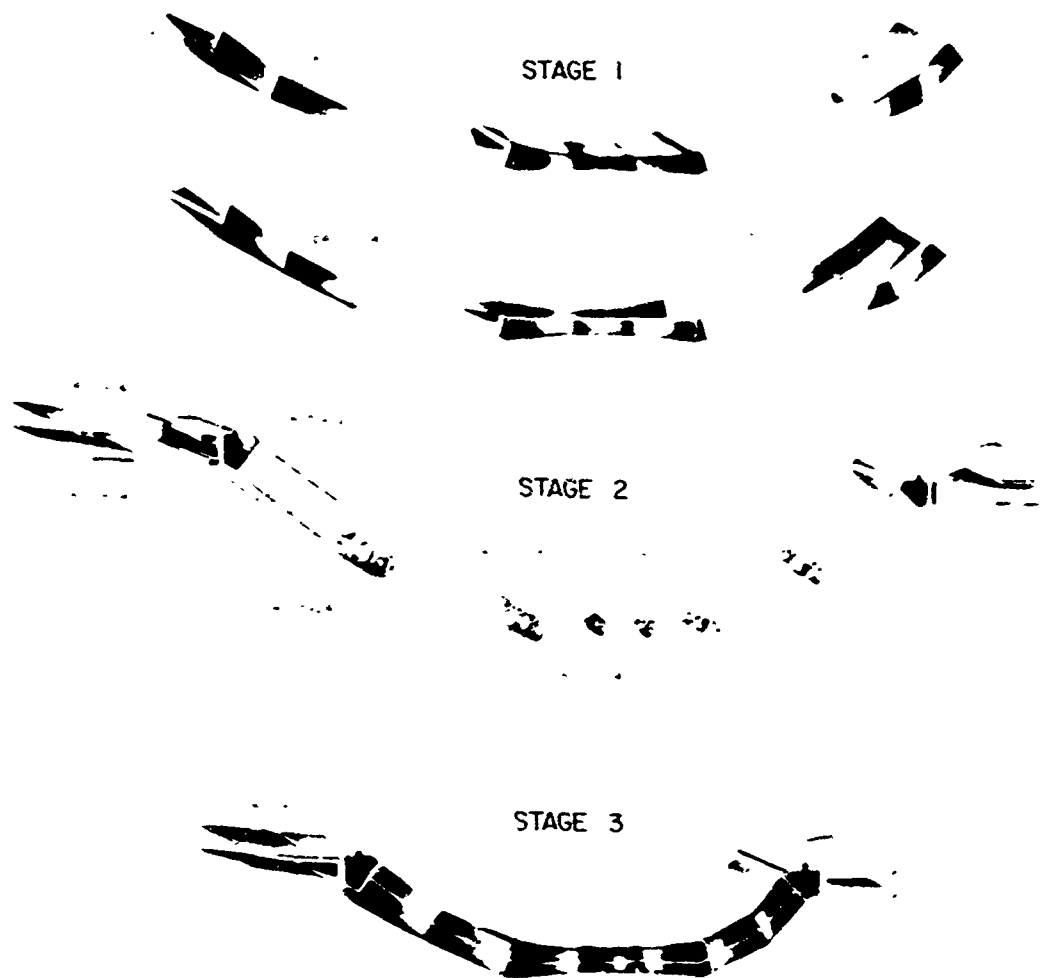


FIGURE 93. FLASH-WELDED FOIL STABILIZER YOKE ASSEMBLY (REF. 52)



FIGURE 94. A YOKE SUBASSEMBLY IN POSITION TO BE FLASH WELDED (REF. 98)

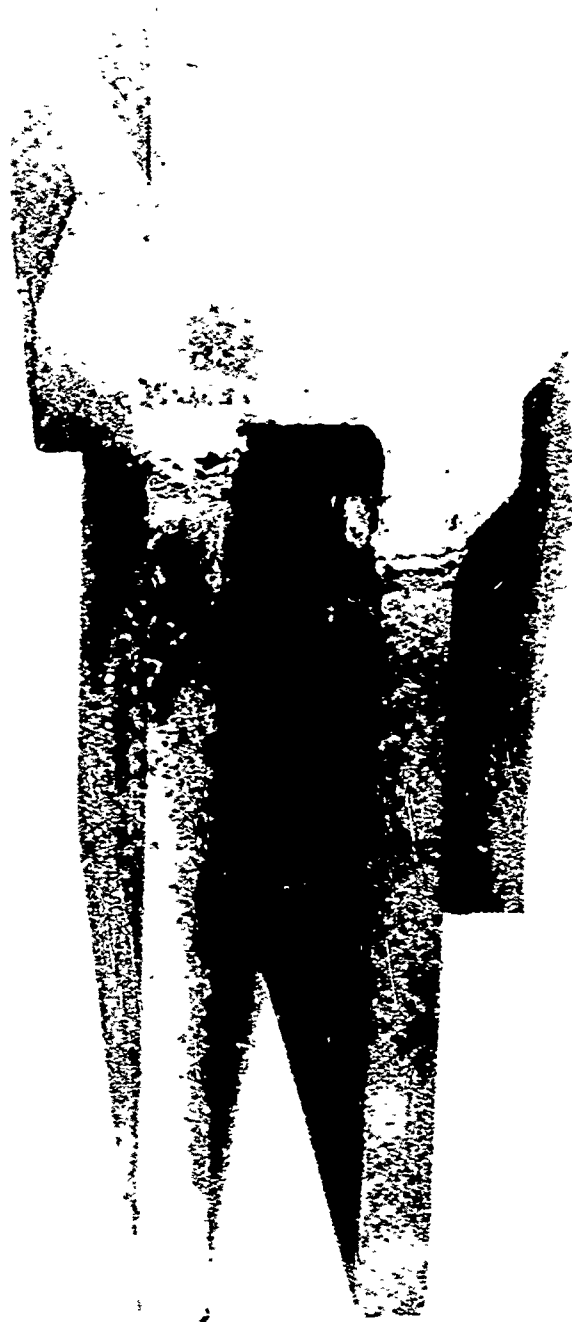
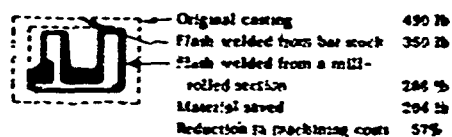


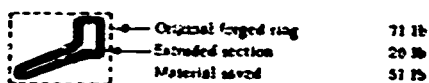
FIGURE 95. WELDED YOKE SUBASSEMBLY PRIOR TO REMOVAL OF FLASH (REF. 96)

Clamping during flash welding had to be clean, secure, and uniform in order to insure low contact resistance and avoid die burns. Flash was removed by chip hammering, grinding, and polishing.

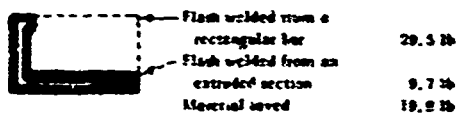
Rings. Titanium rings used primarily as inlet guide flanges and as front compressor flanges in aircraft jet engines also have been fabricated by flash welding (Ref. 95). Cross-section areas that have been welded range from 0.26 to 5.39 square inches for commercially pure titanium and from 0.66 to 3.84 square inches for some titanium alloys. However, 12-square-inch sections of titanium are weldable with commercial flash-welding machines. The rings usually are rolled to near the final size, allowing for material that will be flashed away. The open ends of the rolled rings then are flash welded together to form the completed rings. Substantial cost savings can be realized using this fabricating technique (Ref. 99). Examples of the economy of flash-welded ring products are illustrated in Figure 96 (Ref. 100).



a. Cast Versus Welded



b. Forged Versus Welded



c. Rectangular Versus Shaped Section

FIGURE 96. TYPICAL EXAMPLES OF THE ECONOMY OF FLASH-WELDED RING PRODUCTS (REF. 100)

HIGH-FREQUENCY WELDING

Titanium tubing has been made using the high-frequency welding processes illustrated in Figure 97 (Ref. 101). Although used for development quantities, speeds up to 105 fpm have been used.

At present, only one fabricator has referred to production of high-frequency welded tubing (Ref. 102). The tubing has a 0.025-inch-thick wall and is used in manufacturing a heat-exchanger bundle. The tubing features a 12 per cent cost reduction. Because of high tube mill and material costs, it is unlikely that high-frequency welded titanium or titanium-alloy tubing will become available as a standard product until quantity requirements increase. High-frequency welding, however, does have long-range potential for making titanium tubing economical.

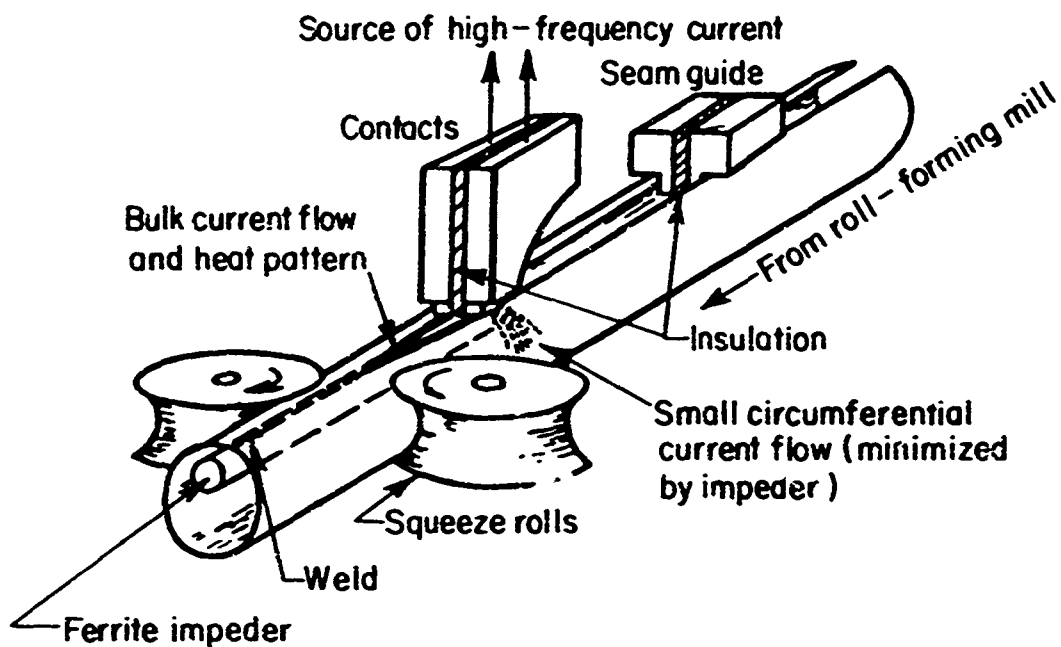
High-frequency welding also has capabilities for manufacturing fabricated structural shapes from titanium. Titanium tees have been fabricated experimentally and indications are that the process can be adapted to fabricate I-beams, stiffened-skin sections, and other structural shapes.

BRAZING

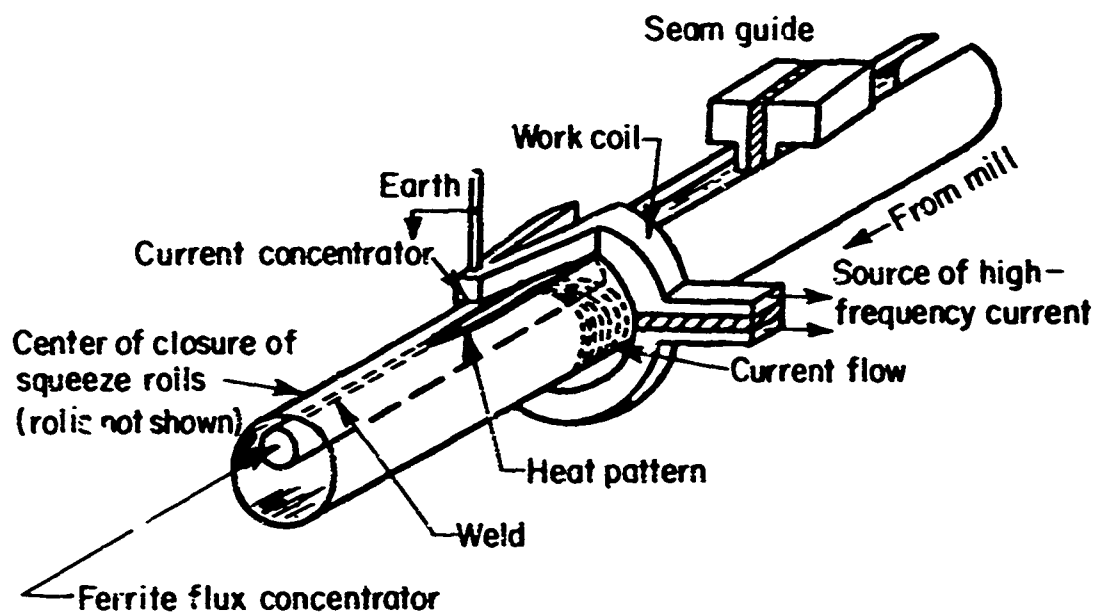
Brazing has attractive advantages over other joining processes in the fabrication of titanium sandwich structure, and in the completion of dissimilar metal joints. Despite the great potential for these two areas, most of the programs that have been conducted to complete required development have not produced universally acceptable procedures for completing such joints.

Most of the problems encountered in attempting to braze titanium are related in one way or another to the characteristics of titanium metal. The high affinity of titanium for other elements leads to a requirement that brazing must be conducted under conditions that prevent contamination or degradation of the material being joined. Also, because of its high reactivity, it is difficult to find suitable braze filler metals that do not react excessively with the titanium base material producing subsequent embrittlement or serious erosion of the base metal. The final problem area has been one of finding brazing filler metals suitable for use with brazing thermal cycles that are compatible with the limited thermal heat-treatment cycles that can be used on titanium alloys.

Filler Metals. To be useful as a brazing filler metal, an alloy must melt within a desired temperature range, it must wet the



a. Method of operation of contact-resistance tube-welding head



b. Method of operation of induction tube-welding head

FIGURE 97. HIGH-FREQUENCY WELDING METHODS FOR MANUFACTURING TITANIUM TUBING (REF. 101)

base material involved, and it should flow to some extent while molten on the base metal. Of all the various metals and alloys that meet one or more of these criteria, only the silver-base alloys have been used with much success for the brazing of titanium. Not all of the silver-base brazing alloys are suitable for use with titanium, but at least several have been found that appear to exhibit many of the desirable properties of a brazing filler metal. The most promising alloys are either silver-lithium, silver-aluminum-manganese, or silver-copper-lithium alloys. The most common problem encountered with other brazing alloys, which on the surface appear usable, is that they react readily with titanium. Only through the use of very short brazing times is it possible to prevent excessive alloying between the filler metal and the titanium-base material.

The most promising alloys at present are those containing aluminum and manganese in a silver base. Although alloys of this type appear to be somewhat better than the silver-lithium alloys with respect to oxidation resistance and salt-spray corrosion resistance, there is still some reluctance to use the materials where exposure to these conditions can be expected. The brazing temperature for the silver-aluminum-manganese alloys ranges between about 1450 to 1650 F.

The silver-lithium alloys are used in a composition ranging from 0.5 to 3 per cent lithium. However, joints made with these alloys do not have good oxidation resistance in air at temperatures of about 800 F and the joint strength is seriously degraded by exposure to these conditions. Joints made with the silver-lithium alloys also appear to have poor corrosion resistance in salt-spray environments.

The silver-cadmium-zinc brazing filler metals also have been developed and have been used for oxyacetylene torch-brazing applications. Consistent joint tensile strengths in the range of from 40,000 to 50,000 psi and single-lap-joint shear-strength values in excess of 30,000 psi are reported. Silver-cadmium-zinc brazing filler alloys containing 20 per cent silver have been patented for combining exceptional mechanical properties (Ref. 104). These alloys were developed for use in joining titanium to itself, steel, stainless steel, and silver alloys. Fluxes for use with these alloys have also been developed.

The experimental palladium-base alloy, Pd-14.3Ag-4.6Si, has some very desirable characteristics (Ref. 103). It has excellent flow characteristics in the temperature range of 1395 to 1450 F (below the beta-transition temperature of pure titanium). The alloy forms a metallurgical bond, with alloy interfacial penetration of 0.0015 inch into titanium and 0.003 inch into stainless steel. Ultimate tensile

strengths of joints as high as 75,000 psi have been achieved. Connections brazed with the alloy are inert to nitric acid and, under vacuum, helium leakage is less than 0.63 cubic centimeters per year.

A wide variety of brazing alloys has been investigated and some are available commercially. A partial listing of patents issued on brazing filler metals and fluxes is given in Table XXVI (Ref. 104). Many additional alloys and properties of brazed joints are described in published literature. Obviously, brazing alloys for titanium alloys must be selected with care, depending on the alloy being joined, thickness, mass, penetration tolerance, and service requirements.

Brazing Methods. The methods that have been used to braze titanium are similar to those used for other materials such as stainless steel. With titanium, however, particular care must be taken to insure against contamination of the base metal during the brazing cycle. This has necessitated the careful use of either inert gas or vacuum environments during the brazing cycle. Heating for brazing is generally accomplished in retorts placed in furnaces or by some type of radiant heating device such as quartz lamp panel. Ceramic blanket brazing also has been used (Ref. 105). Some success has been reported with a conventional oxyacetylene-torch brazing technique (Ref. 104). Brazing methods used on titanium demand careful control throughout all steps to insure that the titanium-base material is not degraded or contaminated from any source.

Properties. The lap-shear strength of brazed joints is listed in Table XXVII. These data were obtained from specimens brazed using inert-gas-filled retorts and conventional furnaces. The brazing cycle for most of the joints consists of heating the retort to a temperature of 1450 ± 10 F, holding for 5 minutes, and air cooling to room temperature. The joints made with the silver-aluminum-manganese alloy were brazed at a temperature of 1600 F. The joints prepared with the silver-aluminum alloys have better elevated-temperature strength and better resistance to salt-spray corrosion and elevated-temperature oxidation than the joints made with the silver-lithium alloys even when the brazing alloys are plated.

Effects of Brazing Cycles on Base-Metal Properties. An important factor in selecting brazing filler metals for titanium alloys is the effect of the brazing cycle on base-metal properties. This factor is especially important in brazing heat-treatable titanium alloys. Several general rules may be outlined.

TABLE XXVI. TITANIUM BRAZING AND SOLDERING PATENTS FROM THE "TITANIUM ABSTRACTS"
OF THE INDUSTRIAL CHEMICAL INDUSTRIES LTD. (ICI) (REF. 104)

Patents	Authors	Annotations
<u>British</u>		
741, 735	Industrial Chemical Industries, Ltd.	Titanium flux containing KHF_2KCl
741, 736	Ditto	Joining titanium articles with aluminum base - 2 to 7% magnesium filler metal
741, 737	"	Titanium brazing aluminum base 5 to 15% silicon filler metal
750, 928	Lundin, H.	Flux for coating titanium 25 to 70% AlF_3 45 to 60% NaF , bal. KF
752, 117	Long, R. A.	Ni-Ti-Cu brazing compounds
768, 126	Nat. Res. Dev. Corp.	Titanium flux containing CuCl , AgCl
788, 589	Kaisha, S. K. K.	Titanium brazing to stainless steel, silver, Ag-Mn, Ag-Cd alloys used
824, 256	Thompson-Houston Co.	Titanium brazing with chromium carbides
<u>German (Applications)</u>		
1003012		Titanium soldering with Al-12% silicon alloys
1003013		Titanium soft solder Al-5% Mg alloy, $\text{KHF}_2\text{-KCl}$ flux
10036017		Like U. S. 2, 666, 725
<u>German</u>		
859, 249	Degussa Co.	Ag-Cd-Zn alloy silver up to 20%
<u>United States</u>		
2, 666, 725	Chemmer, E. S.	LiF , KCl , KHF_2 brazing flux
2, 761, 047	Meredith, H. L.	Joining titanium to aluminum
2, 762, 271	Meredith, H. L.	Brazing titanium with gas tungsten-arc process and silver filler metal
2, 798, 843	Slovin, G. W.	Plating and brazing titanium
2, 822, 269	Long, R. H.	Bonding titanium to base metals by a Ti-Ni eutectic composition
2, 834, 101	Boam, W. M. and Friedman, I.	Plating method for brazing titanium
2, 844, 867	Wernz, D. E. and Swartz, M. M.	Titanium dip-brazing method
2, 847, 302	Long, R. A.	Titanium bonding ceramics by Ti-Ni eutectic with additions of copper, cobalt, manganese, etc.
2, 882, 593	Sobel, M. M. and Weigert, K. M.	KHF_2 , KCl , BaCl_2 , LiF brazing flux
2, 914, 848	Phillips, E. and Blum, S.	Titanium brazing alloy with 2 to 4% tin, 2 to 5% aluminum, balance silver
2, 919, 984	Eutectic Welding Co.	Silver 5%, cadmium, zinc alloy

TABLE XXVII. SHEAR STRENGTHS OF TITANIUM BRAZED JOINTS (REF. 106)

Condition	Test Temperature. F	Shear Strength, ksi		
		Low	High	Average
<u>Ti-5Al-2.75Cr-1.25Fe Base Metals</u>				
<u>Nickel-Plated 97Ag-2Li Filler Metals</u>				
As brazed	RT	12	16	14
As brazed	800	3	5	4
<u>Ti-5Al-2.75Cr-1.25Fe Base Metals</u>				
<u>Platinum-Plated 97Ag-2Li Filler Metals</u>				
As brazed	RT	17	23	19
As brazed	800	2	4	3
<u>Ti-5Al-2.75Cr-1.25Fe Base Metals</u>				
<u>Ag-Al-Mn Filler Metals</u>				
As brazed	RT	22	26	24
As brazed	800	14	17	16

The brazing temperature should be 100 to 150 F below the beta transus for the alloy. If the brazing temperature exceeds the beta transus, the base-metal ductility may be impaired, especially in the alpha-beta alloys. In beta-type alloys, the beta transus may be exceeded without impairing base-metal properties but if the temperature is too high, the ductility of the alloy after heat treatment may be impaired.

In brazing heat-treatable alloys, the brazing temperature may affect the ultimate and yield strengths of the alloy after final heat treatment unless it is possible to fully heat treat the assembly after brazing. For example, full heat treatments for most of the heat-treatable alpha-beta alloys consist of two operations: solution treatments to adjust the ratio of alpha and beta phases (thereby adjusting the composition of the beta phase) for optimum heat-treatment response, and age-hardening treatments. If the brazing operation is part of the heat-treatment cycle, it is desirable to braze at either the solution-treating or age-hardening temperatures. However, the age-hardening temperatures are low (800 to 1100 F) and satisfactory alloys that melt and flow at these temperatures are not available.

If the brazing operation is performed near the solution-treating temperature as part of the heat-treating operation, then, the cooling rate from brazing temperature may affect the final properties of the base metals. This is especially true for alloys, such as Ti-6Al-4V,

that have low beta content and require rapid cooling from solution-treating temperature to obtain good heat-treatment response. Some of the all-beta alloys retain good heat-treatment response after furnace-cooling operations.

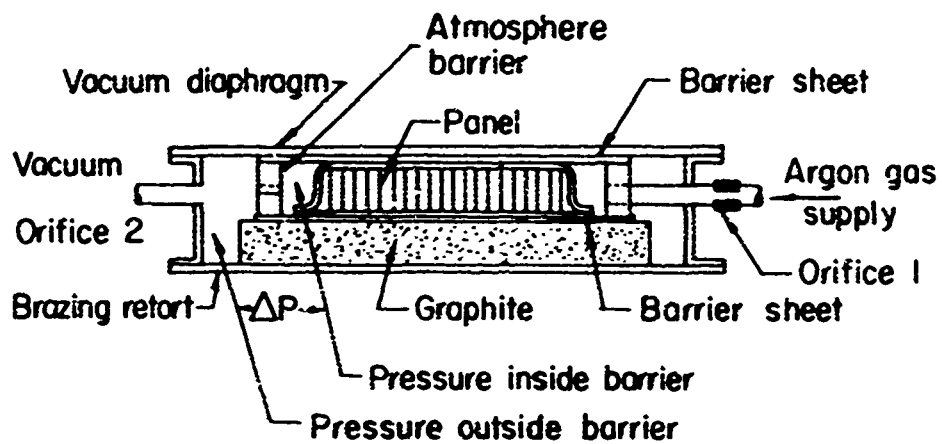
Applications. Brazing has been used for joining titanium experimentally for about 20 years, and in production applications for about 10 years; the widest use has been in fabricating honeycomb sandwich panels. This application has been studied by many organizations (Refs. 103, 105, 107-109). Representative applications of titanium brazing techniques are described in the following.

Honeycomb Sandwich Structures. In furnace and retort brazing operations, titanium can be contaminated by leakage of air into the brazing atmosphere. To insure against such leakage, one fabricator has developed a double-layer inert-gas shroud retort for brazing titanium (Ref. 110). The shroud retort has been used mainly for fabricating brazed honeycomb panels from titanium and from stainless steel. In addition to providing good protection against contaminants, the process provides for lower argon consumption and shorter brazing cycles than were obtained with conventional retorts. The technique permits the use of gas or electric furnaces and eliminates the need for a secondary argon-filled retort around the brazing retort.

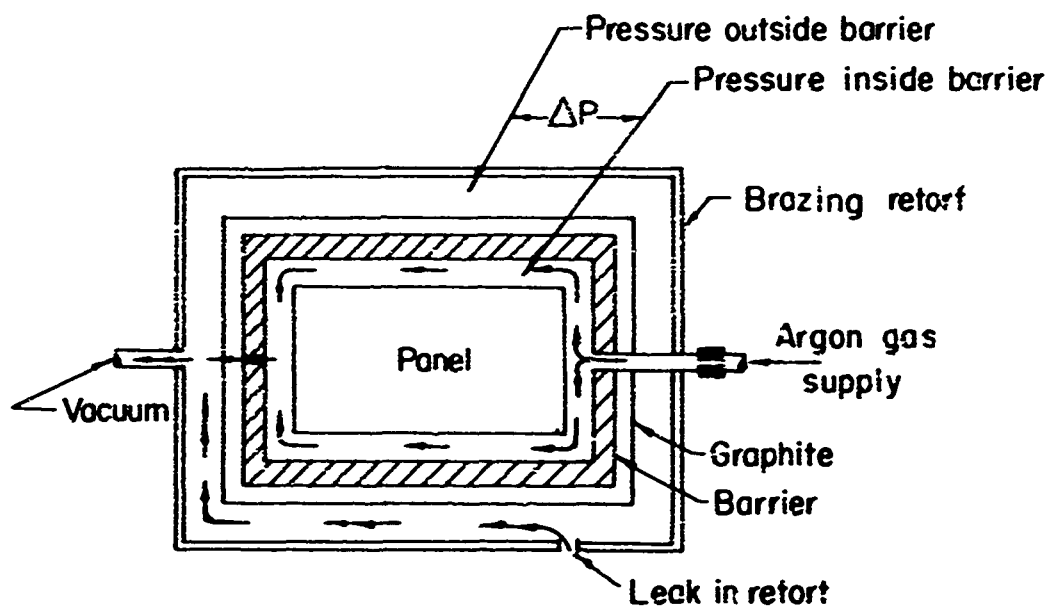
The technique isolates the titanium from contamination both dynamically and mechanically. Protection is afforded by two separate atmosphere zones and a pressure differential that insures more effective protection. This system, shown in Figure 98, is similar to a conventional retort, except that it is larger and is divided into two pressure zones. The outer zone is maintained at a reduced pressure while the inner zone is filled with argon gas. Air entering through a leak in the retort is removed between the retort and the barrier and exhausted through the vacuum tube. The pressure differential helps hold the parts in intimate contact during the brazing cycle. A typical brazing sequence of operations is described below.

Thin contoured skins are cold stretch formed. Only the close-tolerance sheet-metal edge members are hot formed to obtain correct dimensions and contour. After the titanium parts are produced, they are checked for fit, dimensions, and tolerances in a prefit operation, or trial assembly. Then they are cleaned as follows:

- (1) Vapor degrease thoroughly
- (2) Soak 10 to 15 minutes in caustic cleaner (180 to 190 F)
- (3) Rinse in tap water (120 to 140 F)



a. Honeycomb Panel Shielded by Two Pressure Zones to Keep Contaminants Out



b. When Retort Leaks, Contaminants Are Exhausted Through Evacuation Tube

FIGURE 98. DOUBLE-WALL RETORT SYSTEM FOR BRAZING TITANIUM ALLOYS SANDWICH PANELS (REF. 110)

- (4) Acid clean 15 to 30 seconds (3% Hf-15% HNO₃)
- (5) Rinse in tap water (RT)
- (6) Soak 2 minutes in caustic cleaner (180 to 190 F)
- (7) Rinse in tap water (120 to 140 F)
- (8) Rinse in distilled or demineralized water (RT)
- (9) Dry in hot air.

Brazing alloy foil, Ag-Al-Mn, is cleaned by vapor degreasing, soaking 2 to 5 minutes in caustic cleaner, rinsing in hot tap water (120 to 140 F), and wiping with soft cheesecloth. From this point on, extreme care must be taken to keep the parts clean. Operators must wear clean gloves and perform the following operations as rapidly as possible to minimize the formation of oxides on the clean metal surfaces.

First the panel is assembled and checked in a lay-up fixture that has copper chill bars for tack brazing. Here the parts are fastened in position with light tack-braze spots. Then the panel is placed inside the stainless steel brazing retort and the atmosphere barrier tool. Slip sheets that prevent the skins from bonding to the diaphragm and fillers are added. Next, antibraze "stop-off" material is painted on surfaces where adhesion is not desired. After this, the vacuum diaphragm, or cover sheet, is welded in position on the retort, and the unit is checked for leaks. If leaks are not eliminated, air cannot be purged from the retort satisfactorily. Purging consists of alternately drawing a vacuum on the retort and then supplying it with argon gas, the number of repeat cycles depends on retort capacity and vacuum pressure. Pressures of 25 to 50 microns are desirable, but effective purging can be done with pressures as high as 1.92 inch Hg (absolute).

Next, thermocouples are attached to the vacuum diaphragm directly over the panel, and the diaphragm is covered with insulating material to offset the effect of the graphite reference tool - one layer of 0.080-inch aluminum silicate paper for each inch of graphite thickness. This balances the heat input to the panel from both sides. Then the automatic vacuum control is set to maintain the desired pressure. This setting is critical, because insufficient vacuum fails to provide enough contact pressure for a good quality braze; but too much vacuum can crush the honeycomb core, which becomes extremely weak at brazing temperatures. The rate of heating to brazing temperature (1625 F) does not appear to be critical. However, to reduce the risk of contamination, it is desirable to complete the hot cycle as quickly as possible.

The retort is then removed from the furnace and air cooled. With some titanium alloys the retort may be inserted into an aging furnace, although additional cooling will do no harm.

Residual antibraze material is removed by scrubbing with aluminum oxide powder and a stiff-fiber brush. Then a light coating of silicone oil is applied to prevent surface contamination in subsequent handling. All panels are inspected radiographically to verify the quality of internal brazed joints, but visual examination determines the extent of possible external defects. The basic retort is re-useable. The parts are cleaned and straightened after each brazing operation for re-use. The vacuum diaphragm and slip sheets, however, are expendable.

Three titanium-5Al-1.25Fe-2.75Cr sandwich panels used on the B-58 aircraft, as illustrated in Figure 99, have been made by brazing using the system described above. The panels included an elevon surface panel, a nacelle panel, and an elevon training wedge.

Brazing Stainless Steel to Titanium. Commercially pure titanium and stainless steel tubes, 1-inch OD by 0.035-in. wall have been brazed (Ref. 111). The titanium tube was inserted in the expanded end of a stainless tube, with various amounts of 98Ag-2Li alloy foil and wire. The assembly was placed in a Vycor glass tube with a flowing argon gas atmosphere. An induction coil with five turns was placed around the joint. A 10-kw (450-kc) induction generator was used as the heating source. The brazing cycle consisted of argon purge for 5 to 10 minutes and heating to the brazing temperature of 1450 to 1500 F in 2 to 4 minutes. Up to 75 per cent of the circumference of the tubing joint was brazed. No benefits were obtained from either silver plating the titanium tubing or nickel plating the stainless steel tubing. All the sections of the brazed joints that were exposed to salt spray failed within 100 hours.

SOLID-STATE WELDING

In solid-state welding, joints are formed with all components of the joining system being maintained as solids. Welds can be made under these conditions if two metallic surfaces, which have been prepared properly, are brought together under an applied pressure at a suitable temperature for a sufficient length of time. Deformation and diffusion are important mechanisms of solid-state welding. It is convenient to subdivide this type of welding on the basis of whether deformation or diffusion is the predominant mechanism contributing to weld formation. Actually, both mechanisms always operate to some

extent during the formation of a joint, but there are significant differences in the extent to which these two mechanisms control a given welding process. Deformation may be limited to very small surface areas during welding that is controlled primarily by diffusion mechanisms. When considerable deformation is used during the welding operation, diffusion can be quite limited. Both deformation and diffusion welding have been applied successfully to titanium.

Solid-state welding consists of many joining processes that have been referred to by a number of different names. As used in this report, the term solid-state welding is intended to cover all joining processes in which either diffusion or deformation plays a major role in the formation of the joint and in which a liquid phase is absent during welding.

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

Some of the merits that make this process attractive as a method of fabrication 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 which will produce welds.

Diffusion welding is primarily a time- and temperature-controlled process. The time required for welding can be shortened considerably by using a high welding pressure or temperature because diffusion is much more rapid at high temperatures than at low temperatures. Both the welding time and temperature often can be reduced by using an

intermediate material of different composition to promote diffusion. This procedure reflects the increase in diffusion rate that is obtained by the introduction of a dissimilar metal.

The steps involved in diffusion welding are as follows:

- (1) Preparation of the surfaces to be welded by cleaning or other special treatments
- (2) Assembly of the components to be welded
- (3) Application of the required welding pressure and temperature in the selected welding environment
- (4) Holding under the conditions prescribed in Step 3 for the required welding time
- (5) Removal from the welding equipment for inspection and/or test.

The preparation step involved in diffusion welding usually includes a chemical etching and other cleaning steps similar to those employed during fusion welding or brazing. In addition, the surfaces to be welded may be coated with some other material by plating or vapor deposition to provide surfaces which will weld more readily. Coatings, such as ceramics, are sometimes applied to prevent welding in certain areas of the interface. The 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 given load, and placing the assembly in autoclaves so that high gas pressures can be applied. A variety of heating methods also can be used in diffusion welding, but generally, the temperature is raised by heating with some type of radiation heater. As suggested above, the environment during welding is another important factor during this type of joining. With titanium, a vacuum environment is desirable, although it is possible to bond in an inert gas.

Diffusion-welded joints have been made in titanium and several of its alloys at selected conditions including the following ranges:

Temperature	1500 to 1900 F
Time	30 minutes to 6 hours
Pressure	5,000 to 10,000 psi.

Welding conditions reported in the published literature are given in Table XXVIII. In all cases, the environment during welding was a vacuum. Some success has been reported with the diffusion welding

TABLE XXVIII. SUMMARY OF DIFFUSION WELDING PROCESSES FOR TITANIUM ALLOYS

Alloy	Surface Preparation	Stop-Weld	Intermediate	Welding Parameters			Welding Atmosphere	Reference
				Time, min	Temp, F	Pressure, psi		
CP titanium	Polish with metallo-graphic paper, degrease	None	None	15	<1700	200-600	Inert	112
Ditto	--	None	None	240	1750	10,000	Evacuated container	113
"	Abrasion clean	None	None	180-240	1550	10,000	Ditto	114
"	--	None	None	15	1475	1,000	Vacuum, 5x 10 ⁻⁵ torr	115
5Al-2.5Sn	Abrasion clean, degrease	None	None	60	1850	--	Vacuum, 3x 10 ⁻⁴ torr	116
Ti-3Al-2Sn	Mechanically scraped, degrease	None	None	1-5	1550-2000	700	Vacuum, 1x 10 ⁻³ torr	117
Ti-3Al-2.5V to Ti-6Al-4V	--	--	--	180	1600	--	Vacuum, 5x 10 ⁻⁶ torr	--
Ti-2Al-1Mo-1V to CP titanium	Abrasion clean, alkaline clean, water rinse, acid etch (20H ₂ O:5HNO ₃ :1HF), water rinse, abrasion clean, water rinse, oven dry	None	None	30-1200 (240 at 1750 F best to date)	1620-1800	3-1/2 on face sheet of noney-comb sandwich	Vacuum, 10 ⁻⁵ to 10 ⁻⁶ torr	118

of titanium employing an intermediate material to either decrease the welding temperature or the required time. The usefulness of this method with titanium is limited by the difficulty in finding an intermediate material which will not react excessively with the titanium to form either brittle intermetallic compounds or other undesirable phases.

Deformation Welding. Deformation welding differs from diffusion welding primarily in that a measurable reduction in the thickness of the parts being joined occurs during deformation welding. The large amount of deformation involved makes it possible to produce a weld in much shorter times and frequently at lower temperatures than are possible during diffusion welding. The major application of deformation welding of titanium to date has been in the fabrication of roll-welded sandwich structures. Unidirectional structural panels with either a corrugated or ribbed structure have been produced with this process. In addition, the process shows promise for the fabrication of structural shapes such as tees or I-beams.

The steps involved in deformation welding are very similar to those used in diffusion welding. The major difference between these two solid-state-joining methods is the amount of deformation used. Diffusion welding uses only that deformation required to bring the facing surfaces, with commonly encountered roughnesses, into intimate contact. The deformation is confined to a narrow region on either side of the interface. In deformation welding, however, the restrictions given above do not apply. Welding deformations as great as 95 per cent may be used, for example. The use of high deformations, applied rapidly, can substantially reduce the time required for welding; e. g., 1 second or less.

Roll Welding. Roll welding is a solid-state deformation-welding process that has been used for the fabrication of titanium sandwich panels and other structural shapes (Refs. 119, 120). Truss-core panels, with the structural members supported by a matrix material of mild steel, are fabricated using a hot-plate rolling-mill reduction sequence. The cleaned and assembled pack, Figure 100, is sealed by welding, evacuated, and outgassed at 1600 F for about 2 hours. For most titanium alloys, the rolling temperature is in the range of 1400 and 1800 F. Subsequent to rolling, the composite can be formed with conventional equipment in the same manner as a solid plate. After forming, the mild-steel supporting structure can be removed by leaching with a nitric-acid solution.

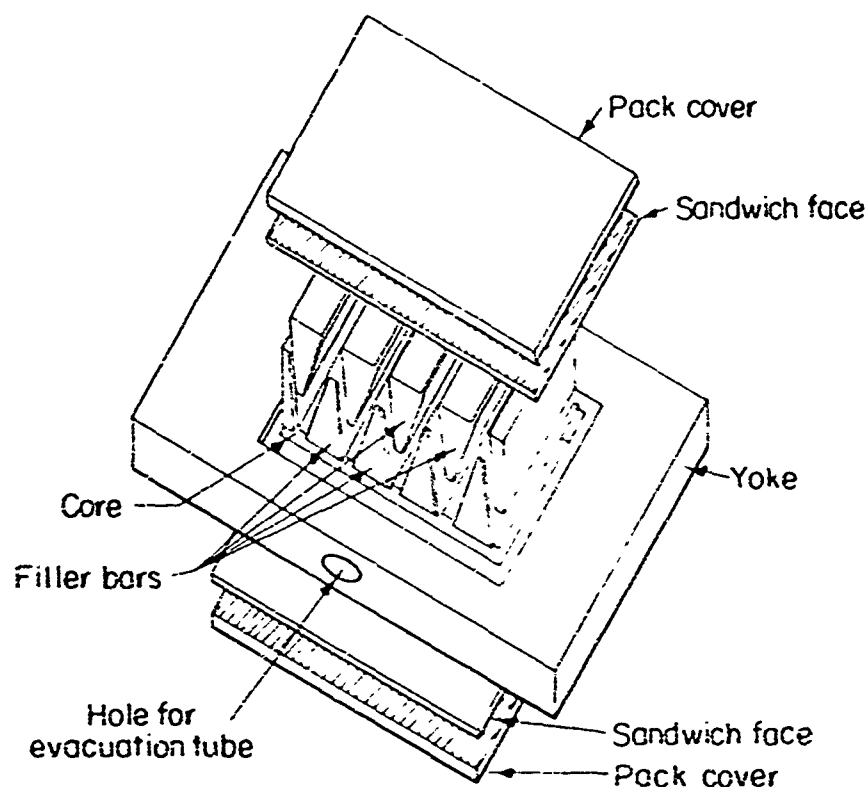


FIGURE 100. EXPLODED VIEW OF ROLL-WELDED PACK PRIOR TO HOT ROLLING (REF. 119)

Materials which have been investigated and found to be suitable for this method of fabrication include:

- (1) Aluminum alloys, 2024 and 5052
- (2) Titanium, alpha and alpha-beta alloy
- (3) 300 series stainless steels
- (4) PH 15-7 Mo precipitation hardening stainless steel
- (5) Nickel-base alloys, René 41 and Inconel
- (6) Refractory metals, tantalum, columbium, molybdenum, and tungsten.

Roll welds between columbium and molybdenum, B66 columbium-base alloy and TZM molybdenum base alloy, tantalum and tungsten, tungsten and Ta-10W, copper and titanium, stainless steel and titanium, and stainless steel and tantalum have recently been reported (Ref. 121).

Examples of products made from titanium by roll welding are illustrated in Figure 101.

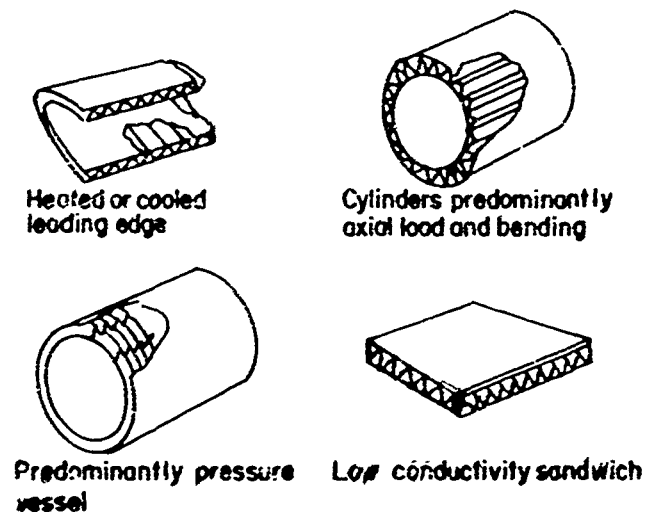


FIGURE 101. TYPICAL APPLICATIONS OF ROLL-WELDED CORRUGATED SANDWICH CONSTRUCTION (REF. 119)

Pressure-Gas Welding. Pressure-gas welding (Refs. 122, 123, 124) is a welding process in which the joint is produced simultaneously over the entire area of abutting surfaces, by heating with gas flames and by the application of pressure, without the use of filler metal. Pressure-gas welding may or may not be a solid-state-welding process, depending on the actual welding procedure used. The two 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 by gas flames until a predetermined upsetting of the joint occurs. This method of pressure-gas welding has been used for welding several titanium alloys for tubing and pressure vessel applications. In the open-joint method the faces to be joined are individually heated by the gas flames to the melting temperature and then brought into contact for upsetting. The open-joint method has not been used for welding titanium or titanium alloys. The process in both modifications is ideally adapted to a mechanized operation, and practically all commercial applications are either partially or fully mechanized. The process is adaptable also to the welding of low- and high-carbon steels, low- and high-alloy steels, and several nonferrous metal alloys.

Since the metal along the interface in the closed-joint method does not reach the melting point, the mode of welding is different from that of fusion-type welding. Generally speaking, welding takes place by the action of grain growth, diffusion, and grain coalescence across the interface under the impetus of high temperature and upsetting or pressure. It has been demonstrated in several research programs that these forces are capable of creating a high grade weld. Pressure-gas welds are characterized by a smooth-surfaced bulge or upset at the weld and by the general absence of fused metal in the weld zone.

In the open-joint method, welding takes place in the molten state but most of the molten metal is squeezed from the interface by impact pressure. The welds made by the open-joint technique resemble flash welds in general appearance.

Pressure-gas welding has been successfully applied to the fabrication of titanium alloys for liquified-gas container tanks, tubing and pipe, and stabilizer arms for B58 aircraft escape capsules. A wide range of thicknesses and sizes have been welded by this method. To be acceptable, for these applications weld strength must equal or exceed 95 per cent of the average base-metal strength.

Pressure-gas welding equipment used for joining titanium is the same as for pressure-gas welding other materials. The process produces a forged butt weld by upsetting the faying surfaces under heat and pressure. The heating system consists of a multi-orifice circular oxyacetylene torch equipped with suitable pressure regulators and flowmeters to provide a controlled heating rate at the joint. In one application for joining titanium the circular torch is oscillated so the individual pinpoint flames are oscillated back and forth around the joint to avoid local overheating. The welding pressure is supplied by a hydraulic system of a size sufficient to produce the required forging pressures. Pressures may vary from 3,000 to 15,000 psi of weld area. An overall view of a pressure-gas welding machine is shown in Figure 102. A close-up view of the welding station showing the torch, gas flames, and joint being welded are shown in Figure 103. Although the equipment used for pressure-gas welding is a conventional machine for heating and applying pressure, details of the equipment such as the circular-heating-torch design are considered proprietary. Pressure-gas welding has been successfully applied to the welding of the following alloys: Ti-5Al-2.5Sn, Ti-6Al-4V, Ti-6Al-6V-2Sn, and Ti-7Al-4Mo. Prior to welding, all of these materials are in the annealed or solution-treated condition. Whether the process can be applied to other titanium alloys remains to be determined. Size



FIGURE 102. APPARATUS FOR PRESSURE-GAS WELDING (REF 124)

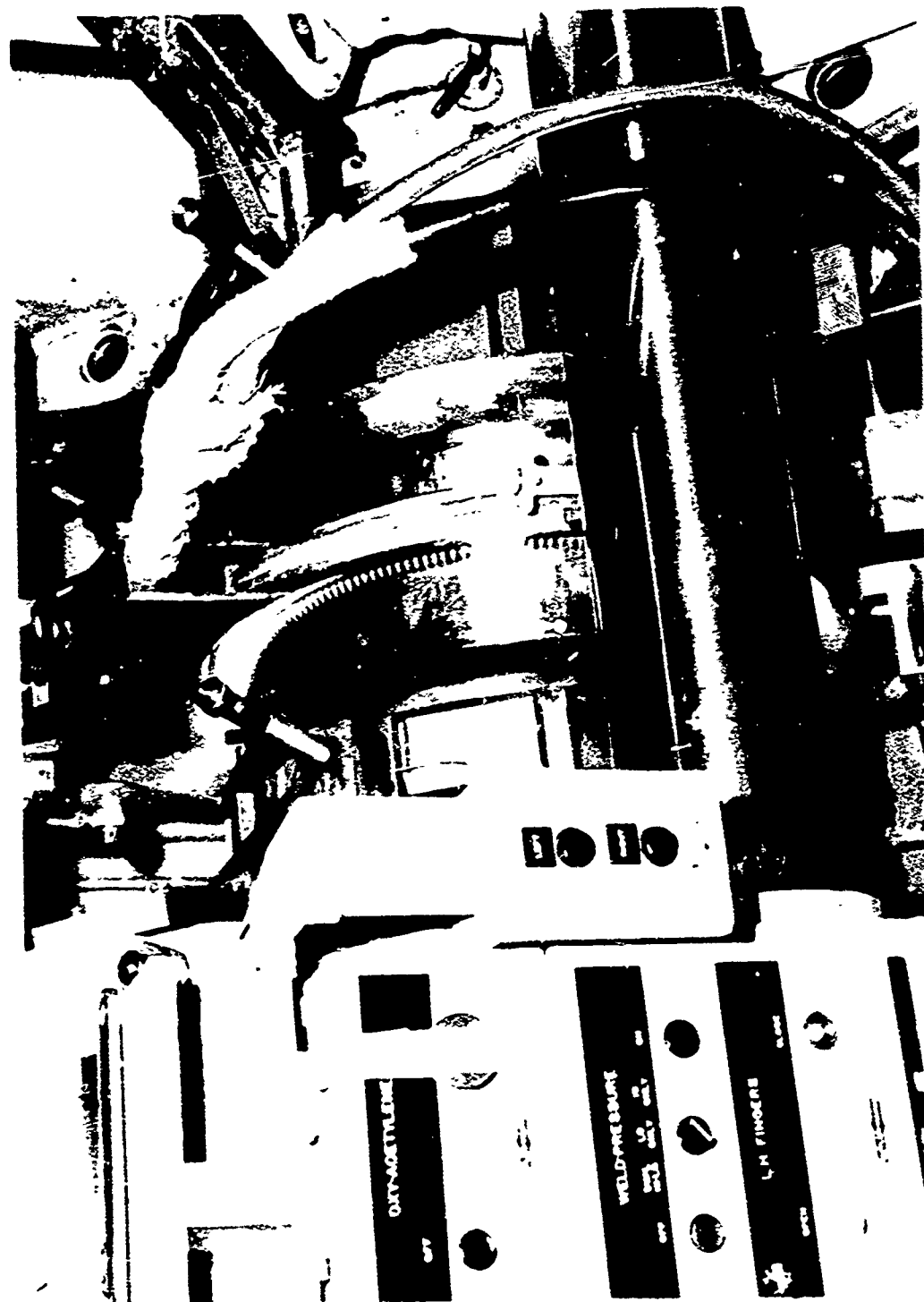


FIGURE 103. CLOSE-UP VIEW OF THE PRESSURE-GAS WELDING STATION (REF. 124)

ranges that are pressure-gas welded include thicknesses ranging from 1/8 to 1-1/4 inches, diameters up to 26 inches, and lengths up to about 60 inches.

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

- (1) The parts to be welded are aligned in the machine.
- (2) A controlled welding force is applied.
- (3) The torch is ignited.
- (4) Heating is continued until sufficient forging has been produced to upset the joint a predetermined amount to complete the joint.
- (5) The gas flame is extinguished.
- (6) Hydraulic welding force is released.
- (7) The part is removed from the machine after cooling to a predetermined temperature.

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

It should be noted that there is no shielding gas used to protect either the inside or outside of the titanium vessels during pressure-gas welding. Argon gas is used to help protect the inside of the tanks or containers during heat-treating operations.

Ti-6Al-4V is the only alloy for which information is available on pressure-gas-weld properties. The tensile, notch-tensile, and impact properties of pressure welds are listed in Table XXIX. These data seem to indicate that the pressure welds have lower strength than the base metal; this is true for some welds but not others. Usually the joints have strengths equivalent to or exceeding those of the base metals.

Experience has indicated that forgings and extrusions are superior to plate or spun sections for high-strength light-weight pressure-vessel assemblies. Heat treating after welding is employed to provide maximum tensile strength both in steel and titanium-alloy pressure vessels currently in production.

Although not directly concerned with welding, pressure-gas-welding equipment has another interesting application. This application is called upsetting and may be compared with the process known as resistance-metal gathering. During fabrication of cylindrical

TABLE XXIX. TENSILE, NOTCHED TENSILE, AND IMPACT PROPERTIES OF PRESSURE WELDS IN Ti-6Al-4V TUBING

Specimen	Testing Temperature, F	Ultimate Tensile Strength, ksi	Tensile Yield Strength, ksi	Elongation, per cent in 4D	Reduction in Area, per cent	Impact Energy ^(a) , ft-lb	
						-65 F	80 F
Unnotched, base metal	80	172	156	10	28	12-13	12-17
Unnotched, pressure weld	80	166	146	8	33	9-11	10-12
Notched, base metal	80	221	--	--	--	--	--
Notched, pressure weld	80	214	--	--	--	--	--
Notched, base metal	-65	230	--	--	--	--	--
Notched, pressure weld	-65	220	--	--	--	--	--

(a) Vee-notch Charpy specimens.

sections, inside or outside shoulders are often required. Normally when additional material is required for such shoulders, it is necessary to start with stock or forgings of sufficient size so that these can be machined. By using the upsetting method, the wall thickness can be increased locally, and the design located for either external or internal shoulder. This has the double advantage of requiring less weight initially plus the fact that less machining is required to make the final part. More detailed information on solid-state welding may be found in the literature (Ref. 125).

DISSIMILAR METAL JOINTS

Occasionally, it is desirable to join titanium-base alloys to other metals for various applications. Titanium is difficult to weld to steels, aluminum, nickel, and copper alloys because brittle structures result when it is highly alloyed with these metals. Highly alloyed structures are formed in the fusion zones of welds that are made with processes that result in melting of both base metals. These highly alloyed zones contain intermetallic compounds and are extremely brittle. Columbium, molybdenum, tantalum, and zirconium are more compatible for welding to titanium than are steel, nickel, and copper. When titanium is highly alloyed with columbium, molybdenum, tantalum, or zirconium, brittle intermetallic compounds are not formed. The resulting solid solutions usually have low ductility.

Titanium can be joined to some other metals by the use of special techniques. The problem usually is to join titanium to aluminum, copper, stainless steels or carbon steels while providing a leak-proof, reliable joint or a good electrical contact. There are many different approaches geared to suit the individual problem. Some of these approaches are listed in the literature as follows (Ref. 8):

- (1) Welding, using pure vanadium rod as a filler material
- (2) Welding, using ultrasonic or electron-beam techniques to avoid formation of high-temperature phases
- (3) Brazing, by furnace, torch, induction, or resistance brazing. Techniques are most advanced for silver-base brazing alloys, however, these have some limitation in corrosion applications.
- (4) Titanium-lined steel. Heavy walled pressure vessels have been lined successfully by expanding a light-gage titanium cylinder into a steel shell. Successful joining

techniques have been developed to prevent contamination of the titanium liner with the steel shell.

- (5) Titanium-clad steel. Special welding techniques have been developed for joining either brazed or rolled clad titanium.

Examples of titanium-dissimilar metal applications are described in the following.

MIG SPOT WELDING ALUMINUM TO TITANIUM

MIG welding has been adapted for attaching titanium to aluminum alloys (Ref. 126). With this process, a lap joint is welded with aluminum filler metal through the titanium into the aluminum to produce a "fused rivet". The shear strength of the assembly depends on the product of the shear strength of the deposited filler metal and its cross-section area.

It is well known that direct fusion welds between aluminum and most other metals produce brittle intermetallic compounds that seriously limit strength and ductility. In gas metal-arc spot welds, however, the brittle intermetallic compounds formed at the periphery of the welds do not extend across the shear plane and have little effect on strength and ductility in shear loading. This joint geometry permits metal-arc spot welding of metal combinations that cannot be resistance seam welded without the use of special techniques.

The equipment is the same type used for gas metal-arc spot welding all-aluminum joints. Good spot timing controls should be combined with a reliable wire feeder and a constant potential (and preferably variable slope) power supply. Argon shielding is used.

Welded lap joints between aluminum and titanium are made by MIG arc spot welds fused through one sheet into the bottom sheet. When the titanium is thin, the weld can be made simply by melting through it with the arc. The in-rushing filler metal and arc force push the other metal away from the center of the weld so that the core and head are composed of relatively ductile aluminum. Another technique that is used involves drilling a hole through the top sheet and filling the hole with filler metal. This technique helps minimize dilution and resulting embrittlement. An illustration of a dissimilar metal arc spot weld is shown in Figure 104 (Ref. 126). These fused-rivet joints are about as strong as gas metal-arc spot welded all aluminum joints. Typical tensile-shear strengths and welding parameters for a variety of titanium-to-aluminum joint thickness combinations are shown in Table XXX.

TABLE XXX. WELDING PARAMETERS AND TYPICAL TENSILE SHEAR STRENGTHS OF GAS METAL-ARC SPOT WELDS
IN VARIOUS METAL COMBINATIONS^(a) (REF. 127)

Material	Top Sheet		Bottom Sheet		Pilot Hole Diameter, in.	Filler Metal Feed ^(b) , ipm	Arc Volts	Weld Time, sec	Tensile Shear, Average, lb/spot
	Thickness, in.	Alloy Temper	Thickness, in.						
Ti (Ti-75A)	0.016	3003-H18	0.064		None	480	25	0.6	820
Ti (Ti-75A)	0.040	3003-H18	0.064		None	500	25	0.6	525
Ti (Ti-75A)	0.040	3003-H18	0.064		1/4	480	25	0.6	800
Al 3003-H18	0.064	Titanium	0.040		None	480	25	0.6	805

(a) Shielding gas - 30 cfm argon.

(b) 3/64-in. dia 4043 aluminum filler metal.



7.5X

Keller's Etch

FIGURE 104. CROSS SECTION OF GAS METAL-ARC SPOT WELD JOINING 0.025-INCH ALUMINIZED STEEL AND 0.064-INCH 3003 ALUMINUM WITH 4043 ALUMINUM ALLOY FILLER METAL, NO PILOT HOLE (REF. 126)

TIG PLUG WELDING

TIG plug welding has been used to join titanium to steel (Ref. 127). In development work, two procedures were used to weld 0.040-inch-thick commercially pure titanium to 1/4-inch-thick low-carbon steel. Both were modifications of plug welding using a standard gas tungsten-arc torch. Vanadium and molybdenum were investigated as the intermediate filler metals. Aluminum and silver were not considered because of the considerable difference between their melting temperature and those of titanium and steel.

The first method of fabrication, which was used only with the vanadium, was to bottom drill 1/16 inch deep, a 9/16-inch-diameter hole in the steel. A standard counterboring tool with a replaceable pilot drill was used for this purpose. This hole was filled by depositing two layers of vanadium using 1/16-inch-diameter filler wire. A 1/4-inch-diameter hole was drilled through the titanium, aligned concentrically with the vanadium, and welded to it using commercially pure titanium filler wire.

The second procedure was similar to the first. Instead of surfacing the mild steel, however, a solid disk of the intermediate material was inserted in the steel, flush with the top, and welded around its periphery. Both 0.062-inch-thick vanadium and 0.032-inch-thick molybdenum were used. As in the first procedure, the titanium was welded to the intermediate material. Results were more promising

with vanadium than with molybdenum. Process equipment has been fabricated using these methods.

RESISTANCE SPOT WELDING

Limited development work has been done on resistance spot welding of titanium to other metals (Refs. 127, 128). Process equipment utilizing titanium-to-steel joints made by resistance spot welding has been fabricated and is being evaluated (Ref. 127). Titanium can be spot welded to steel if an intermediate layer of vanadium is sandwiched in the joint. Both conventional and series-spot-welding arrangements have been used successfully. Properties of series-welded titanium-to-steel joints are given in Table XXXI.

TABLE XXXI. STRENGTH OF JOINTS^(a) BETWEEN COMMERCIALLY PURE TITANIUM AND 0.255-IN.-THICK LOW-CARBON STEEL USING A VANADIUM^(b) INTERMEDIATE (REF. 127)

Titanium Thickness, in.	Electrode Force, lb	Electrode Separation, in.	Welding Current, amp	Welding Time, cycles	Tension- Shear Strength, lb
0.025	450	3-3/4	6,900	15	1490
0.025	450	3-3/4	6,900	15	1320
0.025	450	3-3/4	6,900	15	1433
0.025	450	2-1/2	6,900	15	1125
0.025	450	2-1/2	6,900	15	1508
0.025	110	2-1/2	6,100	15	625
0.025	110	2-1/2	6,100	15	1325
0.025	110	2-1/2	6,100	15	1342
0.062	675	2-1/2	10,300	15	2730
0.062	675	2-1/2	10,300	15	2785
0.062	375	2-1/2	10,300	15	2080
0.062	375	2-1/2	10,300	15	3120
0.062	375	2-1/2	10,300	15	3110
0.062	375	2-1/2	10,300	15	3122

(a) Series-type resistance spot weld.

(b) Vanadium was 0.010 in. thick.

Resistance spot welding of commercially pure titanium to AISI 301 and 446 stainless steel, iron, nickel, chromium, zirconium, aluminum, and magnesium alloys also has been surveyed (Ref. 128). Titanium-zirconium spot welds had the highest strength of any combination; ductility was poor, and the tension-shear strength was about 1100 pounds.

Magnesium and aluminum produced braze-type joints having tension-shear strength of 525 pounds. The maximum tension-shear strength of titanium-stainless steel spot welds, 640 pounds, was obtained with solid-state bonds. Increasing welding heat caused cracking and rapid decrease in tension-shear strength accompanied by the formation of intermetallic compounds.

CAPACITOR DISCHARGE WELDING

Capacitor discharge welding of titanium to aluminum for miniature missile and electronic components has been reported (Ref. 129), but no details are available.

CONCLUSIONS AND RECOMMENDATIONS

Titanium and titanium alloys normally are considered to be difficult-to-weld materials. This is because titanium will react readily with most other materials when heated to elevated temperatures such as those encountered with most welding processes. These reactions can reduce the ductility and toughness of titanium, and in addition, can cause porosity, cracking, and embrittled welds. Titanium is welded, however, on a day-to-day basis by many fabricators and the techniques that were considered "special" or highly sophisticated are now often considered commonplace.

Experience has shown that good-quality welds can be prepared with a variety of joining processes, provided the heated metals are protected from contamination by foreign materials. Processes and procedures that minimize joint contamination must be used. Dust, dirt, grease, fingerprints, and a wide variety of foreign materials can lead to embrittlement and porosity when the base metals or filler metals are not properly cleaned prior to joining. Contamination that arises either from the open atmosphere or from foreign material on the filler metal or surfaces to be joined must be strictly avoided for the successful joining of titanium.

Although titanium and many titanium alloys can be joined readily with conventional processes combined with special techniques to prevent contamination, a significant number cannot be welded satisfactorily and additional information on joining these materials is still needed. The needed information is concerned with nearly all phases

of joining - cleaning and preparation of the base metals and filler metals, welding processes, postweld heat treatments and inspections. Particular areas in which additional information would be helpful for joining titanium and titanium alloys are described in the following.

WELDING METALLURGY

Although titanium and titanium alloys have been fabricated extensively by various welding processes during recent years, a better understanding of the welding metallurgy of these alloys is needed in order to develop successful joining processes and procedures. Studies of the metallurgical changes that occur in these alloys during welding and related processing are recommended. These studies should be aimed at establishing the effects of potentially important processing variables such as prior working history, heating and cooling rates, postweld heat treatments, intermetallic reaction, dilution when adding filler metals, and microstructure on weld-joint properties. Existing information should be evaluated and additional needed information developed.

CLEANLINESS

Limits need to be established for the cleanliness requirements for titanium-base metals and filler metals, welding atmospheres, and fluxes; also, more reliable and simpler methods for establishing cleanliness would be helpful. Instruments and monitoring devices are available for detecting surface contact resistance and the presence of some contaminants in the welding atmosphere, while chemical analytical methods can be used for analysis of flux compositions. However, these methods often cannot be used and may be cumbersome or expensive. Since extensive cleaning procedures are employed for cleaning titanium, it appears that studies aimed at developing improved cleanliness standards and methods of evaluation would be helpful to titanium-welding fabricators.

FILLER METALS

Filler-metal development programs probably will be needed to fulfill future needs for preparing higher strength, high-quality joints between similar and dissimilar metals and titanium alloys. Filler-metal development has been slow due to the lack of suitable markets and funds. In this area of development, a thorough knowledge of the welding metallurgy of titanium alloys will be required. Filler-metal

quality requirements and inspections methods also need further development and will be worthy of study.

WELDING CONDITIONS

Conditions for joining and related processing need to be established for the older and often infrequently used joining processes and for new joining processes that are promising for titanium and titanium alloys. Examples of such processes include pressure-gas and other solid-state joining processes, flash, seam, MIG, electron-beam, and plasma-arc welding.

TACK WELDING

Tack welding is often used to help position and maintain alignment of weld joints in preparation for final welding. Unless tack welding is performed properly, the weld joint may become contaminated and ruin the joint. Studies to establish satisfactory tack-welding procedures and quality requirements are recommended to supplement the meager information that is now available. One result of such a study could be the elimination of cumbersome and expensive tooling that might otherwise be required for large-size weldments in addition to improved-quality tack welds.

CONTAMINATION AND POROSITY

Embrittled welds and porosity in titanium are attributed to various kinds of foreign materials that react with titanium. However, there are no known nondestructive techniques for detecting contamination when present in a titanium or titanium-alloy weld. Detection of contamination requires destructive inspections such as hardness tests, metallographic examinations, or chemical analyses that often render the part useless. Studies are recommended, therefore, to develop reliable nondestructive methods of detecting contamination in titanium welds. In addition, specific identification of the causes of the porosity in titanium welds is needed. Porosity is a troublesome and recurrent problem in titanium welds; probably every welding fabricator who is inexperienced with titanium alloys will encounter porosity early when attempting to weld these alloys. Less complex, less expensive, more reliable solutions to the porosity and contamination problems are needed, however, by all titanium welding fabricators.

CRACKING

Specific identification of the mechanisms and causes of stress-corrosion cracking, hydrogen-induced cracking, and delayed cracking of welded joints in titanium and titanium alloys is needed. There appears to be no easy solution to these problems. However, studies of the welding metallurgy of these alloys and the metallurgical changes that take place during welding and related processing will provide information that will be useful in overcoming these problems.

THICK TITANIUM PLATE

The future needs for joining of thick titanium or titanium-alloy plate should be evaluated. Present information on the joining of titanium alloys over 1/2 inch in thickness is limited to relatively few alloys. Studies aimed at developing welding and related joining procedures for thick plates of titanium alloys not yet welded in thick-plate form can provide useful information. Oxygen-fuel-gas cutting of thick titanium plates, for example, has been performed for armored-tank welding development. Gas cutting methods may be useful for thick-plate joint preparation prior to welding.

STRESS RELIEF

Stress-relieving requirements and procedures need to be established for various titanium alloys. Although thermal and mechanical stress-relieving procedures are used by current titanium fabricators, the question of when and how to stress relieve titanium weldments still requires more definitive answers. Studies need to be undertaken to establish proper techniques for determining residual-welding-stress magnitudes and their effects, and ways to prevent or eliminate them.

REPAIR WELDING

Information available on repair welding of titanium alloys is limited. Studies are needed, therefore, to provide information on making satisfactory weld-joint repairs in alloys and weld seams where they may be anticipated. Information available should be evaluated and new information developed to fulfill expected future needs.

APPENDIX A

DESCRIPTORS FOR LITERATURE ON
FABRICATION OF TITANIUM AND
TITANIUM ALLOYS BY WELDING

DESCRIPTORS FOR LITERATURE

on

FABRICATION OF TITANIUM AND TITANIUM ALLOYS BY WELDING

Descriptors for titanium welding and joining fabrication are reviewed below.

GENERAL AREA OF INTEREST

Fabrication of titanium and titanium alloys by welding and joining.⁽¹⁾

DESCRIPTORS FROM THE "THESAURUS OF ASTIA DESCRIPTORS, SECOND EDITION"

12a - 96 Metals Joining, p. 39

Arc welding	Silver solders	Spot welds
Arc welds	Soldered joints	Thermal joining
Brazing	Soldering	Welding
Flash welds	Soldering alloys	Welding fluxes
Fluxes (fusion)	Soldering fluxes	Welding rods
Resistance welding	Spot welding	Welds

DESCRIPTORS FOR RELATED AREAS SELECTED FROM THE "THESAURUS OF ASTIA DESCRIPTORS, SECOND EDITION"

1-7 - Aircraft Structures, p. 12

Air frames	Fuselages
Airplane panels	Wings

1-150 Spacecraft, p. 55

Space tools

⁽¹⁾ Adhesive bonding and mechanical joining excluded.

11-8 - Alloys, p. 13

Titanium alloys
Metals
Titanium

11-38 - Containers & Packaging, p. 23

Propellant Tanks
Storage tanks
Tank liners
Tanks (containers)

13-153 - Structural Engineering, p. 55

Angle bars
Beams (structural)
Filament wound construction
Honeycomb cores
Monocoques
Pipe bends
Pipe
Sandwich construction

17-114 - Ordnance, p. 45

Armor
Armor plate
Body armor
Tanks

20-141 - Rockets, p. 53

Rocket cases

22-104 - Models, p. 41

Rocket models
Ship models
Submarine models

23-145 - Ship Structures & Marine Equipment, p. 53

Hulls
Hydrofoil boats
Hydrofoils
Submarine hulls

25-163 - Vehicle Parts, p. 57

Tank turrets
Vehicle tracks
Vehicle wheels

25-164 - Vehicles, p. 58

Armored vehicles

RELATED KEY WORDS AND PHRASES

Key words and phrases listed below also may be helpful in isolating the information desired.

Brazing
Fabrication
Postweld operations
Preweld operations
Recommendations for welding titanium
Soldering
Tack welding
Titanium and titanium alloys
Welding

Arc
Electron-beam
Friction
Plasma
Pressure

Diffusion bonding
Roll welding

Resistance

- Butt
- Flash
- Projection
- Seam
- Spot
- Upset
- Upset butt

Ultrasonic welding

- Welding equipment
- Welding problems & solutions
- Welding procedures
- Welding techniques

APPENDIX B

DESIGNATIONS, PROPERTIES, AND TREATMENTS
OF TITANIUM AND TITANIUM ALLOYS

Nominal Composition (Balance Ti), per cent	Producers' Nomenclature				
	Crucible Steel Co., Titanium Division	Harvey Aluminum, Titanium Division	Reactive Metals Products	Republic Steel Co., Special Metals Division	Titanium Metals Corporation
99.5		HA-1930	MST-30	RS-25	Ti-35A
99.2	A-40	HA-1940	MST-40	RS-40	Ti-55A
99.0	A-55	HA-1950	MST-55	RS-55	Ti-65A
99.0	A-70	HA-1970	MST-70	RS-70	Ti-75A
99.9					Ti-100A
0.15 to 0.20Pd	A-40Pd	HA-1940Pd	MST-Ti-0.2Pd		Ti-0.15Pd
ALPHA ALLOY GRADES					
5Al-2.5Sn	A-110AT	HA-5137	MST-5Al-2.5Sn	RS-110C	Ti-5Al-2.5Sn
5Al-2.5Sn (low O)	A-95AT	HA-5137ELI	MST-5Al-2.5SnELI	RS-110C-L	Ti-5Al-2.5SnELI
5Al-5Sn-5Zr					Ti-5Al-5Sn-5Zr
7Al-12Zr			MST-7Al-12Zr		Ti-7Al-12Zr
7Al-2Cb-1Ta (b)			MST-721		Ti-7Al-2Cb-1Ta
8Al-1Mo-1V		HA-8116	MST-811	RS-811X	Ti-8Al-1Mo-1V
ALPHA-BETA ALLOY GRADES					
8Mn	C-110M		MST-8Mn	RS-110A	Ti-8Mn
2Fe-2Cr-2Mo					Ti-140A
2.5Al-15V			MST-16V-2.5Al		
3Al-2.5V			MST-3Al-2.5V		
4Al-4Mn	C-130AM	HA-4145	MST-4Al-4Mn	RS-130	
4Al-3Mo-1V			MST-4Al-3Mo-1V	RS-115	Ti-4Al-3Mo-1V
5Al-1.25Fe- 2.75Cr				RS-140	Ti-5Al-4FeCr
5Al-1.5Fe-1.4Cr- 1.2Mo					Ti-155A
6Al-4V	C-120AV	HA-6510	MST-6Al-4V	RS-120A	Ti-6Al-4V
6Al-4V (low O)		HA-6510ELI		RS-120A-L	Ti-6Al-4VELI
6Al-6V-2Sn- 1(Fe,Cu)		HA-5153	MST-6Al-6V-2Sn		Ti-6Al-6V-2Sn
7Al-4Mo	C-135AMo	HA-714C	MST-7Al-4Mo	RS-135	Ti-7Al-4Mo
BETA ALLOY GRADES					
1Al-8V-5Fe			MST-1Al-8V-5Fe		
3Al-13V-11Cr	B-120VCA		MST-13V-11Cr-3Al	RS-120B	Ti-13V-11Cr-3Al

(a) Other numbers: T-12117 and WA-PD-76C(1) apply to all grades and all products; T-14557, T-14558, T-9046C, and T-9047C apply to all grades; and T-9884(ASG) applies to various grades.

Other Designations		Forms Available (c)	Formability, Minimum Bend Radius, T	Weldability Remarks	Melting Temperature, F	Nominal Composition (Balance Ti), per cent
AMS No.	Military No. (a)					
		B, b, P, S, s, T, W, E	1 to 2	All unalloyed	3038	99.5
4902				grades		
4941	T-9047B-1	B, b, P, S, s, T, W, E	1 to 3	are	3000-3100	99.2
4951				completely		
4900A	T-7993B	B, b, P, S, s, T, W, E	1 to 3	weldable (W)	3000-3100	99.0
4901B		B, b, P, S, s, T, W, E	2 to 3		3020	99.0
4921		B, b, W, E	--		3025	98.9
		B, b, P, S, s, T, W, E	1 to 4	Completely W	3000-3100	0.15 to 0.20Pd

4910						
4926		B, b, P, S, s, W, E	3 to 5	Weldable	2820-3000	5Al-2.5Sn
4953						
4956						
		B, b, P, S, s, W, E	3 to 5	Weldable	2820-3000	5Al-2.5Sn (low O)
	In preparation	B, b, P, S, s	3 to 5	Weldable	~3000	5Al-5Sn-5Zr
	In preparation	B, b, P, S, s	3-1/2 to 5	Weldable	~3000	7Al-12Zr
	In preparation	B, b, P, S, W, E	4 to 6	Weldable	3065-3115	7Al-2Cu-1Ta (b)
In preparation	In preparation	B, b, P, S, s, W, E	3 to 5	Weldable		8Al-1Mo-1V

4908A		P, S	2-1/2 to 4	W not recommended	2730-2970	8Mn
4923		B, b, S, s	3 to 5	W not recommended		2Fe-2Cr-2Mo
	T-5894(1)	B, b, P, S, s, W	2	W not recommended		2.5Al-16V
		S, T	2 to 3			3Al-2.5V
4925A		B, b, P, W	--	W not recommended	2820-3000	4Al-4Mn
4912		P, S, s	2-1/2 to 4	Special conditions	~3000	4Al-3Mo-1V
4913				permit some W		
		B, b, P, S	3-1/2 to 5	Special conditions		5Al-1.25Fe-2.75Cr
				permit some W		
4929		B, b, P	--	W not recommended	~3100	5Al-1.5Fe-1.4Cr-1.2Mo
4969						
4911						
4928A	OS-10737	B, b, P, S, s, W, E	3 to 5	Weldable	~3000	6Al-4V
4935	OS-10740					
		B, b, P, S, s, T, W, E	3 to 5	Weldable	~2000	6Al-4V (low O)
	T-46035	B, b, P, W, E	--	Special conditions	~3100	6Al-6V-2Sn-1(Fe, Cu)
	T-46038			permit some W		
		B, b, P, W, E	--	Special conditions	~3000	7Al-4Mo
				permit some W		

		B, b, P	--	W not recommended		1Al-8V-5Fe
4917		B, b, P, S, s, W	2 to 4	Weldable		3Al-13V-11Cr

(b) Formerly 8Al-2Cu-1Ta. All data given are for the 8-2-1 composition.

(c) B, billet; b, bar; P, plate; S, sheet; s, strip; T, tubing; W, wire; E, extrusions.

Nominal Composition (Balance Ti), per cent	Recommended Forging Temperature Range, F		Beta Transform Temp. F $\pm$ 25 F	Stress-Relief Annealing	Recommended Heat Treatment Annealing Treatment
	Start	Finish			
99.5	1500-1700	1200-1500	1630	1000 to 1100 F, 1/2 hr, AC	1250 to 1300 F, 2 hr, AC
99.2	1500-1700	1200-1500	1675	1000 to 1100 F, 1/2 hr, AC	1250 to 1300 F, 2 hr, AC
99.0	1600-1700	1200-1600	1690	1000 to 1100 F, 1/2 hr, AC	1250 to 1300 F, 2 hr, AC
99.0	1700-1750	1300-1600	1740		
99.9	1750	1550	1750	1000 to 1100 F, 1/2 hr, AC	1250 to 1300 F, 2 hr, AC
0.15 to 0.20 Pd	1700	1550	1675	1000 to 1100 F, 1/2 hr, AC	1250 to 1300 F, 2 hr, AC

ALPHA ALLOY GRADES

5Al-2.5Sn	1600-1950	1400-1750	1900	1000 to 1200 F, 1/4 to 2 hr, AC	1325 to 1350 F, 10 min to 4 hr, AC
5Al-2.5Sn (low O)	1600-1900	1400-1750	1910	1000 to 1200 F, 1/4 to 2 hr, AC	Ditto
5Al-5Sn-5Zr	1800-1900	1600	1815	1100 F, 1/2 hr, AC	1650 F, 4 hr AC
7Al-12Zr	1825-1925	1900	1825	1000 F, 1/2 hr, AC	(1) 1600-1650 F, 1/2 to 4 hr, AC (2) 1300 F, 1 hr, AC
7Al-2Zr-1Ta	1950	1650	1920	1100 to 1200 F, 1/2, AC	1650 F, 1 hr, AC
8Al-1Mo-1V	1950	1850	1900	1100 to 1200 F, 1 hr, AC	(1) 1450 F, 8 hr, FC (Consult (2) 1450 F, 8 hr, FC + 1450 F, and plate (3) 1450 F, 8 hr, FC + 1850 F, (Triplex)
				For forgings	(4) 1950 F, 1 hr, AC + 1200 F,

ALPHA-BETA ALLOY GRADES

8Mn	Forging not recommended		1475	900 to 1100 F, 1/2 to 2 hr, AC	1250 to 1300 F, 1 hr, FC to 1000 F
2Fe-2Cr-2Mo	1700	1300		900 to 1000 F, 1/2 to 1 hr, AC	1200 F, 1/2 hr, AC
2.5Al-16V	1400 (max)	1350 (min)	Solution treating is recommended for both annealing and stress relieving		
3Al-2.5V	Forging not recommended				1300 F, 1 hr, AC
4Al-4Mn	1600-1750	1300-1600	1700	1300 F, 2 hr, FC	1300 F, 1 to 4 hr, FC
4Al-3Mo-1V	1750	1650	1755	1000 to 1100 F, 1 hr, AC	1225 F, 4 hr, SC to 1050 F, AC
	Forging not recommended				
5Al-1.25Fe-2.75Cr	1400-1750	1400-1500	1725	1100 F, 1 hr, AC	1450 F, 1 hr, SC to 1050 F, AC
5Al-1.5Fe-1.4Cr-1.2Mo	1650-1750	1650	1755	1200 F, 2 hr, AC	1200 F, 4 to 24 hr, AC
6Al-4V	1750-1900	1400-1750	1820	900 to 1200 F, 1 to 4 hr, AC (Usual: 1 hr, 1100 F, AC)	1300 to 1550 F, 1 to 8 hr, SC to 1050 F, AC
6Al-4V (low O)	1750-1900	1400-1750	1820	Ditto	Ditto
6Al-6V-2Sn-1(Fe, Cu)	1725	1550	1735	1100 F, 2 hr, AC	1300 to 1400 F, 1 to 2 hr, AC
7Al-4Mo	1800-1950	1550-1600	1840	900 to 1300 F, 1 to 8 hr, AC	1450 F, 1 to 8 hr, SC to 1050 F, AC

BETA ALLOY GRADES

1Al-8V-5Fe	1500	1450	1525	1000 to 1100 F, 1 hr, AC	1250 F, 1 hr, FC to 900 F, AC
3Al-13V-11Cr	1800-2150	1400-1800	1325	Solution treating is synonymous with annealing for this alloy.	

(a) Abbreviations: AC = air cool, SC = slow cool, FC = furnace cool, WQ = water quench, CR = cold rolled.

(b) Numbers in parentheses refer to heat treatments used to generate the data given in later tables. See Condition columns.

Treatment: (a)	Typical Tensile Properties														Nominal Composition (Balance Ti), per cent
	Form	Condition	Room Temperature				600 F				Extreme Temperatures				
			E _t ^{10⁶} psi	US, ksi	YS, ksi	EL, %	E _t ^{10⁶} psi	US, ksi	YS, ksi	EL, %	Test Temp, F	US, ksi	YS, ksi	EL, %	
Solution Treatment (Aging Treatment)															
Not heat treatable	S	Ann	14.9	38	27	30	12.1	20	10	50					99.5
Not heat treatable	S	Ann	14.9	60	45	28	12.3	28	13	45	-423	175	--	--	99.2
Not heat treatable	S	Ann	15.0	75	60	25	12.5	33	19	33	-321	165	--	--	99.0
	S	/ in	15.1	90	75	23	12.5	43	27	28	-321	175	--	--	99.0
Not heat treatable	S	Ann	15.5	100	85	17	12.6	47	30	25					98.9
Not heat treatable	S	Ann	14.9	62	46	27	12.3	28	13	30					0.15 to 0.20 Pd
Not heat treatable	S	Ann	16.0	125	117	18	13.4	82	65	19	1000	75	56	18	5Al-2.5Sn
	b	Ann	15.0	115	110	20									
Not heat treatable	S	Ann	16.0	110	95	20	13.4	78	60	20	-423	229	206	15	5Al-2.5Sn (low O)
Not heat treatable	S	Ann	15.0	125	120	18	14.2	94	74	20	1000	84	67	21	5Al-5Sn-5Zr
Not heat treatable	S	(1) Ann	16.0	135	130	15	14.3	109	86	21	1000	93	75	23	7Al-12Zr
	b	(2) Ann	--	165	159	14	--	130	119	18					
	b	Ann	17.7	126	120	17	15.1	100	81	25					7Al-2Cu-1Ta
producers for other treatments)	S	(1) Ann	18.5	160	150	18					1000	85	70	20	8Al-1Mo-1V
1/4 hr, AC (Dupl. -)	S	(2) Ann	18.0	145	138	15									
5 min; AC + 1375 F, 1/4 hr. AC	S	(3) Ann	--	150	142	13									
8 hr, AC	b	(4) Ann	--	141	130	18	--	107	85	19	1000	88	71	20	
Solution treat not recommended	S	Ann	16.4	137	125	15	14.4	98	75	13	800	80	59	15	BMn
1400 to 1480 F, 1 hr. WQ or AC	b	Ann	16.7	137	125	18	14.7	95	65	19	800	75	55	30	2Fe-2Cr-2Mo
(900 to 950 F, 2 to 8 hr, AC)	b	Aged	--	179	171	13	--	136	112	16					
1350 to 1400 F, 10 to 30 min, WQ	S	SHT	--	165	145	16									2.5Al-15V
(950 to 990 F, 4 hr, AC)	S	Aged	15.0	180	165	6	13.5	155	140	8	800	140	125	19	
Solution treat not recommended	S	Ann	15.5	100	85	20	12.0	70	50	25					3Al-2.5V
1400 to 1500 F, 1/2 to 2 hr, WQ	b	Ann	16.4	148	135	15	13.9	110	90	17	800	100	85	21	4Al-4Mo
(800 to 1000 F, 3 to 24 hr, AC)	b	Aged	--	162	143	16	--	125	100	11					
1625 to 1650 F, 1/4 hr, WQ	S	Ann	16.5	140	120	15	14.0	--	--	--					4Al-3Mo-1V
(925 F, 8 to 12 hr, AC)	S	Aged	--	195	167	6	--	152	120	7	800	145	115	8	
1350 to 1500 F, 2 hr, WQ	b	Ann	16.8	155	145	15	15.5	122	102	20					5Al-1.25Fe-2.75Cr
(900 to 950 F, 5 to 6 hr, AC)	b	Aged	17.6	190	175	6	16.2	144	117	10					
1690 to 1625 F, 1 hr, WQ	b	Ann	16.5	154	145	16	15.0	115	109	15	800	118	100	20	5Al-1.5Fe-1.4Cr-
(1000 F, 24 hr, AC)	b	Aged	17.0	195	184	9	14.6	156	125	14					1.2Mo
1550 to 1750 F, 5 min to 1 hr, WQ	S, b	Ann	16.5	138	128	12	13.5	105	95	11	800	90	78	18	5Al-4V
(900 to 1000 F, 4 to 8 hr, AC)	S	Aged	--	170	155	8	--	120	105	7	800	120	100	8	
Solution treat not recommended	S	Ann	16.5	135	127	15	13.5	105	95	12	-320	220	205	13	6Al-4V (low O)
1600 to 1675 F, 1 hr, WQ	b	Ann	15.0	155	150	15	13.4	132	117	20	800	80	80	15	5Al-6V-2Sn-
(900 to 1100 F, 4 to 8 hr, AC)	b	Aged	16.5	190	180	10	14.5	150	132	15					1 (Fe, Cu)
1650 to 1750 F, 1/2 to 1-1/2 hr, WQ	b	Ann	16.2	160	150	16	14.2	127	108	18	800	117	94	15	7Al-4Mo
(900 to 1200 F, 4 to 16 hr, AC)	b	Aged	16.9	185	175	10	15.0	150	123	12					
1375 to 1425 F, 1 hr, WQ	b	Ann	16.5	177	170	9	14.7	128	115	15	800	103	85	32	1Al-8V-5Fe
(925 to 1000 F, 2 hr, AC)	b	Aged	16.5	221	215	10	14.5	140	123	12	800	120	100	30	
1400 to 1500 F, 1/4 to 1 hr, WQ or AC	S	Ann	14.2	135	130	16	13.2				800	115	800	16	3Al-13V-11Cr
(900 F, 2 to 96 hr, AC) 1450 F,	S	Aged	14.8	185	175	8	13.8	175	145	8	800	160	920	12	
1/3 hr, AC + CR + 800 F, 24 hr, AC	S	CR+Aged	--	260	245	4									

Nominal Composition (Balance Ti), per cent	Creep Data						Stress Rupture Data					
	Form	Condition	Test Temp. F	Stress, ksi	Time, hr	Total Plastic Def, %	Form	Condition	Test Temp. F	Stress, ksi	Time, hr	K _t Factor
99.5												
99.9												
99.0							b	Ann	800	25	100	1
99.0	S	Ann	850	8	150	0.15	b	Ann	800	17	450	1
99.9												
0.15 to 0.20 Pd												

ALPHA ALLOY GRADES

5Al-2.5Sn	S	Ann	800	48	100	0.10	S	Ann	800	62	1000	1
	S	Ann	1000	8	150	0.15	S	Ann	1000	19	1000	1
5Al-2.5Sn (low O)												
5Al-5Sn-5Zr	S	Ann	1000	30	150	0.15	S	Ann	1000	60	99	1
7Al-12Zr	S	(1) Ann	1000	30	150	0.15	S	(1) Ann	1000	60	330	1
	b	(1) Ann	1000	20	300	0.10						
7Al-2Cu-1Ta	S	Ann	1000	12	150	0.15	b	Ann	1000	32	1000	1
8Al-1Mo-1V	S	(1) Ann	1000	18	150	0.15						
	S	(3) Ann	1000	21	150	0.20						
	b	(4) Ann	1000	25	150	0.40	b	(4) Ann	1000	60	40	1

ALPHA-BETA ALLOY GRADES

3Mn	S	Ann	800	5	100	0.50	S	Ann	400	100	1000	1
2Fe-2Cr-2Mo												
2.5Al-16V							S	Aged	600	90	100	1
3Al-2.5V												
4Al-4Mn	b	Ann	400	99	800	4.50	b	Ann	800	47	1000	1
							b	Aged	600	120	100	1
4Al-3Mo-1V												
	S	Aged	800	44	200	0.50	S	Aged	800	72	500	1
5Al-1.25Fe-2.75Cu												
5Al-1.35Fe-1.4Cr-1.2Mo	b	Ann	800	46	1000	0.20	b	Ann	800	75	150	1
5Al-4V	b	Ann	600	70	1000	0.10	b	Ann	850	68	100	1
							b	Aged	850	72	100	1
5Al-4V (low O)												
5Al-6V-2Sn	b	Ann	600	100	150	0.20						
1 (Fe, Cu)	b	Aged	600	100	191	0.22						
7Al-6Mo	b	Ann	1000	14	150	0.20	b	Ann	800	117	153	1
							b	Aged	1000	50	325	1

BETA ALLOY GRADES

1Al-8V-5Fe	b	Ann	600	110	310	0.78						
	b	Aged	800	45	212	6.60						
3Al-13V-11Cr	S	Ann	600	107	500	0.20	b	Ann	600	107	500	1

Fatigue Data						RT			
Form	Condition	Test Temp, F	Type Test	Stress, ksi, 10^7	K_t Factor and (Stress range) ^(a)	Charpy V Impact, ft-lb	Hardness ^(b)	Usage Remarks	Nominal Composition (Balance Ti), per cent
	Ann						120 B	Highest formability grade	99.5
b	Ann					25-40	200 B	Aerospace,	99.2
							225 B	Chemical, and	
b	Ann	600	Rot. beam	22	1	20-35	265 B	Marine applications	99.0
b	Ann	RT	Rot. beam	63	1	11-15			99.0
	Ann						295 B	Engine forgings	98.9
	Ann						200 B	Corrosion resistant grade	0.15 to 0.20 Pd

S	Ann	RT	Direct axial	93	1(A= .9) ^(a)		36 RC	Weldable, high strength grade with good oxidation resistance	5Al-2.5Sn
b	Ann	RT	Rot. beam	27	3.2	19			
b	Ann					19	36 RC	Cryogenic grade	5Al-2.5Sn (low O)
								High creep strength grade	5Al-5Sn-5Zr
								High creep strength grade	7Al-12Zr
b	Ann	RT	Rot. beam	81	1		36 RC	High fracture toughness	7Al-2Cu-1Ta
								High strength plus long time creep resistance	8Al-1Mo-1V
S	(3) Ann								
b	(4) Ann								

S	Ann	RT	Direct axial	96	1(A=∞)			Good formability with moderate strength	8Mn
S	Ann	600	Reverse bend	44	4.6	12-15			2Fe-2Cr-2Mo
b	Aged					8-10			
S	Ann							Excellent formability as annealed	2.5Al-16V
S	Aged	RT	Direct axial	32	1(A=1)			Heat treatable to high strength	3Al-2.5V
T	Ann							Tubing alloy	
b	Ann	RT	Rot. beam	90	1	10-15		Heavy section aircraft components including fasteners	4Al-4Mn
b	Aged	RT	Rot. beam	105	1				
S	Ann						32-38 RC	Good formability. Heat treatable to high strength. Stable	4Al-3Mo-1V
S	Aged	RT	Direct axial	124	1(A= .6)				
b	Ann	RT	Rot. beam	88	1	10-15	32-38 RC	Airframe components	5Al-1.25Fe-2.75Cr
b	Aged	RT	Rot. beam	105	1				
b	Ann	RT	Rot. beam	100	1	10	38 RC	Airframe and ordnance components	5Al-1.5Fe-1.4Cr
b	Aged	RT	Rot. beam	110	1				1.2Mo
b	Ann	RT	Rot. beam	75	1	10-20	36 RC	Wide versatility grade. Heat treatable to high strength	6Al-6V
b	Aged	RT	Rot. beam	92	1				
b	Ann					10	36 RC	Cryogenic grade	6Al-6V (low O)
b	Ann					15		Ordnance applications and aircraft components	5Al-5V-2Sn-1 (Fe, Cu)
b	Ann	RT	Rot. beam	100	1	18	38 RC	Engine and airframe applications	7Al-4Mo
b	Aged					10			

								Fastener grade	1Al-8V-5Fe
b	Aged	RT	Direct axial	60	Threaded bolts				
							32-38 RC	Excellent formability and heat treatable to very high strength.	3Al-13V-11Cr
b	Aged	RT	Rot. beam	34	3.9	8		Advanced aerospace components.	

(a) A = Alternating stress/mean stress.

(b) Brinell (B) or Rockwell (R_C).

Nominal Composition (Balance Ti), per cent	Physical Properties											
	d, lb/in. ³	Thermal Expansion Mean Coefficient per F (10 ⁻⁶)			Thermal Con- ductivity, Btu/hr ft ² /F/ft		Instantaneous Specific Heat, Btu/lb/F		Electrical Resistivity, microhm-cm.		Elastic Moduli, 10 ⁶ psi	
		RT to 200 F	RT to 500 F	RT to 1000 F	RT	800 F	RT	800 F	RT	800 F	E	G
99.5	0.163	4.8	5.2	5.5	9	--	0.124	--	57	--	14.9	6.5
99.2	0.163	4.8	5.2	5.5	9.5	--	0.125	--	56	--	14.9	6.5
99.0	0.163	4.8	5.2	5.5	9.5 to 11.5	10.5	0.125	0.151	48 to 57	117.7	15.0	6.5
99.0	0.164	4.8	5.2	5.5	9.8 to 10.1	10.0	0.129	0.155	55 to 60	122.3	15.1	6.5
98.9	0.164	4.5	5.2	5.5	9.8	--	0.129	--	58	--	15.5	6.5
0.15 to 0.20 Pd	0.163	4.8	5.1	5.4	9.5	--	0.125	--	56.7	--	14.9	6.5

ALPHA ALLOYS

5Al-2.5Sn	0.161	5.2	5.3	5.3	4.5	7.2	0.125	0.152	157	180	16.0	7.0
	to .162											
5Al-2.5Sn (low O)	0.161	5.2	5.3	5.4	4.5	--	0.125	--	157	--	16.0	--
5Al-5Sn-3Zr	0.162	--	--	--	--	--	--	--	--	--	16.0	--
7Al-12Zr	0.165	--	--	--	--	--	--	--	--	--	16.5	--
7Al-2Cu-1Ta	0.159	--	--	--	--	--	--	--	--	--	17.7	--
8Al-1Mo-1V	0.158	4.7	5.0	5.6	--	--	--	--	199	203	18.5	--

ALPHA-BETA ALLOYS

8Al	0.171	4.8	5.4	6.0	6.3	9.0	0.118	0.152	92	140	16.4	7.0
2Fe-2Cr-2Mo	0.171										16.7	--
2.5Al-16V	0.165										--	--
											15.0	(Aged)
3Al-2.5V	0.162										15.5	--
4Al-4Mn	0.163	4.9	5.1	5.4	4.2	7.4	0.126	0.159	183	172	16.4	7.3
4Al-3Mo-1V	0.163	5.0	5.3	5.5	3.9	6.8	0.132	0.142	165	--	16.5	7.0
5Al-1.25Fe-	0.162	5.2	5.3	5.5	--	--	--	--	--	--	16.8	--
2.75Cr	to .163										17.6	(Aged)
5Al-1.5Fe-1.4Cr-	0.162	5.2	5.5	5.7	4.7	7.0	--	--	163	180	16.5	6.3
1.25Mo	to .163										17.0	(Aged)
6Al-4V	0.160	4.9	5.1	5.3	4.2	6.8	0.135	--	171	157	15.5	6.1
											--	--
6Al-4V (low O)	0.160	5.3	5.3	5.3	--	--	0.135	--	171	--	16.5	6.1
6Al-6V-2Sn-	0.164	5.0	5.2	5.3	4.2	--	0.155	--	157	--	15.0	--
1/2(Fe, Cu)									157	170	16.5	(Aged)
7Al-4Mo	0.162	5.0	5.2	5.6	3.7	7.0	0.123	0.151	175	183	16.2	6.5
											16.9	(Aged)

BETA ALLOYS

1Al-5V-3Fe	0.168											
2Al-13V-11Cr	0.175	5.2	5.6	5.9	4.0	8.0	0.120	0.198	153	--	14.2	6.2
	to .176								142	--	14.8	(Aged)

Approximate Magnetic Permeability at RT for above alloys ≈ 1.00005 at 20 Oersteds.

202

(2) Approximate magnetic permeability is RT for titanium alloys at 0000° at 50 oersteds.

REFERENCES

- (1) Faulkner, G. E., and Voldrich, C. B., "The Welding of Titanium and Titanium Alloys", Defense Metals Information Center, Columbus, Ohio, DMIC No. 122, 66 pp (December 31, 1959) (RSIC 0508).
- (2) Martin, G. E., "Design and Fabrication of Weided Titanium Wing Leading Edge", Paper 64-163, American Institute of Aeronautics and Astronautics, General Aviation Aircraft Design and Operations Meeting, Wichita, Kansas (May 25-27, 1964), 9 pp (RSIC 0762).
- (3) Rosenberg, R. A., "Applications of Mitron's Non-Reactive Flux in Welding MST-40 Titanium and Ti-5Al-2.5Sn Plates", Final Report, Mitron Research and Development Corporation, Waltham, Massachusetts, Contract No. N140(131)74959B(x) (June 15, 1963) (RSIC 0764).
- (4) Rosenberg, R. A., Pulkonik, K. J., Irons, G. S., and Regan, R. D., "Tungsten-Inert-Gas Arc Welding Titanium Using a Non-Reactive Flux", Interim Engineering Progress Report No. IR8-213(III), Mitron Research and Development Corporation, Waltham, Massachusetts, Contract No. AF 33(615)-1384 (September 1, 1964 - November 30, 1964) (RSIC 0799).
- (5) Glasgal, B. M., and Kalajian, Z., "Out-of-Chamber Welding of Thick Titanium", Welding Journal, 43 (5) 405-14 (May 1964) (RSIC 0011).
- (6) Glasgal, B. M., "Development of Welding Procedures for Titanium Alloy Armor", DMIC Accession No. 52112, Laboratories Division, Detroit Arsenal, Centerline, Michigan, Final Report No. 7594, 7 pp (April 1, 1963) (RSIC 0023).

- (7) Phelps, D. E., "Investigation and Development of a Welding Procedure Applicable to Titanium Alloy Armor", Final Report No. 3895, Detroit Arsenal, Centerline, Michigan (August 2, 1957) (RSIC 0665).
- (8) Goodford, J. A., and Manfre, J. A., "Welding Titanium", Crucible Steel Company of America, Pittsburgh, Pennsylvania, 21 pp (RSIC 0666).
- (9) Rolston, P. W., Chandley, G. D., and Adams, C. M., Jr., "Fabrication of a Titanium Tank Cupola", Welding Journal, 41 (2) 128-34 (February 1962) (RSIC 0801).
- (10) Pratt, W. M., "Control Surfaces, Welded Titanium for Fin-Fuselage Fitting", Convair/Fort Worth, Report No. FGT-2245, Contract No. AF 33(600)-36200 (May 6, 1959) (RSIC 0808).
- (11) "Titanium Welding Techniques", Titanium Engineering Bulletin No. 6, Titanium Metals Corporation of America, pp 29-36 (Revised September 1964) (RSIC 0672).
- (12) "Investigation of Weldability of Hot-Work Tool Steels and a Titanium Alloy", Final Report, Wright-Patterson AFB, Report No. ASD-TDR-62-993, 94 pp (March 1963) (RSIC 0012).
- (13) Makowski, B., and Hauser, H. A., "Fourteenth Quarterly Report on Research and Development of Titanium Rocket Motor Case", Technical Report No. WAL 766.2/1-16, Pratt & Whitney Aircraft Division, United Aircraft Corporation, East Hartford, Connecticut, Contract No. DA-19-020-ORD-5230 (July 31, 1964) (RSIC 0669).
- (14) Personal Communication from D. G. Anderson, Airite Division, Electrada Corporation, Los Angeles, California (RSIC 0647).
- (15) Personal Communication from A. M. Krainess, Space and Information Systems Division, North American Aviation, Inc., Downey, California (RSIC 0673).

- (16) "Pickling, Standard Process Specification", McDonnell Aircraft Corporation, St. Louis, Missouri, Specification No. P. S. 12050, issued January 31, 1950; Revision J (January 29, 1965) (RSIC 0676).
- , "General Specifications for Cleaning Titanium", Airite Division, Electrada Corporation, Los Angeles, California, Specification No. 71-00051, Revision J (January 13, 1964) (RSIC 0675).
- (18) "Compilation of Unpublished Materials Information", Second Semiannual Report, Republic Aviation Corporation, Farmingdale, Long Island, New York, Report No. RAC 357-5, Contract No. AF 33(616)-8084 (March 31, 1962) (RSIC 0175).
- (19) Deesing, E. F., and Fogarty, E. J., "Investigation of Spot-Welding Characteristics of Titanium Alloys", U. S. Naval Air Material Center, Philadelphia, Pennsylvania, Aeronautical Materials Laboratory, Report No. NAMC-AML-1500, 13 pp (August 1962) (RSIC 0761).
- (20) Koppenhofer, R. L., Lewis, W. J., Faulkner, G. E., and Rieppel, P. J., "Development of Procedure for Welding 2-Inch-Thick Titanium Alloy Plate", Bimonthly Report to Bureau of Naval Weapons, Battelle Memorial Institute, Columbus, Ohio, Contract No. NOw-60-0390-c (October 31, 1960) (RSIC 0668).
- (21) Johnson, M. M., and Roseman, P., "Titanium Joins the Family of Commonly Used Metals", Welding Journal, 43 (4) 267-74 (April 1964) (RSIC 0010).
- (22) Close, G. C., "Transparent Welding Chamber Provides Clean Room Conditions", Modern Machine Shop, 37 (3) 98-101 (August 1964) (RSIC 0670).
- (23) Cary, H., "You Can Weld Titanium", Hobart Arc-Welding News, AWN 177, Hobart Brothers Company, Hobart Square, Troy, Ohio, p 16 (Winter, 1965) (RSIC 0115).
- (24) Logan, D. J., and Dacus, T. H., "Studying 'Invisible' TIG Shield Gases", Metalworking Production, 106 (32) 50 (August 8, 1962) (RSIC 0671).
- (25) Masubuchi, K., and Martin, D. C., "Residual Stresses in Steel Weldments", Summary Report on Contract Nobs-84738, Battelle Memorial Institute, Columbus, Ohio (December 1963) (RSIC 0860).

- (26) Nippes, E. F., and Savage, W. F., "Residual Stresses in Welded Titanium Plates", Welding Journal, 37 (10) 433s-39s (1958) (RSIC 0751).
- (27) "Assembly and Joining (Fusion Weld Distortion Control)", Private Communication from Lockheed Aircraft Corporation (November 16, 1964) (RSIC 0861).
- (28) "Research and Development of Titanium Rocket Motor Case", Final Report on Contract DA-19-020-ORD-5230, Volume 1, Pratt & Whitney Aircraft Division, United Aircraft Corporation, East Hartford, Connecticut (October 31, 1963) (RSIC 0271).
- (29) "Welding: Aluminum, Magnesium, Non-Hardening Steels or Alloys, and Titanium, Spot, Seam, and Stitch", MIL-W-6858B (RSIC 0798).
- (30) "Tests: Aircraft Welding Operations Qualification", MIL-T-5021 (RSIC 0862).
- (31) "Components, Motor, Titanium-Fabrication Of", Aerojet General Specification AGC-36319B(A4) (October 7, 1963) (RSIC 0843).
- (32) "Fusion Welding of Titanium for the RA-5C Leading Edge-BLC", North American Aviation, Columbus Division, Process Specification HA0107-015 (RSIC 0863).
- (33) "Fusion Welding of Titanium", BAC5947, and "Spot Welding, Roller Spot Welding, and Seam Welding Titanium Alloy Parts", BAC5925, Boeing Process Specifications (RSIC 0864).
- (34) Evans, R. M., "Porosity in Titanium Welds", DMIC Memorandum 194, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio (June 8, 1964) (RSIC 0509).
- (35) Mitchell, D. R., "An Investigation Into the Causes of Porosity In Titanium Welds", Progress Reports 1 and 2, Titanium Metals Corporation of America, New York, New York (April 15 and May 28, 1964) (RSIC 0858 and RSIC 0859).
- (36) Pagnotta, G., and Hume, G. W., "Welding Thin-Walled Titanium Pressure Vessels", Welding Journal, 42 (9) 709-14 (September 1963) (RSIC 0752).

- (37) Mitchell, D. R., "Porosity in Titanium Welds", Welding Journal, 44 (4) 157s-67s (April 1965) (RSIC 0182).
- (38) "Tentative Specifications for Tungsten-Arc Welding Electrodes", AWS Designation A5.12-55T, American Welding Society, New York, New York (1955) (RSIC 0796).
- (39) "How Planemakers Weld Thin, Curved Pieces", Steel, 148, 116-17 (May 22, 1961) (RSIC 0797).
- (40) "The Production of Contamination-Free Welds in Titanium (Report of Work Carried Out by Bristol Aerojet Ltd. on Behalf of the Ministry of Aviation)", Ministry of Aviation, Technical Information and Library Services, United Kingdom, DMIC 58883, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio (May 1963) (RSIC 0765).
- (41) "Wing Box Fuel Containment", Report FDL-TDR-64-140, Vol. 3, Manufacturing, Contract AF 33(657)-1146C, Lockheed-California Co., Burbank, California (November 1964) (RSIC 0803).
- (42) "Welding Characteristics", Technical Documentary Report ML-TDR-64-237, Contract AF 33(657)-11461, A Joint Venture, Boeing-North American, Los Angeles, California (July 1964) (RSIC 0804).
- (43) "Studies of Interstitial Elements in Titanium Alloy Weldments", Final Report on Contract DA-33-019-ORD-3401, Battelle Memorial Institute, Columbus, Ohio (September 30, 1961) (RSIC 0795).
- (44) Brothers, A. J., Masters, H. E., and Wood, H. E., "Properties of Welded High-Strength Titanium Alloy Sheet", ASTM Preprint (RSIC 0510).
- (45) Unpublished Materials, Research and Development Program, Report A-758, McDonnell Aircraft Corporation, St. Louis, Missouri (June 10, 1964) (RSIC 0847).
- (46) Morita, W. K., "Titanium Tankage Program. Phase II", Final Report AFRPI-TR-64-154, North American Aviation, Inc., Downey, California (June 1, 1962 - September 15, 1964) (RSIC 0304).

- (47) Murphy, J. F., and Carpenter, S. R., "Alpha Titanium Manufacturing Sheet Program", General Dynamics/Convair, San Diego, California, Report RTD-TDR-63-4010 (May 23, 1962 - August 1, 1963) (RSIC 0492).
- (48) Mitchell, D. R., "Thermal Stability of Arc Welds in Ti-8Al-1Mo-1V Titanium Alloy", Titanium Metals Corporation of America, New York, New York. Titanium Data Case Study 9-2 (April 17, 1964) (RSIC 0844).
- (49) Mitchell, D. R., and Day, D. L., "The Cryogenic and Elevated Temperature Properties of 'Super Alpha' Titanium Alloy Weldments", Welding Journal, 42 (3) 134s-44s (1963) (RSIC 0758).
- (50) Helfrich, W. F., and Hauser, H. A., "Ninth Quarterly Report on Research and Development of Titanium Rocket Motor Case", Technical Report No. WAL 766.2/1-8, Pratt & Whitney Aircraft Division, United Aircraft Corporation, East Hartford, Connecticut, Contract No. DA-19-020-ORD-5230 (October 31, 1962) (RSIC 0674).
- (51) "Preliminary Evaluation of 6Al-6V-6Sn Titanium Alloy", Aerojet General Corporation, Sacramento, California (June 28, 1963) (RSIC 0652).
- (52) Dubusken, W., "How They Made the Space Capsule", American Machinist/Metalworking Manufacturing, 105, pp 130-132 (May 15, 1961) (RSIC 0503).
- (53) Green, H. R., Jr., "Stress Relieving Titanium Alloy Weldments in Vacuum", Metal Progress, 87 (4) 72-75 (April 1965) (RSIC 0176).
- (54) "Welding Titanium", Light Metals, 26 (296) 40 (January 1963) (RSIC 0504).
- (55) "Tracer Guides Titanium Welds", Iron Age, 189, p 83 (May 3, 1962) (RSIC 0505).
- (56) Savas, J., "Development of Fusion Welding Techniques for Two-Inch Thick Titanium Plates", Final Report, Republic Steel Corporation, Canton, Ohio, Contract No. NOas 60-6091-F (May 1961) (RSIC 0794).

- (57) "Development of Procedures for Welding 2-Inch-Thick Titanium Alloy Plate", Final Report on Contract Now-60-0390-c, Battelle Memorial Institute, Columbus, Ohio (July 31, 1962) (RSIC 0791).
- (58) Stark, J. E., et al., "Welding of One-Inch Thick Ti-6Al-4V Plate", Welding Journal, 41 (9) 805-14 (1962) (RSIC 0756).
- (59) "Welding Thick Plates of the Ti-8Al-2Cb-1Ta Alloy", Final Report on Contract Nobs-86838, Battelle Memorial Institute, Columbus, Ohio (February 1963) (RSIC 0865).
- (60) Motl, B. C., "Keep Your Weld Wire Moving", Welders' Digest, Scott Tarbell, Inc., Cleveland, Ohio, Reprint from American Machinist, pp 4-8 (March 1965) (RSIC 0792).
- (61) Personal Communication from G. Garfield, Aerojet General Corporation, Downey, California (RSIC 0793).
- (62) Daley, D. M., Jr., and Hartbower, C. E., "Metal-Arc Welded Ti-6Al-4V, Ti-4Al-4V, and Ti-5Al-2-1/2Sn Titanium Alloys", Watertown Arsenal Laboratories, Watertown, Massachusetts, Report No. WAL TR 401/250-1, 20 pp (May 1959) (RSIC 0789).
- (63) Faulkner, G. E., Lewis, W. J., and Martin, D. C., "The Status and Properties of Titanium Alloys for Thick Plate", DMIC Report 185, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio (June 14, 1963) (RSIC 0693).
- (64) Koppenhofer, R. L., Lewis, W. J., Faulkner, G. E., and Rieppel, F. J., "Development of Procedures for Welding 2-Inch-Thick Titanium Alloy Plate", Bimonthly Report to Bureau of Naval Weapons, Battelle Memorial Institute, Columbus, Ohio (December 31, 1960) (RSIC 0790).
- (65) "Electron-Beam Welds Salvage Costly Machining Rejects", Metalworking, 18, pp 24-25 (May 1962) (RSIC 0802).
- (66) White, S. S., Lander, H. J., Hess, W. T., and Bakish, R., "A Study of Electron-Beam Welding", Welding Journal, 41 (6) 279s-88s (June 1962) (RSIC 0757).
- (67) Personal Communication from W. O. Sunafrank, General Dynamics, Fort Worth, Texas (RSIC 0788).

- (68) Kern, W. I., and Lubin, L. E., "Electron-Beam Welding of Aerospace Materials", Hamilton Standard Division, United Aircraft Corporation, Windsor Locks, Connecticut, Final Report, Wright-Patterson AFB, Contract AF 33(557)-7763, 191 pp (February 1963) (RSIC 0800).
- (69) White, H., "Rolls-Royce Puts Electron Beams to Work", Metalworking Production, 106, pp 85-87 (June 13, 1962) (RSIC 0645).
- (70) Bakish, R., "Metals Joining In the Space Age. Part 1. By Electron Beams", Journal of Metals, 16 (3) 238-39 (March 1964) (RSIC 0640).
- (71) Groves, M. T., "Evaluation of Electron-Beam Welds in Thick Materials", Thompson Ramo Wooldridge, inc., Cleveland, Ohio, First Quarterly Progress Report to Air Force Systems Command, Report No. ER-6294, Contract No. AF 33(615)-1626 (December 15, 1964) (RSIC 0766).
- (72) Personal Communication from F. Johnson, Airite Division, Electrada Corporation, Los Angeles, California (RSIC 0747).
- (73) Hokanson, H. A., and Meier, J. W., "Electron-Beam Welding of Aircraft Materials and Components", Welding Journal, 41 (11) 999-1008 (November 1962) (RSIC 0646).
- (74) Filipski, S. P., "Plasma Arc Welding", Welding Journal, 43 (11) 337-43 (November 1964) (RSIC 0755).
- (75) O'Brien, R. L., "Plasma-Arc Welding Applications", American Society for Metals, Metals Park, Ohio, Technical Report No. P (January 1, 1964) (RSIC 0644).
- (76) Resistance Welding Manual, Edited by E. J. Del Vecchio, Resistance Welder Manufacturers' Association, Philadelphia, Pennsylvania, Third Edition, Volume 1, p 171 (RSIC 0866).
- (77) Fogarty, E. J., "Investigation of the Spot-Welding Characteristics of Titanium Alloys Ti-5Al-5Zr-5Sn, Ti-7Al-12Zr, and Ti-8Al-1Mo-1V", U. S. Naval Air Engineering Center, Philadelphia, Pennsylvania, Aeronautical Materials Laboratory, Report No. NAEC-AML-1815 (November 1963) (RSIC 0643).
- (78) Nolen, R. K., et al., "Spot Welding of Ti-6Al-4V", Welding Journal, 37 (4) 129s-36s (April 1958) (RSIC 0754).

- (79) "Spot Welding of 6Al-4V Titanium Alloy. Shear, Tension, and Fatigue Characteristics", Report No. D-4748, Convair, San Diego, California (October 1955) (RSIC 0867).
- (80) "Static and Fatigue Strength of Dissimilar Alloy Spot Welds", Report No. 8926-170, Convair, San Diego, California (April 1957) (RSIC 0845).
- (81) "Development of Elevated Temperature Sheet Spot-Welded and Seam-Welded Joints", Final Report on Contract AF 33(616)-6293, ASD TR 61-617, Convair, San Diego, California (March 1962) (RSIC 0513).
- (82) "Titanium Development Program. Volume V", Final Report on Contract AF 33(600)-34876, ASD-TR-61-7-756, General Dynamics/Convair, San Diego, California (May 1961) (RSIC 0786).
- (83) Kearns, W. H., et al., "The Static and Fatigue Behaviour of Spot-Welded Joints in Titanium", Welding Journal, 34 (5) 241s-50s (1955) (RSIC 0753).
- (84) "All0AT Titanium Alloy Sheet Evaluation of Spot Welding Characteristics", Report No. ERM-13, Republic Aviation Corporation (July 23, 1956) (RSIC 0511).
- (85) "Effect of Peeling Loads on Resistance Welds in 17-7PH, Aluminum and Titanium Welds", North American Aviation, Missile Development Division, Report No. AL-2594, Contract No. AF 33(600)-28469 (September 5, 1957) (RSIC 0767).
- (86) Drumm, F. X., "Evaluation of Titanium Sheet Alloys", Quarterly Progress Report No. 9, Grumman Aircraft Engineering Corporation, Bethpage, Long Island, New York, Contract No. NO(as) 58-100C (April 30, 1950) (RSIC 0472).
- (87) "Spot, Stitch and Seam Welding", McDonnell Aircraft Corporation, St. Louis, Missouri, Standard Process Specification, P.S. 22000 (RSIC 0642).
- (88) "Sciaky at Work", Sciaky Bros. Inc., Chicago, Illinois, Volume 6, No. 6 (RSIC 0641).
- (89) "Say Ti Skin, Spot Welded, Has SST Use", Metalworking News, p 11 (March 1, 1965) (RSIC 0868).

- (90) Myers, P. E., "DOD High Strength Titanium Alloy Sheet Research Program", North American Aviation, Inc., Columbus Division, Columbus, Ohio, Report No. NA57H-527-11, File No. NA-9510, Contract No. NOas 57-785d (April 29, 1960) (RSIC 0787).
- (91) "Construction of the Mercury Spacecraft", Welding and Metal Fabrication, 30, pp 116-18 (March 1962) (RSIC 0639).
- (92) Koelling, H. A., "Roll-Seam Welded Titanium", McDonnell Aircraft Corporation, St. Louis, Missouri, Contract No. AF 33(657)-11215, 7 p (September 10, 1963) (RSIC 0638).
- (93) Stier, H. H., Bergstedt, P. W., and Turner, H. C., "Embossed Titanium Welding Analysis", General Dynamics/Convair, San Diego, California, Report 57-980, Contract No. AF 33(600)-30169 (June 16, 1958) (RSIC 0768).
- (94) "Processing and Materials Review for Aircraft Design Manual", A. O. Smith Corporation, Report No. ARDC-TR-56-7-Pt. I, on Contract No. AF 18(600)-1513 (RSIC 0512).
- (95) Foster, R. N., "Flash Butt-Weld Procedures for Extruded Titanium Parts", Welding Engr., 43 (2) 29-30 (February 1958) (RSIC 0637).
- (96) "Evaluation of Titanium Flash and Fusion Welds for Aircraft Design Manual", A. O. Smith Corporation, Aeronautical Division, Milwaukee, Wisconsin, Report No. ARDC-TR-56-7-Pt. IV on Contract No. AF 18(600)-1513 (June 30, 1958) (RSIC 0514).
- (97) "Typical Flash Weld Properties", Unpublished data from American Welding & Manufacturing Company (January 18, 1956) (RSIC 0869).
- (98) Conover, J. E., and Cyphers, R. J., "Development of Roll Forging and Flash Welding Techniques for Production of Titanium Aircraft Parts", Grumman Aircraft Engineering Corporation, Bethpage, Long Island, New York, Interim Engineering Report No. TAB No. AD-200143, Report No. GAEC-RD57-1-3, Contract AF 33(600)-34257 (January 3, 1957, March 29, 1958, April 15, 1958) (RSIC 0636).
- (99) "Rings for Exacting Requirements", American Welding Company, Warren, Ohio (RSIC 0677).

- (100) Savage, W. F., "Flash Welding - The Process and Applications", Welding Journal, 41 (3) 227-37 (March 1962). (RSIC 0635).
- (101) Wollaston, K. H., "High-Frequency Welding of Titanium Tube", Institute of Metals Journal, 90 (2) 33-37 (October 1961) (RSIC 0506).
- (102) Brochure, Astro Metallurgical Corporation, Wooster, Ohio (RSIC 0030).
- (103) "Design Concepts for Minimum Weight, High Performance Supersonic Aircraft Structures", Douglas Aircraft Company, Inc., Aircraft Division, Long Beach, California, Report No. 31237, Contract No. AF 33(657)-8541 (April 1, 1963) (RSIC 0857).
- (104) Weigert, K. M., "High-Strength Titanium Bonding by Torch Heating", Welding Journal, 41 (2) 84s-88s (February 1962) (RSIC 0690).
- (105) "Titanium Honeycomb Panels Being Produced Experimentally", Industrial Heating, 30 (7) 1250-54 (July 1963) (RSIC 0634).
- (106) Faulkner, G. E., and Lewis, W. J., "Recent Developments in Titanium Brazing", DMIC Memorandum 45, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio (RSIC 0692).
- (107) Johnson, W. E., Sunafrank, W. O., Kaarlela, W. T., Kastrop, C. J., and Slifer, W. M., "Titanium Sandwich Panel Research and Development", General Dynamics Corporation, Convair Division, Fort Worth, Texas, Final Report, Report No. AMC TR 59-7-618, Contract No. AF 33(600)-34392, 2 (November 1959) (RSIC 0633).
- (108) Elsner, N. B., Mack, E. B., Metcalfe, A. G., and Troy, W. C., "Development of Low-Temperature Brazing Alloys for Titanium Honeycomb Sandwich Panels", Solar Aircraft Company, ASD Technical Report 61-313, Contract No. AF 33(616)-7249, Task No. 735102 (December 1961) (RSIC 0632).
- (109) Sliney, J. L., "Feasibility of Brazing High-Strength Sheet Titanium", Watertown Arsenal, Watertown, Massachusetts, Technical Report No. WAL TR 401.54/1 (November 1960) (RSIC 0631).

- (110) Cochran, J. F., and Torgenson, D. R., "Double-Wrap Shroud Wards Off Brazing Contaminants", Metalworking Production, 106, pp 56-58 (January 3, 1962) (RSIC 0691).
- (111) Levy, V., "Process-Brazing Stainless Steel to Titanium Evaluation", General Dynamics Corporation, Fort Worth, Texas, Report No. FTDM-2123, Contract No. AF 33(657)-7248 (January 16, 1962) (RSIC 0846).
- (112) Albom, M. J., "Solid-State Bonding", Welding Journal, 43 (6) 491-504 (1964) (RSIC 0871).
- (113) Irving, R. R., "Pressure Bonding Contains Powders", Iron Age, 192 (16) 85-87 (October 1963) (RSIC 0507).
- (114) "Bonding, Cladding and Densification by Pressure Bonding". Battelle Memorial Institute, Columbus, Ohio (RSIC 0515).
- (115) Afanas'ev, I. V., Kesichkin, N. V., Khudyshev, A. F., and Eibakidze, V. G., "Vacuum Diffusion Welding and Diffusion Welding in a Controlled Atmosphere", Welding Production, 4, pp 28-29 (1963). British Welding Research Association Translation, pages 49-52 (RSIC 0499).
- (116) Clark, E. J., "Vacuum Diffusion Joining of Titanium", Welding Journal, 38 (6) 251s-58s (1959) (RSIC 0749).
- (117) Kazakov, M. F., Shiskova, A. P., and Charukhina, K. E., "Vacuum Diffusion Bonding Titanium", Automatic Welding, 10, pp 82-86 (1963), British Welding Research Association Translation, pages 71-74 (RSIC 0498).
- (118) McGowan, P. R., Williams, N. R., and Allen, J. I., "Diffusion Bonded Titanium Alloy Honeycomb Panels", Interim Engineering Progress Report from Douglas Aircraft Company, to Air Force Systems Command, Contract No. AF 33(615)-1399 (July-October, 1964) (RSIC 0856).
- (119) U. S. Patent 3, 044, 160 "Method of Producing Ribbed-Metal Sandwich Structures" (March 3, 1958) (RSIC 0500).
- (120) Leach, J. E., Jr., "Diffusion Bonding of Structures by Hot Rolling Plate Mill Techniques", Douglas Missile and Space Systems Division, Presented at the SAE National Aeronautic and

Space Engineering and Manufacturing Meeting, Los Angeles, California (October 5-9, 1964) (RSIC 0678).

- (121) Bianchi, L. M., "Fabricating Under an Inert Atmosphere", Metal Progress, 87 (3) 127-31 (March 1965) (RSIC 0750).
- (122) Lage, A. P., "Pressure-Vessel Fabrication", DMIC Accession No. 58137, Paper presented at SAE Aerospace Manufacturing Forum, Los Angeles, California (October 5, 1964) (RSIC 0763).
- (123) Pressure Gas Welding, Welding Handbook, Section 2, Fifth Edition, American Welding Society, New York, New York (1963), pp 22.2-22.22 (RSIC 0870).
- (124) Lage, A. P., "Application of Pressure Welding to the Aircraft Industry", Revision of a paper presented at the 1956 American Welding Society National Spring Meeting in Buffalo, New York, May 7-11, 1956 (Revised February 1959) (RSIC 0178).
- (125) Hauser, D., Kammer, P. A., and Martin, D. C., "Fundamentals of Solid-State Welding and Their Application to Beryllium, Aluminum, and Stainless Steels", Contract No. DA-01-021-AMC-11706(Z), Unpublished Report from Battelle Memorial Institute, Redstone Scientific Information Center, Redstone Arsenal, Alabama (RSIC 0872).
- (126) Stoehr, R. A., and Collins, F. R., "Gas Metal-Arc Spot Welding Joins Aluminum to Other Metals", Welding Journal, 42 (4) 302-308 (April 1963) (RSIC 0679).
- (127) Mitchell, D. R., and Kessler, H. D., "The Welding of Titanium to Steel", Welding Journal, 40 (12) 546s-52s (December 1961) (RSIC 0630).
- (128) McBee, F. W., Hensen, J., and Benson, L. R., "Problems Involved in Spot Welding Titanium to Other Metals", Welding Journal, 35 (10) 481s-87s (October 1956) (RSIC 0785).
- (129) "Capacitor Discharge Process Welds Dissimilar Metals", Iron Age, 184 (14) 78-79 (October 1, 1959) (RSIC 0748).
- (130) Wood, R. A., "A Tabulation of Designations, Properties and Treatments of Titanium and Titanium Alloys", DMIC Memorandum 171, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio, 8 pp (July 15, 1963) (RSIC 0293).

- (131) Alcoa Aluminum Handbook, Aluminum Company of America, Pittsburgh, Pennsylvania (1956) (RSIC 0760).
- (132) "Properties and Selection of Metals", Metals Handbook, Vol. 1, 8th Edition, Published by American Society for Metals, Metals Park, Novelty, Ohio, p 44-62 (RSIC 0339).
- (133) "Stainless Steel Fabrication", Table 1-2, Allegheny Ludlum Steel Corporation, Pittsburgh, Pennsylvania, pp 5-10 (1957) (RSIC 0759).

APPROVAL

NASA TM X-53432

WELDING PROCEDURES FOR TITANIUM
AND TITANIUM ALLOYS

By J. J. Vagi, R. E. Monroe, R. M. Evans, and D. C. Martin

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.

W.A. Wilson R.H.
W. A. WILSON
Chief, Methods Development Branch

J.P. Orr
J. P. ORR
Chief, Manufacturing Research and
Technology Division

W. Kuers
for WERNER R. KUERS
Director, Manufacturing Engineering
Laboratory