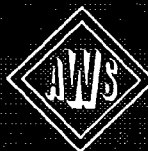


ANSI/AWS D3.7-90
An American National Standard

**Guide
for
Aluminum
Hull Welding**



American Welding Society

Keywords — Aluminum hull welding, ship welding, hull welding, aluminum hulls, boats, crafts, ships

ANSI/AWS D3.7-90
An American National Standard

Approved by
American National Standards Institute
October 27, 1989

Guide for **Aluminum Hull Welding**

Superseding
ANSI/AWS D3.7-83

Prepared by
AWS Committee on Welding in Marine Construction

Under the Direction of
AWS Technical Activities Committee

Approved by
AWS Board of Directors

Abstract

This guide provides information on the welding of sea going aluminum hulls and other structures in marine construction. Included are sections on hull materials, construction preparation, welding equipment and processes, qualification requirements, welding techniques, and safety precautions.



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* Chairman June 1, 1985 to May 31, 1988

Foreword

(This Foreword is not a part of ANSI/AWS D3.7-90, *Guide for Aluminum Hull Welding*, but is included for information purposes only.)

This guide has been developed to aid the boat and craft builder using aluminum as the primary metal for construction. An effort has been made to include principal design elements as well as construction details that experience has proven to be suitable for welded aluminum marine structures. This guide, along with thorough training in aluminum welding procedure including qualification of welding procedures and personnel, are of prime importance in maintaining high quality construction.

This guide was originally developed by the Aluminum Association Technical Committee on Welding and Joining after identifying the need to assist the builders of commercial pleasure craft and work boats with proven construction techniques. Their work was presented to the American Welding Society in 1979 and became the ANSI/AWS publication D3.7-83, *Guide for Aluminum Hull Welding*.

This updated document, D3.7-90, includes recent advances in welding power supplies and techniques along with the inclusion of SI Units.

Comments and inquiries concerning this guide are welcome. They should be sent to the Secretary of Welding in Marine Construction Committee, American Welding Society, 550 N.W. LeJeune Road, P. O. Box 351040, Miami, Florida 33135.

Table of Contents

	Page No.
<i>Personnel</i>	iii
<i>Foreword</i>	iv
<i>List of Tables</i>	vii
<i>List of Figures</i>	viii
 1. <i>General</i>	 1
1.1 Scope	1
1.2 Welding Processes	1
1.3 Comparison of Welding Processes	1
1.4 Serviceability of Welded Aluminum Hulls	1
1.5 Workmanship	2
1.6 Sources of Information	2
 2. <i>Aluminum Hull Materials</i>	 2
2.1 General	2
2.2 Marine Aluminum Alloys	2
2.3 Temper Designations	3
2.4 Aluminum Product Forms	4
2.5 Welding Filler Metals	7
2.6 Filler Metal Selection	8
 3. <i>Preparation for Construction</i>	 10
3.1 General	10
3.2 Handling and Storage	10
3.3 Cutting and Edge Preparation	10
3.4 Back Gouging	14
3.5 Finishing and Contouring	14
3.6 Cleaning for Welding	14
3.7 Forming and Bending	16
3.8 Preheat	16
 4. <i>Welding Processes and Equipment</i>	 17
4.1 General	17
4.2 Gas Metal Arc Welding	17
4.3 Gas Tungsten Arc Welding	21
4.4 Mechanized Welding	23
4.5 Stud Welding	23
 5. <i>Qualification Procedures for Welding</i>	 24
5.1 General	24
5.2 Procedure Qualification	25
5.3 Typical Test Coupon	25
5.4 Performance Qualification	25
5.5 Record Keeping	26

6. <i>Welding Procedure and Techniques</i>	26
6.1 General	26
6.2 Fitting, Aligning, and Assembling	26
6.3 Weld Backing	27
6.4 Butt Joints	27
6.5 Fillet Welds	29
6.6 Plug and Slot Welds	29
6.7 Inserts and Doublers	30
6.8 Snipes and Scallops	31
6.9 Oil and Water Stops	32
6.10 Coamings	32
6.11 Avoiding Joint Corrosion	33
6.12 Strongbacks	34
6.13 Clamping	35
6.14 Tack Weld Placement and Size	35
6.15 Residual Welding Stresses and Distortion	36
6.16 Welding Sequence	38
6.17 Angular Distortion	39
6.18 Interpass Temperature	39
6.19 Welding Stress Relief	39
6.20 Inspection of Welds	40
6.21 Repair of Welds	42
6.22 Metal Straightening	46
6.23 Repair Welding of Aluminum Hulls	47
6.24 Welding Power Connections	51
7. <i>Safety</i>	53
7.1 Introduction	53
7.2 Fumes and Gases	53
7.3 Radiation	54
7.4 Electrical Hazards	54
7.5 Fire Prevention	57
7.6 OSHA Regulations	58
<i>Metric Conversions</i>	58
<i>Appendix A—Codes and Standards</i>	59
<i>Appendix B—Quantity of Filler Metal Required for Welded Joints in Aluminum Made by GMAW and GTAW Processes</i>	62

List of Tables

Table	Page No.
1 — Chemical Composition Limits of Aluminum Alloys Used for Marine Construction	5
2 — Minimum Mechanical Properties of Marine Aluminum Alloy Sheet and Plate	5
3 — Minimum Mechanical Properties of Extruded Marine Aluminum Alloys	7
4 — Minimum Mechanical Properties of Forged Aluminum Alloys	7
5 — Minimum Mechanical Properties of Cast Aluminum Alloys for Marine Use	8
6 — Chemical Compositions of Aluminum Welding Filler Metals	8
7 — Aluminum Welding Filler Metal Selection Guide	9
8 — Minimum As-Welded Mechanical Properties of Gas-Shielded Arc Welds in Marine Aluminum Alloys	11
9 — Approximate Minimum Bend Radii for 90 Degree Cold Bends in Aluminum Alloys	17
10 — Typical Procedures for Gas Metal Arc Welding of Groove Welds in Aluminum Alloys with Argon Shielding	30
11 — Typical Procedures for Manual Gas Tungsten Arc Welding of Butt Joints in Aluminum With ac and Argon Shielding	32
12 — Typical Procedures for Gas Tungsten Arc Welding Aluminum Pipe in the Horizontal Rolled Position	34
13 — Typical Procedures for Gas Tungsten Arc Welding Aluminum Pipe in the Horizontal Fixed Position	36
14 — Typical Procedures for Gas Metal Arc Welding Aluminum Pipe in the Horizontal Rolled Position	38
15 — Typical Procedures for Gas Metal Arc Welding of Fillet Welds in Aluminum Alloys with Small Diameter Electrodes and Argon Shielding	40
16 — Typical Procedures for Manual Gas Tungsten Arc Welding of Fillet Welds in Aluminum with ac and Argon Shielding	42

List of Figures

Figure	Page No.
1 — Typical Extrusion Shapes for Shipbuilding Applications	6
2 — Typical Joint Designs for Gas Shielded Arc Welding of Aluminum	12
3 — A Typical Band Saw Blade Design for Aluminum	12
4 — Teeth Arrangements for Circular Saws for Aluminum	13
5 — A Vixon File for Aluminum	14
6 — Chisel Designs Suitable for Aluminum	15
7 — Typical Semiautomatic Gas Metal Arc Welding Guns	19
8 — Typical Water-Cooled Gas Tungsten Arc Welding Torch	21
9 — Equipment Setup for Arc Stud Welding of Aluminum	24
10 — Wrap-Around Guided Bend Test Jig	25
11 — Design of Master Weld Joints to Provide for Fitup in Position	27
12 — Typical Joint Designs for Arc Welding of Aluminum	28
13 — Sizes of Double Fillet Welds to Fully Connect As-Welded 5086-H116 Members at Right Angles	44
14 — Sizes of Double Fillet Welds to Fully Connect As-Welded 6061-T6 Members at Right Angles	45
15 — Welding Sequence for Large Doubler Plate	46
16 — General Design of an Insert Plate	47
17 — Proper Design of Snipes and Scallops	48
18 — Welded Oil or Water Stop at Intersecting Members	49
19 — Typical Strongbacks for Maintaining Alignment During Welding	49
20 — Welding Sequence for Plate Butt and Adjacent Seams	49
21 — Typical Welding Sequence for Plate Butts and Seams Where Butts Are Staggered	50
22 — Welding Sequence at the Intersection of Plate Butts and Seams	51
23 — Typical Welding Sequence for Plate Butt and Adjacent Seams Where Internal Framing Is Attached	52
24 — Typical Welding Sequence for Large Subassembled Plate Panels	52
25 — Placement of Starting and Stopping Tabs at the Ends of a Repair Weld Groove	52
26 — Correction of Distortion in a Panel by Welding on the Concave Side, Using a Predetermined Pattern	53
27 — Welding Sequence for Side Shell Plate Repair	54
28 — Technique for Repairing a Crack by Welding	54
29 — Nomograph for Copper Ground Cable Size	55
30 — Nomograph for Copper Electrode Lead Cable Size	56

List of Figures

Appendix B

Figure	Page No.
B1 — Double-Square-Groove Welds, Convex Beads	62
B2 — Single-V-Groove Welds, No Root Opening, Welded Flush	62
B3 — Single-V-Groove Welds, 1/8 in. (3.2 mm) Root Opening, Welded Flush	63
B4 — Double-V-Groove Welds	63
B5 — Single-V-Groove Welds, 45° Groove Angles, with Backing Strip	63
B6 — Single-V-Groove Welds, 60° Groove Angle, with Backing Strip	64
B7 — Single-V-Groove Welds, 75° Groove Angle, with Backing Strip	64
B8 — Single-V-Groove Welds, 90° Groove Angle, with Backing Strip	64
B9 — Single- and Double-Bevel-Groove Welds	65
B10 — Single-U-Groove Welds	65
B11 — Fillet Welds with Equal Leg Lengths	65

Guide for Aluminum Hull Welding

1. General

1.1 Scope. This guide is intended to provide information on proven processes, techniques, and procedures for welding aluminum hulls and related ship structures. The information presented applies chiefly to the welding of aluminum hulls that are over 30 ft. (9 m) in length and made of sheet and plate 3/16 in. (4.8 mm) thick and greater. The distinction is made because of the different requirements for welding thin- (less than 3/16 in.) and thick-gage (1/4 in. and over) aluminum. Thin-gage aluminum welding usually requires specific procedures in the area of fixturing, welding sequence, and other techniques for distortion control that are not necessarily applicable to thick plates. Similarly, the choice of welding process or applicable process conditions, or both, also differs according to thickness.

1.2 Welding Processes. The inert gas shielded welding processes have been employed as the principal joining method for the majority of aluminum naval and merchant ship structures built since the early 1950's. In their basic forms, these processes employ two distinct types of electrodes, although both use a protective shield of inert gas to prevent oxidation of the hot metal in the weld zone.

1.2.1 Gas Tungsten Arc Welding (GTAW). The first inert gas welding process to be developed was gas tungsten arc welding,¹ which is sometimes referred to as TIG or heliarc welding. Introduced in 1941, this process uses a nonconsumable tungsten electrode. Inert gas is fed through the welding torch while filler metal, when required, is added into the weld pool separately by hand or machine.

1. Refer to AWS C5.5-80, *Recommended Practices for Gas Tungsten Arc Welding*, and the *Welding Handbook*, Vol. 2, 7th Ed. 78-112.

1.2.2 Gas Metal Arc Welding (GMAW). The second process, gas metal arc welding,² is employed for over 90% of the joining in a welded aluminum hull because it is much faster than GTAW. This process also uses an inert gas shield, but employs a continuous aluminum wire electrode that provides filler metal as it is fed mechanically through a welding gun. Introduced in 1948, GMAW is suitable for production welding of aluminum of 1/16 in. (1.6 mm) thickness and greater. This process is sometimes referred to as MIG welding.

1.3 Comparison of Welding Processes. The gas shielded arc welding processes GMAW and GTAW offer speed, good weld strength, and ease of operation in all positions on a wide range of aluminum thicknesses and joint types.

Inert gas shielded arc welded joints in aluminum alloys generally recommended for marine use retain a high percentage of the original base metal strength. Similarly, properly made welded joints, produced with the correct filler metals have virtually the same corrosion resistance as the base metal.

Oxyfuel gas and shielded metal arc welding are not suitable for aluminum ship structures because weld quality is inadequate, and the spent chloride must be removed.

1.4 Serviceability of Welded Aluminum Hulls. Service records of welded aluminum craft and other marine structures are excellent. Maintenance and repair cost records of hulls, which have been in service for 20 years or more, are impressive.

In many respects, preparation of aluminum hull plate for welding is simpler and more flexible than preparation of steel plate. Portable routers and radial saws, operating at relatively high speeds, and

2. Refer to AWS C5.6-79, *Recommended Practices for Gas Metal Arc Welding*, and the *Welding Handbook*, Vol. 2, 7th Ed. 113-152.

plasma arc cutting are widely used to advantage in cutting aluminum.

Machining operations to provide the required joint geometry for sound welds usually can be done with the same equipment employed for steel, but the cutting tools should be designed for aluminum. Shipyards already equipped with plate milling and planing machines, for example, employ the equipment for aluminum edge preparation using tools properly shaped for cutting aluminum.

1.5 Workmanship. Proper fit-up should be maintained for sound aluminum welds and should be more precise than that normally required for welded steel construction. For most ship structures, no root opening in the joint is preferred. However, where base metal thickness or other conditions demand, proper root openings are well defined. Aligning procedures generally follow those used in steel practice.

Many shipyards have discovered that the best fitters for aluminum construction come from carpentry shops. This is due primarily to the fact that most aluminum cutting is done with similar mechanical equipment. A workman with woodworking experience is more likely to follow the cutline more accurately than is a worker versed in steel ship construction where moderately loose fits may be tolerated.

1.6 Sources of Information. Data and opinions presented in this manual are based on the experience of shipyards, aluminum producers, naval architects and engineers, and welding equipment suppliers. The following subjects are covered in sufficient detail to provide reliable and practical guidelines:

- (1) Marine aluminum alloy, temper, and shape availabilities
- (2) Edge preparations
- (3) Forming
- (4) Cleaning for welding
- (5) Welding processes
- (6) Welder training and qualification
- (7) Fitting, aligning, and assembling
- (8) Types of joints and assemblies
- (9) Welding procedures
- (10) Stress relief
- (11) Inspection and testing of welds
- (12) Repair of welds

Additional information is available from the aluminum producers as well as from various comprehensive publications covering structural data, specifications, welding, and related subjects. A number of applicable publications are available from the Aluminum Association, American Weld-

ing Society, Society of Naval Architects and Marine Engineers, American Bureau of Shipping, and U.S. Naval Ship Systems Command. These and other organizations of interest are listed in Appendix A, together with pertinent codes, specifications, and regulations.

2. Aluminum Hull Materials

2.1 General. In the early 1950's, several weldable, medium-to-high strength 5000 series aluminum-magnesium alloys became available, which were suitable for corrosion-resistant, light-weight ship hulls and related structures. These alloys became known as marine alloys. Their as-welded minimum tensile strengths range from 25 to 42 ksi (170 to 290 MPa), and their minimum yield strengths from 15 to 25 ksi (100 to 170 MPa). The 5000 series marine alloys have excellent corrosion resistance and retain good weld strength without postweld thermal treatment. They are available in most mill product forms and custom extrusions.

2.2 Marine Aluminum Alloys. To understand the special characteristics of the principal marine aluminum alloys, a brief description of aluminum alloy groups is helpful.

The addition of specific alloying elements to aluminum produces two distinct alloy groups: nonheat treatable, represented by the 5000 series mentioned above, and heat treatable, represented by the 6000 series aluminum-magnesium-silicon alloys. Alloy 6061, an example of the latter, is used primarily for extruded structural members.

The mechanical properties of heat treatable aluminum alloys depend upon the specific combinations of alloying elements and the applied thermal and mechanical treatments. Such treatments include solution heat treatment, quenching, cold working, and artificial or natural aging, depending upon the specific alloy. The mechanical properties of nonheat treatable alloys depend upon their alloy compositions and the amount of strain hardening or cold work introduced during production and fabrication.

2.2.1 Heat Treatable Alloys. The principal heat treatable wrought aluminum alloy used for marine applications is 6061. It is employed for some extruded structural members and also for extruded pipes. For welded construction, allowance should be made for reduced as-welded strength and ductility as compared with the properties of heat-treated, unwelded base metal. This allowance for design

purposes is given for some heat treatable alloys in Table 8; values for other alloys can be found in reference books.

Since the as-welded strength of heat treatable alloys varies with time at temperature (heat input) in the heat-affected zone, welding heat input can significantly affect the as-welded tensile strength of these alloys.

2.2.2 Nonheat Treatable Alloys. The principal non-heat treatable marine aluminum alloys are 5052, 5083, 5086, 5454, and 5456. Alloy 5052 was one of the first commercial aluminum-magnesium marine alloys and is still in use for small pleasure craft. However, it is not normally employed for structures in commercial or military craft because of its low strength.

Where operating temperatures in excess of 150°F (65°C) are anticipated, 5454 alloy is used to avoid the problem of stress corrosion found in aluminum alloys with higher magnesium content. It is useful in stack structures and similar applications.

Alloys 5083, 5086, and 5456, in the H116 temper, are the chief aluminum materials used in hulls and other marine structures. These alloys are specifically recommended in the Technical and Research Bulletin No. 2-15, *Guide for the Selection of Wrought Aluminum Plate and Shapes for Ship Structure*, published by the Society of Naval Architects and Marine Engineers (SNAME).

Alloy 5086 is recommended for most marine construction.³ The nonheat treatable aluminum alloy in the aforementioned SNAME bulletin, designated as Grade A, is termed "a general purpose material for ship structure requiring a comparatively medium-strength, lower-magnesium-content, weldable alloy having good corrosion-resistance and fabrication characteristics." Typical applications of this alloy include hull, deck, and bulkhead plate and shapes, towers, masts, bulwarks, tanks, and similar components.

Alloys 5083 and 5456 are also employed for commercial marine construction. Designated as Grade "B", nonheat treatable aluminum alloys in the aforementioned SNAME Bulletin, 5083 and 5456 alloys are described as recommended material "for components of ship structure which require a higher-strength, higher-magnesium content, weldable alloy having good corrosion resistance and moderately good fabrication characteristics." Typical applications of these alloys include structures requiring a

high strength-to-weight ratio, such as hydrofoil hulls, surface-effect craft, amphibious vehicles, and similar components. Alloy 5456 has been widely used in naval and crewboat construction.

2.3 Temper Designations. Temper designations for marine aluminum alloys indicate the level of strength achieved by a specific sequence of metallurgical treatments. Basic tempers are indicated by a letter, with subdivisions of basic tempers indicated by one or more digits following the letter. Heat treatable alloy temper designations begin with "T", and nonheat treatable alloys with "H". The letter "O" denotes fully annealed material, and the letter "F" denotes "as fabricated" tempers, which are common to both groups of alloys.

Temper designations of nonheat treatable wrought aluminum alloys consist of the letter "H" in conjunction with two or more digits; e.g., H34, H116. The first digit indicates the process as follows:

H1 Strain Hardened

H2 Strain Hardened and Partially Annealed

H3 Strain Hardened followed by Stabilization

The second digit indicates the degree of work hardening as follows:

1 is 1/8 hard

2 is 1/4 hard

4 is 1/2 hard

6 is 3/4 hard

8 is fully hardened

Sometimes a third digit is used to designate special conditions of tempering and hardening. The third digit indicates a variation of the two digit "H" temper. It is used to control the degree of temper or the mechanical properties that are different from, but are close to, the corresponding two digit "H" temper to which it is added.

For marine aluminum alloys 5083, 5086, and 5456, mildly cold-worked (1/8 to hard) tempers provide the most desirable combination of mechanical properties for welded ship structures.

For general hull construction, and particularly for plate in the bilge areas, these marine alloys are now supplied in the H116 temper. This temper makes them predominately free of continuous grain boundary networks. Such grain boundary networks found in other tempers could, under continuous exposure to stagnant or brackish water, render the metal susceptible to exfoliation or intergranular corrosion.

Heat treatable wrought aluminum alloys respond to heat treatment to give strengths that are higher than obtained by work hardening only. The heat of welding these alloys reduces the mechanical proper-

3. The International Organization for Standardization (ISO) equivalent for 5083 and 5086 alloys are Al-4.5Mg-0.7Mn and Al-4.0Mg-0.5Mn, respectively.

ties, but may be subsequently heat treated to bring the weldment back to original properties.

Heat treated tempers are indicated by the letter T followed by a number. The first number indicates the sequence of operations as follows:

- T1 cooled from an elevated temperature process and naturally aged to a substantially stable condition
- T2 cooled from an elevated temperature process, cold worked, and naturally aged to a substantially stable condition
- T3 solution heat-treated, cold-worked, and naturally aged to a substantially stable condition
- T4 solution heat-treated and naturally aged to a substantially stable condition
- T5 cooled from an elevated temperature process and then artificially aged
- T6 solution heat-treated and then artificially aged
- T7 solution heat-treated and stabilized
- T8 solution heat-treated, cold worked, and then artificially aged
- T9 solution heat-treated, artificially aged, and then cold worked
- T10 cooled from an elevated temperature process, cold worked, and then artificially aged

Sometimes second and third digits are used for variations in the same basic sequence of operations that result in minor changes in mechanical properties; e.g., T54, T451.

Typical marine application of heat treatable alloys are wrought 6061, 6063 and casting alloy 356.0. These metals are normally used in the T6 temper or a variation thereof.

2.4 Aluminum Product Forms. All product forms of aluminum are used in marine construction, including plate, extrusions, forgings, and castings.⁴ Sheet metal gages, electrical conductors, bar, rod, and wire also are employed in various ship fittings. The chemical composition limits of aluminum alloys generally used for marine construction are given in Table 1.

2.4.1 Plate and Sheet. Flat-rolled aluminum product of 0.25 in. (6.4 mm) thickness and over is referred to as plate, while that from 0.006 through 0.249 in. (0.15 through 6.4 mm) thick is called sheet. (The term *strip* is not used for aluminum.)

4. Information on aluminum alloy compositions, tempers, designations, and physical and mechanical properties of various mill products is provided in *Aluminum Standards and Data*, published by the Aluminum Association.

Aluminum plate is used in hulls, decks, shell strakes, bulkheads, flat brackets, and other applications. Specific alloy selection depends upon several factors including design and service requirements.

The marine alloys are available as sheet and plate through 6 in. (150 mm) thickness, and widths through 186 in. (4.72 m). Combined width and maximum length per plate are a function of thickness, with a limiting weight determined by the initial ingot size. Availability of specific plate sizes may vary among different suppliers. Extra-wide plate, at a premium price, may provide a significant net savings if a sufficient number of welded joints are eliminated. Minimum mechanical properties of marine aluminum alloy plate are given in Table 2.⁵

2.4.2 Extrusions. Aluminum also has unique versatility in boat and ship use in the form of extruded sections. Both standard and special extruded shapes may be used to obtain maximum structural and fabrication economic benefits. A typical use of extrusions is in longitudinally framed hulls where the longitudinal stiffeners and shell plate, complete with beveled edges for welding, are extruded in a single shape.

Virtually all interior support stiffeners, angles, bulb angles, and tees are extrusions. When structural shapes are too long for the available extrusion press capacity or quantities are too small to justify an extrusion run, aluminum shapes are often fabricated from formed and rolled sections or made of welded sections.

Typical of the many extruded aluminum shapes that have been used for marine construction are those shown in Figure 1. Minimum mechanical properties of marine aluminum extrusion alloys are given in Table 3.⁶

2.4.3 Forgings. Aluminum forgings are used to an advantage in marine applications, particularly for structural or mechanical parts requiring higher strengths than can be obtained in castings. Two aluminum alloys commonly employed for marine structural components are 5083 and 6061. Mechanical properties of forgings of these and other alloys are shown in Table 4.⁷

5. Refer to ASTM B209-84, *Standard Specification for Aluminum and Aluminum Alloy Sheet and Plate*.

6. Additional extrusion alloy data are given in ASTM B221-85, *Standard Specification for Aluminum Alloy Extruded Bar, Rod, Wire, Shape, and Tube*.

7. Additional data given in ASTM B247-85, *Standard Specification for Aluminum Alloy Die and Hand Forgings*.

Table 1
Chemical Composition Limits of Aluminum Alloys Used for Marine Construction

Composition (Weight Percent) ^{a,b}											
Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others		Al
									Each	Totals	
5052	0.25	0.40	0.10	0.10	2.2-2.8	0.15-0.35	0.10	---	0.05	0.15	Remainder
5083	0.40	0.40	0.10	0.40-1.0	4.0-4.9	0.05-0.25	0.25	0.15	0.05	0.15	Remainder
5086	0.40	0.50	0.10	0.20-0.7	3.5-4.5	0.05-0.25	0.25	0.15	0.05	0.15	Remainder
5454	0.25	0.40	0.10	0.50-1.0	2.4-3.0	0.05-0.20	0.25	0.20	0.05	0.15	Remainder
5456	0.25	0.40	0.10	0.50-1.0	4.7-5.5	0.05-0.20	0.25	0.20	0.05	0.15	Remainder
6061	0.40-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.04-0.35	0.25	0.15	0.05	0.15	Remainder
6063	0.20-0.6	0.35	0.10	0.10	0.45-0.9	0.10	0.10	0.10	0.05	0.15	Remainder
6151	0.6-1.2	1.0	0.35	0.20	0.45-0.8	0.15-0.35	0.25	0.15	0.05	0.15	Remainder
6351	0.7-1.3	0.50	0.10	0.40-0.8	0.40-0.8	---	0.20	0.20	0.05	0.15	Remainder
356.0	6.5-7.5	0.6	0.25	0.35	0.20-0.40	---	0.35	0.25	0.05	0.15	Remainder
A356.0	6.5-7.5	0.20	0.20	0.10	0.20-0.40	---	0.10	0.20	0.05	0.15	Remainder
514.0	0.35	0.50	0.15	0.35	3.5-4.5	---	0.15	0.25	0.05	0.15	Remainder
520.0	0.25	0.30	0.25	0.15	9.5-10.6	---	0.15	0.25	0.05	0.15	Remainder
535.0	0.15	0.15	0.05	0.10-0.25	6.2-7.5	---	---	0.10-0.25	0.05	0.15	Remainder

a. Single values are maximum limits.

b. Registered with the Aluminum Association.

Table 2
Minimum Mechanical Properties of Marine Aluminum Alloy Sheet and Plate

Alloy	Temper	Thickness		Minimum strength				Minimum elongation % in 2 in. (51 mm)
				Tensile		Yield		
		in.	mm	ksi	MPa	ksi	MPa	
5052	H112	1/2 to 3	(13-76)	25	(170)	9.5	(65)	12
	H32	1/8 to 2	(3.2-51)	31	(210)	23	(160)	9
	H34	1/8 to 1	(3.2-25)	34	(230)	26	(180)	7
5083	H112	1/4 to 1-1/2	(6.4-38)	40	(280)	18	(120)	12
	H116	1/8 to 1-1/2	(3.2-38)	44	(300)	31	(210)	10
	H323	1/8 to 1/4	(3.2-6.4)	45	(310)	34	(230)	10
	H343	1/8 to 1/4	(3.2-6.4)	50	(340)	39	(270)	8
5086	H112	1/2 to 1	(13-25)	35	(240)	16	(110)	10
	H116	1/8 to 2	(3.2-51)	40	(280)	28	(190)	8
	H34	1/8 to 1	(3.2-25)	44	(300)	34	(230)	6
5454	H112	1/2 to 3	(13-76)	31	(210)	12	(83)	11
	H32	1/8 to 2	(3.2-51)	36	(250)	26	(180)	8
	H34	1/8 to 1	(3.2-25)	39	(270)	29	(200)	6
5456	H112	1/4 to 1-1/2	(6.4-38)	42	(290)	19	(130)	12
	H116	1/8 to 1-1/4	(3.2-32)	46	(320)	33	(230)	10
	H323	1/8 to 1/4	(3.2-6.4)	48	(330)	36	(250)	8
	H343	1/8 to 1/4	(3.2-6.4)	53	(370)	41	(280)	8
6061	T451	1/4 to 3	(6.4-76)	30	(210)	16	(110)	18
	T651	1/8 to 4	(3.2-100)	42	(290)	35	(240)	9

2.4.4 Castings. Cast aluminum is used extensively in marine applications for bits, chocks, fairleads, pad eyes, handrail sockets, blocks, pulleys, electrical boxes, instrument cases, and many

other items. Commonly used casting alloys for marine applications include 356.0, A356.0, 514.0, 520.0 and 535.0.

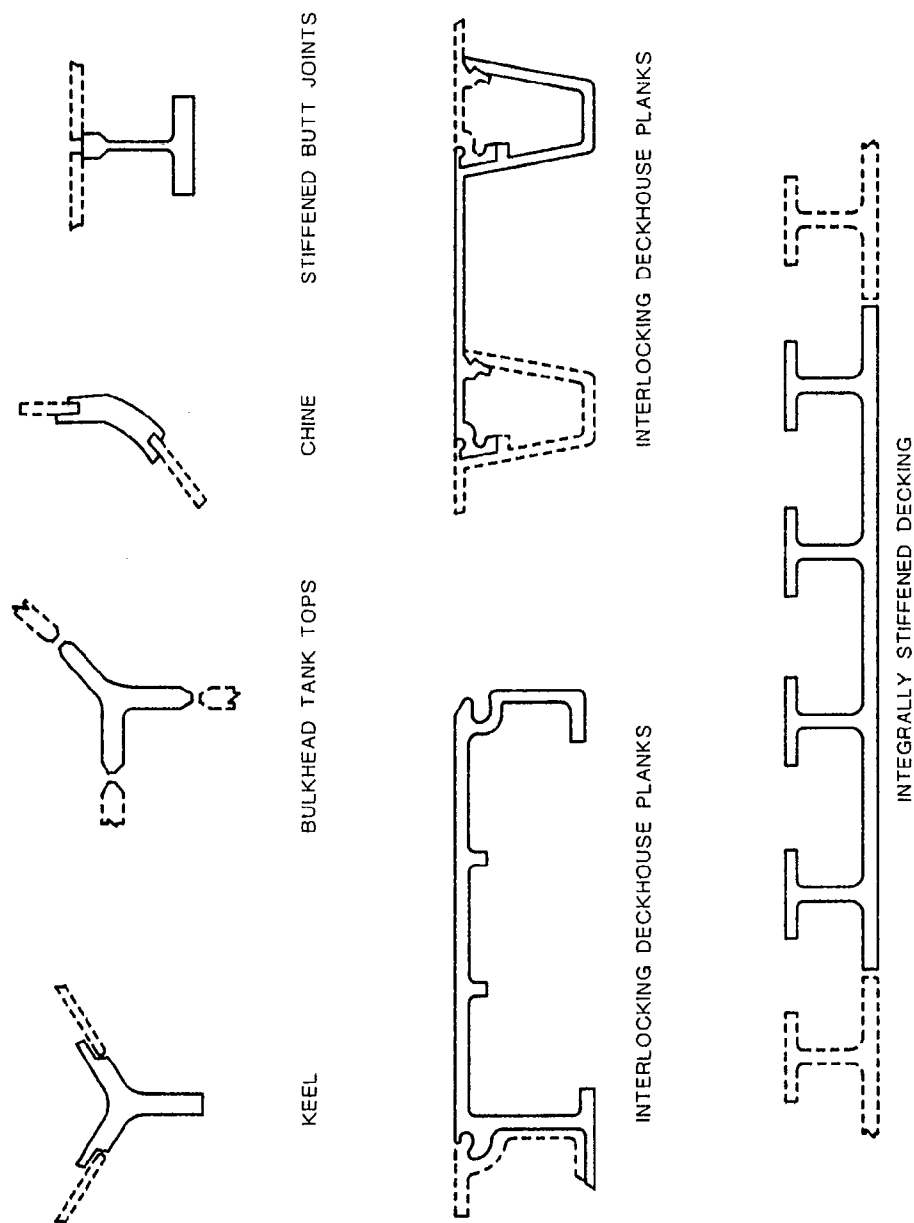


Figure 1 — Typical Extrusion Shapes for Shipbuilding Applications

Table 3
Minimum Mechanical Properties of Extruded Marine Aluminum Alloys

Alloy	Temper	Minimum strength				Minimum elongation % in 2 in. (51 mm)
		Tensile		Yield		
		ksi	MPa	ksi	MPa	
5083	H111	40	(280)	24	(170)	12
	H112	39	(270)	16	(110)	12
5086	H111	36	(250)	21	(140)	12
	H112	35	(240)	14	(96)	12
5454	H111	33	(230)	19	(130)	12
	H112	31	(210)	12	(83)	12
6061	T4, T4511	26	(180)	16	(110)	16
	T6, T6511	38	(260)	35	(240)	10
6063	T5, T52	22	(150)	15	(100)	8
6351	T54	30	(210)	20	(150)	10

Table 4
Minimum Mechanical Properties of Forged Aluminum Alloys

Alloy	Temper	Test Direction	Minimum strength				Minimum elongation % in 4D*
			Tensile		Yield		
			ksi	MPa	ksi	MPa	
5083	H111	Longitudinal	42	(290)	22	(150)	14
		Long Transverse	39	(270)	20	(140)	12
	H112	Longitudinal	40	(280)	18	(120)	16
		Long Transverse	39	(270)	16	(110)	14
6061	T6	Longitudinal	38	(260)	35	(240)	7
	T6	Transverse	38	(260)	35	(240)	5
6151	T6	Longitudinal	44	(300)	37	(250)	10
		Transverse	44	(300)	37	(250)	6

* D is the specimen diameter.

Minimum mechanical properties for some castings are given in Table 5.⁸

2.5 Welding Filler Metals. Aluminum alloy filler metals are supplied as wire electrodes on spools or coils, and as welding rods.⁹ General availability includes spools with nominal weights of 1, 5, 10, 12.5, 15, 20, 30, and 150 pounds (0.45, 2.3, 4.5, 5.7, 6.8, 9.1, 14.6, and 68 kilograms). The same alloys are also available as 36 in. (0.91 m) straight lengths in packages of 5, 10, 25, and 50 pounds (2.3, 4.5, 11,

and 23 kilograms). Sizes range from 0.030 in. through 1/8 in. (0.8 mm through 3.2 mm) diameter for spooled electrode, and 1/16 in. through 1/4 in. (1.6 mm through 6.4 mm) diameter for welding rods. Chemical compositions of aluminum filler metals recommended for welding marine aluminum alloys are given in Table 6. Aluminum filler metals are high quality wire products and are usually packaged to prevent surface contamination from moisture or foreign matter.

Proper storage of aluminum filler metals is important for production of sound welds. They should be kept in a heated, dry storage area with a relatively uniform temperature to prevent condensation on the metal surface. Once a package has been opened, it is good practice to return the filler metal to its package and then to the storage area if it will not be used for an extended period. It is also good practice during times

8. Additional data for sand, die, permanent mold, and investment castings are given in ASTM Standard Specification B26-84, B85-84, B108-82, and B618-84, respectively.

9. Aluminum filler metals are produced in accordance with ANSI/AWS A5.10

Table 5
Minimum Mechanical Properties of Cast Aluminum Alloys for Marine Use

Alloy	Temper	Product	Minimum strength*				Minimum elongation
			Ultimate		Yield		
			ksi	MPa	ksi	MPa	% in 2 in. (51 mm)
356.0	T6	Permanent mold casting	33	(230)	22	(150)	3.0
A356.0	T6	Sand casting	34	(230)	24	(170)	3.5
A356.0	T61	Permanent mold casting	37	(250)	26	(180)	5.0
514.0	F	Sand casting	22	(150)	9	(60)	6.0
520.0	T4	Sand casting	42	(290)	22	(150)	12.0
535.0	F	Sand casting	35	(240)	18	(120)	9.0

* Values represent properties obtained from separately cast test bars.

Table 6
Chemical Compositions of Aluminum Welding Filler Metals

Composition, Weight Percent ^a											
Filler Metal	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others ^b		Al
									Each	Total	
ER4043	4.5-6.0	0.8	0.30	0.05	0.05	---	0.10	0.20	0.05	0.15	Remainder
ER5183	0.40	0.40	0.10	0.50-1.0	4.3-5.2	0.05-0.25	0.25	0.15	0.05	0.15	Remainder
ER5356	0.25	0.40	0.10	0.05-0.20	4.5-5.5	0.05-0.20	0.10	0.06-0.20	0.05	0.15	Remainder
ER5554	0.25	0.40	0.10	0.50-1.0	2.4-3.0	0.05-0.20	0.25	0.05-0.20	0.05	0.15	Remainder
ER5556	0.25	0.40	0.10	0.50-1.0	4.7-5.5	0.05-0.20	0.25	0.05-0.20	0.05	0.15	Remainder
ER5654	c	c	0.05	0.01	3.1-3.9	0.15-0.35	0.20	0.05-0.15	0.05	0.15	Remainder

a. Single values are maximum.

b. Beryllium: 0.0008 percent maximum.

c. Silicon + iron: 0.45 percent maximum.

of high relative humidity to have a heated compartment for the spool on the welding machine to prevent condensation during use.

When welding wire used for critical applications in welds that require NDT, it is good practice to perform a fillet weld break test and to examine the fractured surface for excessive porosity. This will assure that the filler metals and techniques used will produce the desired weld quality.

2.6 Filler Metal Selection. The choice of filler metal for welding various marine aluminum alloys should be made with consideration given to weld strength, weld ductility, corrosion resistance, use at sustained elevated temperatures above 150°F (65°C), and relative freedom from cracking during welding. Table 7 rates suggested filler metals for welding wrought and cast aluminum alloys to them-

selves or to each other, depending upon the desired characteristics. Filler metal requirements in pounds per foot of joint for typical welded joints in aluminum are shown in Appendix B.

The correct choice of filler metal is of vital importance because the mechanical properties of welded aluminum joints are affected by the composition of the weld metal, as well as other factors. As previously pointed out, aluminum mill products of 6061 alloy, like those of other heat treatable alloys, lose appreciable tensile strength as a result of the heat of welding. Ductility is also reduced. When this alloy is welded with ER4043 filler metal, proper postweld heat treatment nearly restores tensile strength to that of the unwelded base metal, but ductility is reduced further.

On the other hand, nonheat treatable alloys retain approximately 90% of their original tensile

Table 7
Aluminum Welding Filler Metal Selection Guide

Base Metal	5052	5083 5456	5086	514.0 520.0 535.0	5454	6061 6063 6151 6351	356.0 A356.0
Base Metal	Filler Metal	Characteristics ^a					
		WSDCT ^b	WSDCT	WSDCT	WSDCT	WSDCT	WSDCT
356.0 A356.0	4043 5356	ABAAA BABBB-	ABBA- AAAA-	ABBA- AAAA-	ABBA- AAAB-	ABBA AAAB-	AAAAA AAAAA
6061 6063 6151 6351	4043 5183 5356 5554 5556 5654	ADCAA BABC- BBAC- CCABA BABC- CCAB-	ADCA- AABA- ABAA- BCAA- AABA- BCAA-	ADCA- AABA- ABAA- BCAA- AABA- BCAA-	ADCA- BABC- BBAC- CCAB- BABC- CCAB-	ADCBA BABC- BBAC- CCAAA BABC- CCAB-	ACBAA BAAC- BBAC- CBABB BAAC- CBAB-
5454	4043 5183 5356 5554 5556 5654	ADCCA AABB- ABAB- CCAAA AABB- BCAB-	----- AABB- ABAB- BCAA- AABB- -----	----- AABB- ABAB- BCAA- AABB- -----	----- AABB- ABAB- BCAA- AABB- BCAA-	----- AABB- ABAB- BCAAA AABB- BCAB-	
514.0 520.0 535.0	4043 5183 5356 5554 5556 5654	ADCC- AABB- ABAB- CCAA- AABB- BCAA-	----- AABA- ABAA- BCAA- AABA- BCAA-	----- AABA- ABAA- BCAA- AABA- BCAA-	----- AABB- ABAB- BCAA- AABB- BCAA-		
5086	5183 5356 5554 5556 5654	AABA- ABAA- CCAA- AABA- BCAA-	AABA- ABAA- ----- AABA- -----	AABA- ABAA- ----- AABA- -----			
5083 5456	5183 5356 5554 5556 5654	AABA- ABAA- CCAA- AABA- BCAA-	AABA- A-AA- ----- AABA- -----				
5052	4043 5183 5356 5554 5556 5654	ADCBA AABC- ABAC- CCAAA AABC- BCAB-					

a. A, B, C, and D are relative ratings in decreasing order of merit. The ratings have relative meaning only within a given block. Combinations having no rating are not usually recommended. Ratings do not apply when the alloys are to be heat-treated after welding.

b. Legend: Filler metals are rated on the following characteristics:

Symbol	Characteristic
W	Ease of welding (relative freedom from weld cracking).
S	Strength of welded joint in as-welded condition. Rating applies particularly to fillet welds. All rods and electrodes rated should develop presently specified minimum strengths for butt welds.
D	Ductility. Rating is based upon free bend elongation of the weld.
C	Corrosion resistance in continuous or alternate immersion in fresh or salt water.
T	Recommended for service at sustained temperatures above 150°F (66°C).

strengths in the as-welded condition. Their as-welded yield strengths are reduced to about 60% of that of the unwelded base metals, but their ductility remains largely unchanged.

Table 8 gives the expected minimum as-welded mechanical properties for marine aluminum alloys welded with the gas tungsten arc (GTAW) or gas metal arc process (GMAW).

3. Preparation for Construction

3.1 General. In a shipyard, careful preparation of properly selected material is essential to sound structures, good workmanship, and overall economy. Aluminum stock preparation begins when the metal arrives in good condition at the shipyard. Proper handling practices and adequate storage facilities are required to maintain the metal in good condition so that special operations will not be necessary prior to edge and surface preparations for welding.

Hull plates and extrusions should be cut to size, formed as required, edges prepared, cleaned, and properly fitted to other components before welding. Each of these steps should be carried out correctly in order to make sound welds economically.

3.2 Handling and Storage. Care of aluminum begins when a shipment of hull plate or extrusions is unloaded. Porous outer wrappings and interleaving should always be removed if there is a possibility of humid conditions or direct contact with water. Prolonged contact of such materials with the aluminum is likely to cause water staining of the metal surface. In case of doubt, it is generally good practice to remove such packing.

Special techniques are not required for handling aluminum mill products used in hull construction. However, good handling practices are required to avoid deep scratches, dents, and bent edges.

Preferably, storage facilities should be indoors, dry, clean, and well ventilated to avoid the possibility of staining from a combination of condensation and dirt. Where plates or shapes are stored on edge or end and separated for good air circulation, the danger of water staining is minimized. However, if the metal has been shipped during cold weather, it often is advisable to place it in a dry, moderately-heated storage area for a time before it is moved to a heated shop having relatively high humidity. This is particularly necessary when plates are stored in stacks rather than on edge.

If storage areas are heated by individual combustion units, the units should be vented to the outdoors

to avoid sulfurous combustion products that can affect the metal finish in the presence of moisture.

Storing plates and shapes on edge can also reduce the chance of surface abrasions. Grit on the floor or trapped between plates can be a major source of scratching and gouging when aluminum plates are stacked flat. In addition, storing on edge greatly reduces the possibility of storing other materials on the aluminum. Free access of air to all surfaces of edge-stored aluminum can be provided by placing nonporous plastic strips or other suitable inert material between the metal and the floor, and between plates along their top edges.

3.3 Cutting and Edge Preparation. Sawing, machining, and other mechanical methods are most commonly used for cutting aluminum.¹⁰ Aluminum is easily and smoothly cut by such methods, provided the equipment is in good condition. Although edge preparations are cut dry whenever possible, cutting lubricants may be used where necessary. Cutting wax is not recommended for use on blades because of the difficulty in complete removal before welding. In either case, correct tool rake and clearance angles are essential. Proper cutting conditions are similar to those required for wood. Many wood-cutting power tools of adequate rating and speeds may be successfully used on aluminum.

Plasma arc cutting is fast and accurate, but equipment cost is relatively high.¹¹ Its cost can be justified for production of identical parts, quantity cutting of aluminum plate of 1 in. (25 mm) thickness and over, or stack cutting of thin plates where production quantities warrant. The process may be adaptable where complex plate shapes are required. However, sawing and automatic or template-controlled routing or milling of pieces that can be readily handled are often more economical.

3.3.1 Edge Preparation. Preparation of the edges may often be done as the sheet or plate is cut to size and shape. Below 3/16 in. (4.8 mm) thickness, a square edge may be satisfactory. Above this thickness, a single- or double-bevel- or J-shaped edge is generally required. Butt joints are frequently used for welding aluminum hull plates. Typical butt joint configurations with square and V-groove designs are shown in Figure 2.

10. For additional information on machining, refer to the *Metals Handbook*, Vol. 3, Machining, 8th Ed., Metals Park, Ohio: American Society for Metals, 1967: 439-64.

11. Plasma arc cutting is described in the *Welding Handbook*, Vol 2, 7th Ed., 500-507, and also in AWS C5.2-83, *Recommended Practices for Plasma Arc Cutting*.

Table 8
Minimum As-Welded Mechanical Properties of Gas-Shielded Arc Welds in Marine Aluminum Alloys

Alloy and Temper	Product and Thickness Range, in.	Property ^a						
		Tension		Compression		Shear	Bearing	
		F _{tuw} ^b ksi (MPa)	F _{tyw} ^c ksi (MPa)	F _{cw} ^d ksi (MPa)	F _{suw} ^e ksi (MPa)	F _{syw} ^f ksi (MPa)	F _{buw} ^g ksi (MPa)	F _{byw} ^h ksi (MPa)
5052-H32, H34	All	25 (172)	13 (90)	13 (90)	16 (110)	7.5 (51)	50 (345)	19 (131)
5083-H111	Extrusions	39 (269)	21 (145)	20 (138)	23 (159)	12 (83)	78 (538)	32 (221)
-H321	Sheet & plate, 0.188-1.500	40 (276)	24 (165)	24 (165)	24 (165)	14 (96)	80 (552)	36 (248)
-H321	Plate, 1.501-3.000	39 (269)	23 (159)	23 (159)	24 (165)	13 (90)	78 (538)	34 (234)
-H323, H343	Sheet	40 (276)	24 (165)	24 (165)	24 (165)	14 (96)	80 (552)	36 (248)
5086-H111	Extrusions	35 (241)	18 (124)	17 (117)	21 (145)	10 (69)	70 (483)	28 (193)
-H112	Plate, 0.250-0.499	35 (241)	17 (117)	17 (117)	21 (145)	9.5 (65)	70 (483)	28 (193)
-H112	Plate, 0.500-1.000	35 (241)	16 (110)	16 (110)	21 (145)	9 (62)	70 (483)	28 (193)
-H112	Plate, 1.001-2.000	35 (241)	14 (96)	14 (96)	21 (145)	8 (55)	70 (483)	28 (193)
-H116, H32, H34	Sheet & Plate	35 (241)	19 (131)	19 (131)	21 (145)	11 (76)	70 (483)	28 (193)
5454-H111	Extrusions	31 (214)	16 (110)	15 (103)	19 (131)	9.5 (65)	62 (427)	24 (165)
-H112	Extrusions	31 (214)	12 (83)	12 (83)	19 (131)	7 (117)	62 (427)	24 (165)
-H32, H34	Sheet & Plate	31 (214)	16 (110)	16 (110)	19 (131)	9.5 (65)	62 (427)	24 (165)
5456-H116, H321	Sheet & Plate 0.188-1.500	42 (290)	26 (179)	24 (165)	25 (172)	15 (103)	84 (579)	38 (262)
-H116, H321	Plate, 1.501-3.000	41 (283)	24 (165)	23 (159)	25 (172)	14 (96)	82 (565)	36 (248)
-H323, H343	Sheet	42 (290)	26 (179)	26 (179)	25 (172)	15 (103)	84 (579)	38 (262)
6061-T6, T651 ⁱ	All	24 (165)	20 (138)	20 (138)	15 (103)	12 (83)	50 (345)	30 (207)
-T6, T651 ^j	Over 0.375	24 (165)	15 (103)	15 (103)	15 (103)	9 (62)	50 (345)	30 (207)
6063-T5, T52	All	17 (117)	11 (76)	11 (76)	11 (76)	6.5 (45)	34 (234)	22 (152)
6151-T6 ⁱ	All	24 (165)	20 (138)	20 (138)	15 (103)	12 (83)	50 (345)	30 (207)
-T6 ^j	Over 0.375	24 (165)	15 (103)	15 (103)	15 (103)	9 (62)	50 (345)	30 (207)
6351-T5 ⁱ	All	24 (165)	20 (138)	12 (138)	50 (103)	12 (83)	50 (345)	30 (207)
-T5 ^j	Over 0.375	24 (165)	15 (103)	15 (103)	15 (103)	9 (62)	50 (345)	30 (207)
356-T6	Castings	23 (159)						
A356-T6	Castings	23 (159)						
514.0-F	Castings	22 (152)						
535.0-F	Castings	35 (241)						

- a. Welding filler metals are those recommended in Table 7.
- b. Ultimate tensile strength across a butt joint. Strengths are AWS and ASME weld qualification test values.
- c. Yield strength across a butt joint, 0.2% offset in a 10 in. (250 mm) gage length.
- d. Compressive yield strength across a butt joint, 0.2% offset in a 10 in. (250 mm) gage length.
- e. Ultimate shear strength within 1.0 in. (25 mm) of a weld.
- f. Yield strength in shear within 1.0 in. (25 mm) of a weld.

- g. Ultimate bearing strength within 1.0 in. (25 mm) of a weld.
- h. Bearing yield strength within 1.0 in. (25 mm) of a weld.
- i. For all thicknesses when welded with 5183, 5356, or 5556 filler metal, and for thicknesses of 0.375 in. (9.52 mm) and under when welded with 4043, 5554, or 5654 filler metal.
- j. Apply when welded with 4043, 5554 or 5654 filler metals.

Edge preparation should be in accordance with the welding procedure specification to achieve the desired results.

Edge preparation can be done in a number of ways: high-speed milling machines, routers, planers, and various types of saws. The equipment should be adapted to suit the job. Normal heavy-duty industrial tools are recommended, as they are expected to operate for extended periods of time. Air-operated tools have a high efficiency rating. However, care should be taken to use an air supply free of oil, moisture, and dirt to prevent contamination of the joint from the air exhaust and subsequent weld porosity upon fabrication.

The use of sanding or grinding for edge preparation is not generally recommended. Where employed, abrasives should be approved for the job and properly used. Any residue from sanding or grinding should be removed from the aluminum surfaces to avoid weld contamination and porosity.

Where a cutting operation leaves a rough surface, a secondary operation, such as milling, planing, routing, sanding, polishing, or filing, should follow to provide adequate smoothness for proper cleaning before welding.

3.3.2 Sawing. The main requirements for sawing aluminum are blades that have relatively coarse teeth and the use of high blade speeds. Band saws, which are commonly used for cutting pieces small enough to be manipulated by hand, should have 2 to 4 teeth per inch (8 to 16 per centimeter) and a blade speed of at least 6000 ft/min (1800 m/min) under load. A typical band saw blade for aluminum is shown in Figure 3.

Hand-held or stationary circular saws that are fitted with high-speed steel blades are run at 8000 surface ft/min (2400 m/min) or faster, and at 4000 to 6000 surface ft/min (1200 to 1800 m/min) with other tool steel blades. Carbide tipped blades are

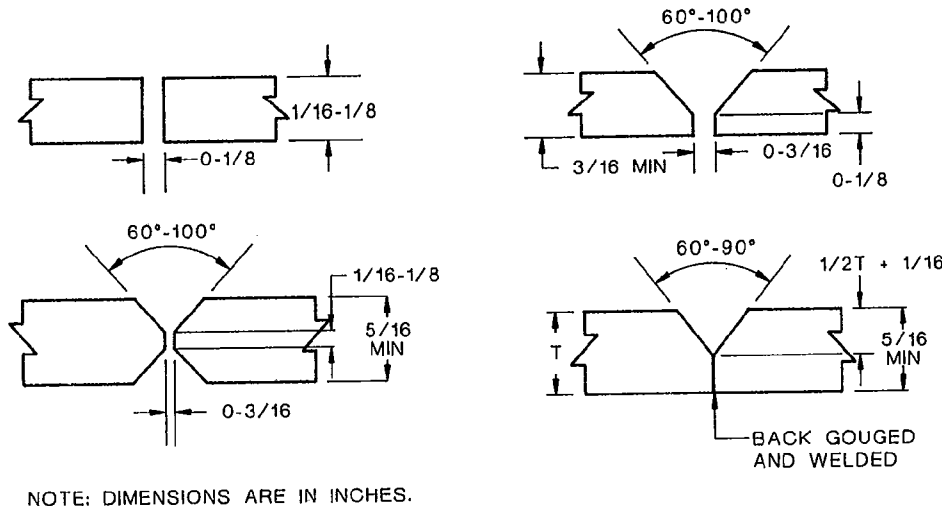


Figure 2 — Typical Joint Designs for Gas Shielded Arc Welding of Aluminum

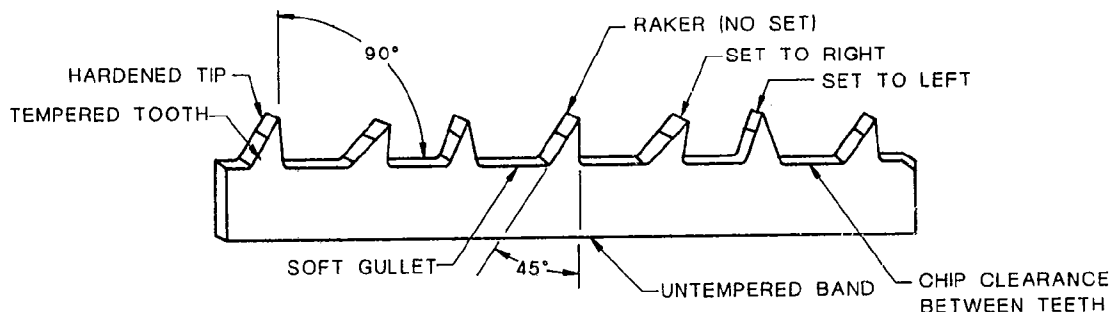


Figure 3 — A Typical Band Saw Blade Design for Aluminum

particularly suitable where lubrication on the blade is not allowed. Two types of circular saw blades are shown in Figure 4. The tooth side-rake angle should be about 15 degrees for the type shown in Figure 4 (A). Circular saws are versatile for cutting plate, as well as for straight or angular cut-off of extrusions. Jig or sabre saws are convenient for cutting holes or intricate shapes in pieces that are too large to be cut with a band saw.

Clean, as-sawed edges are often suitable for welding. If they need cleaning, they should be smoothed first by filing, planing, routing, sanding, polishing, or milling.

3.3.3 Shearing. The shear should be clean and sharp with the correct clearances between blades for the metal thicknesses. Properly sheared edges can be welded satisfactorily with sheet thicknesses up to 3/16 in. (4.8 mm). However, sheared edges, and other weld surfaces, should be clean whether they are welded "as sheared" or after dressing. Sheared edges should be dressed by filing, planing, sanding, or routing before welding.

Shearing is not recommended for aluminum alloys containing 3.5% or more of Mg (5086, 5083, and 5456) because the edges can become sensitive to stress-corrosion cracking. However, sheared edges that are either entirely melted during welding or buttered for welding are satisfactory.

3.3.4 Nibbling. A nibbler cuts material by a shearing action, and the resultant edge may require dressing before welding. A nibbler is advantageous for cutting curved edges and holes.

3.3.5 Filing. A vixon or autobody file, shown in Figure 5, is the most suitable type for aluminum. It has proper tooth shape and spacing for free cutting action and produces a smooth surface that can be readily cleaned.

3.3.6 Routing. Pin, radial-arm, or hand routers are useful tools for cutting and preparing the edges of aluminum sheet and plate for shipbuilding. They are well suited for use with templates of irregular shapes and for stack cutting several sheets simultaneously. Special cutters can be used to cut and bevel at the same time. The cut edges are ready for welding after cleaning.

3.3.7 Planing/Milling. Portable air-powered weld shavers are available to gouge and finish joints and butt welds. They are fast and effective when properly used and produce smoothly finished, easily cleaned surfaces. Depth of cuts are adjustable and various cutter configurations are available, including a flat cutter blade to remove weld bead reinforcement and a vee blade with various angles and bottom radii for making bevels.

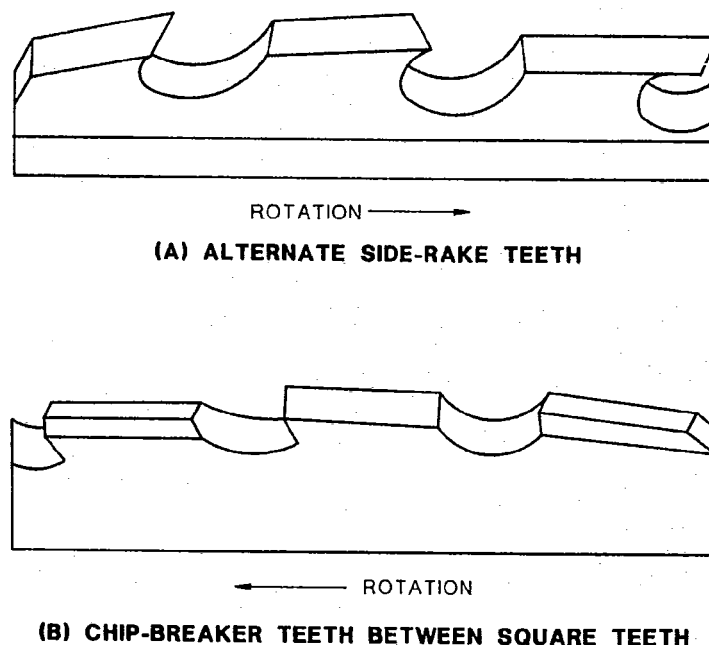


Figure 4 — Teeth Arrangements for Circular Saws for Aluminum

3.3.8 Chipping. Chipping is seldom used for edge preparation because it is slow, noisy, and difficult to control. It is chiefly used for weld metal removal and for back gouging. For optimum chipping speed and clean cutting action, the chisel shapes should be similar to those shown in Figure 6. They are quite different from those normally used for steel.

Significant aspects of these chisel designs are as follows:

- (1) Large rake angle to help control depth of cut and to lift the chip free of the joint
- (2) Shaped cutting edges to provide better tracking
- (3) Proper design and width to obtain the required groove depth and angle

3.3.9 Sanding. When used, care should be taken to select nonloading type sanding discs specifically intended for aluminum, and to maintain them free of lubricants and other foreign material. Discs of 36-80 grit will remove heavy oxide and leave a smooth acceptable surface finish. Polishing pads can be used for light oxide removal.

3.3.10 Grinding. Grinding of aluminum, except as a final weld contouring and finishing operation, is discouraged because it leaves a rough, torn metal surface that is difficult to clean. When used, care should be taken to select nonloading type grinding discs specifically intended for aluminum and to maintain them free of lubricants and other foreign material.

Grinding has been employed for back gouging and weld metal removal for repairs. Satisfactory weld quality can be obtained when care is taken to maintain cleanliness of the grinding discs and the aluminum surfaces prior to welding.

3.4 Back Gouging. Back gouging of joints for welding the second side should be of adequate depth to ensure complete root fusion. Standard air hammers fitted with properly shaped chisels can be used. If the metal chip splits to form a "ram's horn", the root of the first weld has not been reached. The operator can maintain chipping on the center of the joint by observing the size of each part of the "ram's horn." A single, unsplit chip usually indicates that sound metal has been reached. The resulting groove should be smooth and readily cleaned.

Back-gouging can also be accomplished using portable power saws with small cutters or portable milling cutters. Disc grinders with appropriate wheels are also used.

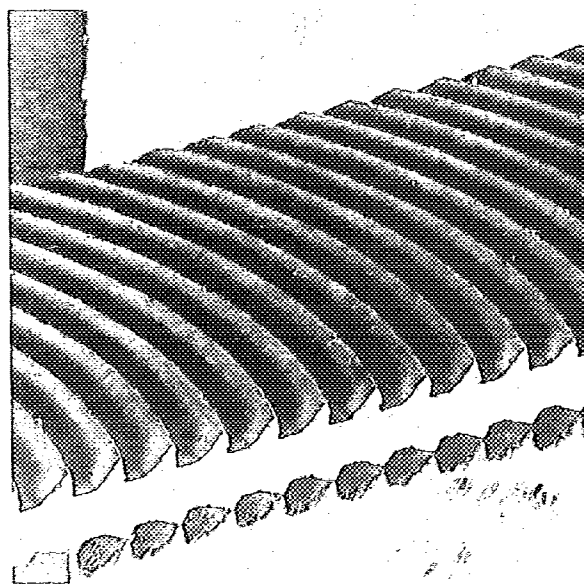


Figure 5 — A Vixon File for Aluminum

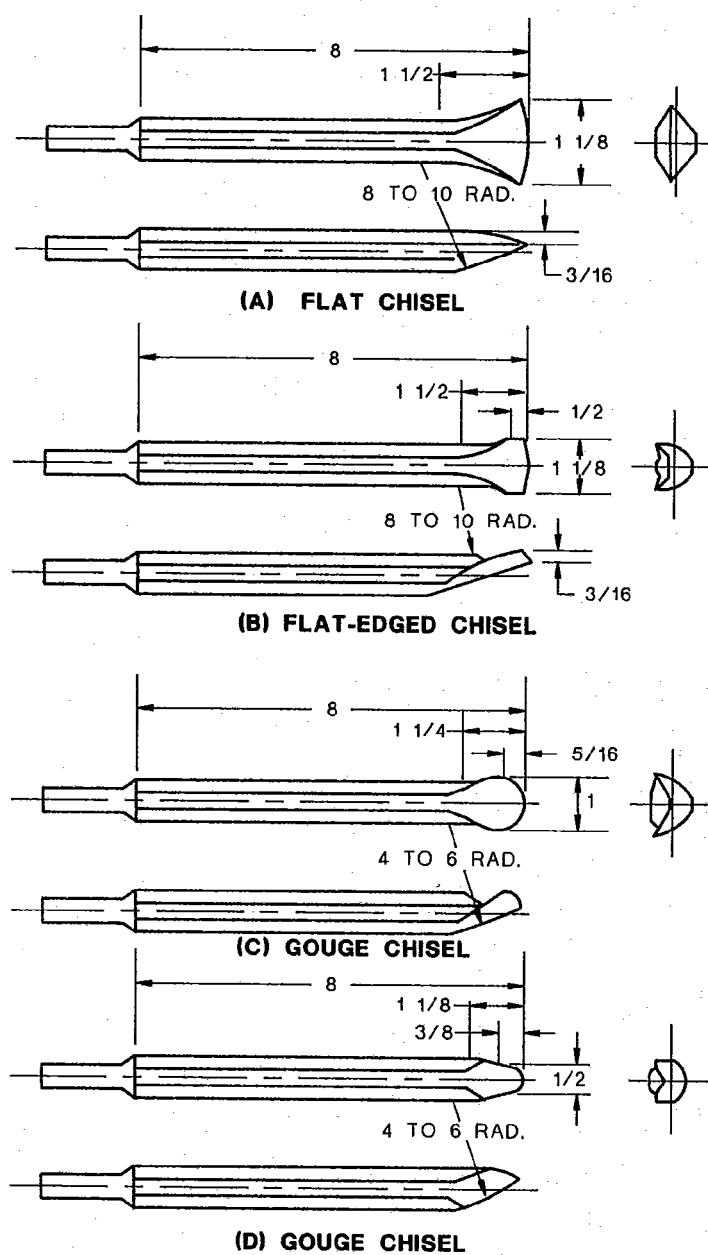
3.5 Finishing and Contouring. Finishing of welds is seldom required. When specified, weld finishing can be readily accomplished by grinding or sanding, provided care is taken to avoid damaging or thinning the base metal adjacent to the weld. Chipping with pneumatic chisels or portable milling equipment along with final light disc sanding or polishing is often the most economical method of finishing welds.

3.6 Cleaning for Welding. Shipyard cleaning procedures most commonly used for aluminum welding consist of degreasing followed by hand or power wire brushing or sanding of the joint surfaces and adjacent surfaces just prior to assembly and welding. When sanding is employed, it is necessary to remove all sanding dust, prior to welding, with a clean stainless steel brush.

Degreasing is usually done with a commercial solvent by wiping, spraying, dipping, or vapor degreasing. Such solvents may be toxic, and the cleaning and welding areas should always be well ventilated.¹² Always follow the safe handling guidelines provided by the chemical manufacturer.

Wire brushes should have stainless steel bristles of from 0.005 to 0.015 in. (0.13 to 0.38 mm) diame-

12. Refer to ANSI/AWS Z49.1, *Safety in Welding and Cutting*, published by the American Welding Society.



NOTE: DIMENSIONS ARE IN INCHES

Figure 6 — Chisel Designs Suitable for Aluminum

ter. They should be degreased periodically to prevent contamination of the aluminum surface. Pressure on the brush should be light to avoid burnishing the surface and imbedding foreign matter.

For more tightly adhering contaminants or very thick oxide, other cleaning methods may be used. Mechanical methods include machining, scraping, filing, grinding and sanding. Chemical methods include the use of caustic soda, acids, and proprietary solutions.¹³ It is always important to remember that when mixing any solutions, the chemical should always be added slowly into the water or solvent while stirring.

Cleaning should be done before fit-up of the joint because it is difficult to remove solvents or solutions from assembled joints.

Weld joint surfaces and adjacent surfaces may become contaminated again if they are exposed to the shop atmosphere for a period of more than eight hours. An effective way to prevent this is to cover the joints with strips of strong paper, 2 to 3 in. (51 to 76 mm) wide, taped in place along their length. Tape should not be applied directly to the joint faces, or within 1 in. (25 mm) on either side, because the adhesive may be difficult to remove. Any residue on the joint faces may cause porosity in the weld. It is also important to remember that the addition of strong paper will not stop oxidation or moisture on the joint surface.

Compressed air is useful for cleaning joints of dust or metal particles that may have collected, but it should be free from water and oil. It should come from a reliable supply of dry, clean air, and there should be no lubricators in the lines. Always follow safe practices when using compressed air.

Rough, contaminated surfaces are very difficult to clean properly. They require a dressing operation, such as milling, routing, smooth sanding, polishing, or filing, before they are cleaned.

Cleaning should not be limited to the joint faces. Sufficient adjacent surface areas should be cleaned to remove any oil or grease that could flow into the joint or vaporize into the inert gas shield during welding. It is good practice to degrease all surfaces for a distance of 3 to 6 in. (76 to 150 mm) from the joint edge. Wire brushing, sanding, and polishing should be limited to the joint faces and other areas that will be exposed to the arc.

13. Additional information may be found in the Metals Handbook, Vol. 5, *Surface Cleaning, Finishing, and Coating*, 9th Ed., Metals Park, Ohio: American Society for Metals, 1982: 571-85.

3.7 Forming and Bending. Many aluminum shapes can be formed cold. Table 9 gives the minimum bend radii for 90-degree cold bends in principal marine aluminum alloys. For more severe forming, heat may be used, but precautions need to be taken to avoid undesirable changes in the metal properties. The effects of cold work and of heating are different for nonheat treatable and heat treatable alloys.

3.7.1 Nonheat Treatable Alloys. Alloys possessing 3.5% or more of Mg should not be formed at temperatures in the range of 150° to 400°F (66° to 204° C) because of the risk of causing the metal to become sensitive to stress-corrosion. Forming above 400°F (204° C) affects the strength of work-hardened metal. The effect is more pronounced as the annealing temperature of 650°F (343°C) is approached. Forming temperatures should be carefully controlled, and the time at forming temperature kept as short as possible.

3.7.2 Heat Treatable Alloys. Annealing 6061 alloy to completely remove the effects of hardening markedly reduces its tensile strength. The annealing treatment for this alloy is 2 to 3 hours at 775°F (413°C) followed by a slow cool of 50°F (28°C) per hour down to 500°F (260°C). It is generally used only where required to form the part, and then only when the part can be heat-treated to restore or obtain maximum strength. When it is desired to partially remove the effects of cold working or heat treatment to make the metal more formable, 6061 alloy is heated to 650°F (343°C), followed by rapid cooling. Time at elevated temperature is critical for 6061 alloy.

3.8 Preheat. Temperature changes can result in condensation. Therefore, it is almost a universal practice among shipyards to heat and dry off aluminum components before welding during early morning hours. Temperatures for drying need not exceed 150°F (66°C); i.e., hand warm.

Clean-burning gas is used in torches that are adjusted to produce a soft, reducing flame. Local overheating should be avoided. It is essential to monitor temperature with pyrometric instruments or temperature-indicating crayons or paint. A maximum temperature of 250°F (121°C) should not be exceeded, and time at temperature should not exceed 15 minutes.

The use of resistance heater bars is another alternate way to preheat the base metal before welding is commenced.

Table 9
Approximate Minimum Bend Radii for 90-degree Cold Bends in Aluminum Alloys

		Minimum Bend Radius*							
Alloy	Temper in. (mm)	Base Metal Thickness, t							
		1/64 (0.4)	1/32 (0.8)	1/16 (1.6)	1/8 (3.2)	3/16 (4.8)	1/4 (6.4)	3/8 (9.5)	1/2 (13)
0	0	0	0	0.5t	1t	1t	1.5t	1.5t	
H32	0	0	1t	1.5t	1.5t	1.5t	1.5t	2t	
5052	H34	0	1t	1.5t	2t	2t	2.5t	2.5t	3t
H36	1t	1t	1.5t	2.5t	3t	3.5t	4t	4.5t	
H38	1t	1.5t	2.5t	3t	4t	5t	5.5t	6.5t	
0	---	---	0.5t	1t	1t	1t	1.5t	1.5t	
H321	---	---	1t	1.5t	1.5t	1.5t	2t	2.5t	
5083	H243	---	---	1.5t	2t	2.5t	3t	---	---
H343	---	---	1.5t	2.5t	3t	3.5t	---	---	
0	0	0	0.5t	1t	1t	1t	1.5t	1.5t	
H32	0	0.5t	1t	1.5t	1.5t	2t	2.5t	3t	
5086	H34	1.5t	1t	1.5t	2t	2.5t	3t	3.5t	4t
H36	---	---	---	3t	3.5t	4t	4.5t	5t	
0	0	0.5t	1t	1t	1t	1.5t	1.5t	2t	
5454	H32	0.5t	0.5t	1t	2t	2t	2.5t	3t	4t
H34	0.5t	1t	1.5t	2t	2.5t	3t	3.5t	4t	
0	---	---	---	1t	1.5t	1.5t	2t	2t	
H321	---	---	---	2t	2t	3.5t	3t	3.5t	
5456	H323	---	---	2.5t	3t	3.5t	4t	---	---
H343	---	---	3t	3.5t	4t	4.5t	---	---	
0	0	0	0	1t	1t	1t	1.5t	2t	
6061	T4	0	0	1t	1.5t	2.5t	3t	3.5t	4t
T6	1t	1t	1.5t	2.5t	3t	3.5t	4.5t	5t	

* The radii listed are the minimum recommended for bending sheets and plates without fracturing in a standard press brake with air bend dies. Other types of bending operations may require larger radii or permit smaller radii. The minimum permissible radii will also vary with the design and condition of the tooling.

4. Welding Processes and Equipment

4.1 General. The gas metal arc welding (GMAW) process is recommended for over 90% of the welding in marine construction because welds can be produced at high speeds as a result of the high heat input and the continuous feeding of filler metal. It is used for semiautomatic, machine, and automatic welding operations. The process can be used to weld sheet as thin as 0.050 in. (1.3 mm) with pulsed power, and about 0.062 in. (1.6 mm) with continuous power.

Gas tungsten arc welding (GTAW) can be used for joining aluminum parts with small cross-sections, such as piping, handrails, and similar fittings that

have curved or relatively inaccessible joints. This process is suitable for welding aluminum ranging from thin sheet gauges to a practical maximum thickness of approximately 3/8 in. (9.5 mm). Proper application requires a high degree of torch maneuverability and welder skill.

Stud welding is used extensively by shipyards to fasten aluminum studs to aluminum hulls, decks, and bulkheads for the attachment of insulation; hangers for electrical brackets, cable troughs and pipe; and other similar applications.

4.2 Gas Metal Arc Welding. In gas metal arc welding, filler metal can be transferred from the electrode to the workpiece in two ways:

(1) Discrete droplets are moved across the arc un-

der the influence of gravity and electromagnetic forces. Transfer can be either globular (large droplets) or spray type (small droplets). The pulsed spray process variation is gaining wider usage on thin base metals.

(2) The electrode contacts the weld pool, thereby creating a short circuit. This is known as short-circuiting transfer.

Short-circuiting arc welding uses the lowest range of welding currents and electrode diameters associated with GMAW. It is not recommended for welding aluminum because of the danger of incomplete fusion in the welded joint.

The GMAW process employs an aluminum wire electrode and an inert gas shield. With some GMAW equipment, electrode feed starts the instant the arc is initiated and stops when the arc is stopped. With other types, electrode feed is controlled by the welder. Gas flow is similarly controlled. The arc is produced by direct current flowing between the electrode at positive and the work at negative polarity (dcep).

4.2.1 Shielding Gas. Argon and helium, or mixtures of the two gases, are used exclusively for welding aluminum. The purity and moisture content of the inert shielding gas is extremely important. Gas suppliers exercise great care to ensure that commercial welding grades are free from moisture, oils and other contaminants. The dewpoint of the gas should be below -76°F (-60°C) at the manifold or cylinder and -40°F (-40°C) at the nozzle as a minimum. All welding machine, shop, and yard pipelines and hoses should be kept clean and free of moisture and other contaminants that cause weld porosity. Hoses that were previously used for other than welding grade inert gas should not be used with welding equipment. When high quality welds are called for, oxyacetylene hoses should not be used, and synthetic hoses like PVC are recommended.

Weld quality and economy for a given set of welding conditions are markedly affected by the type of inert gas employed. The primary function of the inert gas is to exclude oxygen, nitrogen, and hydrogen from the molten metal. It also provides an ionized path for the electrical transfer of energy and a stable arc action.

Either argon, helium, or a mixture of the two is used for GMAW of aluminum. Pure argon is usually preferred for welding plate in thicknesses up to about 3/4 in. (19 mm). Argon is most effective in oxide removal when used with a direct current, electrode positive arc.

A direct current, electrode positive arc, operating at any given amperage, has a higher voltage with

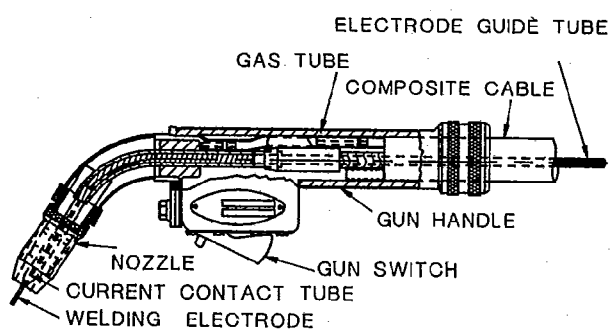
helium shielding than with argon shielding. For joining thick aluminum plate, mixtures of argon and helium are often employed with GMAW to obtain the higher arc energy associated with helium and the good cleaning action with argon. Helium-argon mixtures are also recommended for out-of-position welding of hull plates. Mixtures of 50 to 75% helium are commonly used to take advantage of the good penetration characteristics and weld metal soundness. Most dealers supply cylinders with a mixture of 75% helium and 25% argon. In addition, mixing valves and gas proportioners are commonly employed to produce any desired mixture of these gases.

4.2.2 Equipment. Gas metal arc welding equipment is available in a range of capacities for both semiautomatic and automatic operation. Several basic designs of semiautomatic GMAW guns are available to fit various combinations of electrode wire feed and power source equipment. Typical semiautomatic GMAW guns are shown in Figure 7. Pull-type guns, Figure 7(C), and push-pull guns, Figure 7(E), may be used with remote wire feeders to reach distant welding locations and should be used to feed 3/64 in. (1.2 mm) diameter and smaller electrodes. Most welding guns rated for higher amperage need to be water-cooled and are preferred for aluminum welding. Factors controlling the suitability of the arc welding gun design and wire feed system include accessibility, electrode diameter, and distance from the electrode wire supply to the location of welding.

Wire feeders usually are located some distance from the welding power supply. Depending on the system employed, the GMAW gun can be used at extended distances from the electrode supply to enhance the most efficient use of the equipment. Control of welding current arc voltage, depending upon the type of power supply being employed, can be provided at the welding station with a remote pendant.

4.2.3 Power Sources. Several types of dc power sources are available for semiautomatic, machine, and automatic gas metal arc welding (GMAW). Semiautomatic welding requires welding currents up to about 400 A. Machine and automatic welding generally require currents in the range of 300 to 600 A.

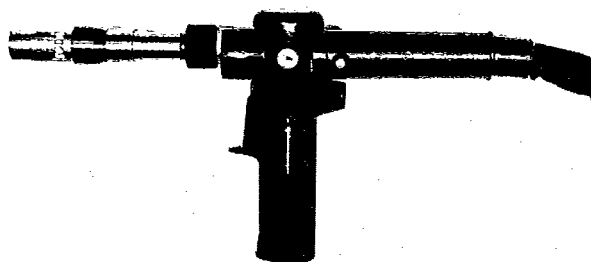
Important factors in selecting a GMAW power source for aluminum include size of the weld, electrode diameter, welding position, amount of welding to be done, desired production rate, and other factors.



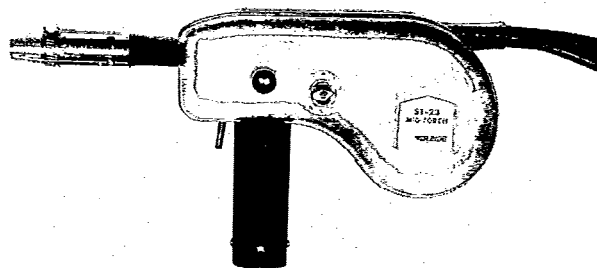
(A) GAS-COOLED, CURVED-NECK GUN FOR PUSH WIRE FEED



(B) PISTOL-GRIP GUN FOR PUSH WIRE FEED



(C) PUSH-PULL TYPE GUNS



(D) GUN WITH SELF-CONTAINED WIRE DRIVE AND SPOOL

Figure 7 — Typical Semiautomatic Gas Metal Arc Welding Guns

Power is generally supplied for GMAW by single operator, dc rectifiers, motor-driven generators, inverters, or pulsing type power sources. Rectifiers have higher electrical efficiency and lower noise level. Motor-driven generators are not affected by normal line voltage fluctuations. Engine-driven generators are used essentially away from power lines and, if properly maintained, give long, dependable service. For semiautomatic GMAW of aluminum, three types of dc power sources are normally used, namely:

(1) Constant Potential (CP) having flat or slightly drooping volt-ampere characteristic (1 to 3 V/100A)

(2) Constant Current (CC) having a drooping volt-ampere characteristic (1V/5 to 10A)

(3) Pulsed direct current (PA)

Modifications of these types are also used for machine and automatic GMAW.

The principal differences in performance of these power sources when welding aluminum are manifested when specific welding variables are adjusted. A prime factor in choosing a given type of power source is, therefore, the type of welding to be done. Electrode feed control requirements are different for constant-current and constant-potential machines.

With a constant-current machine, the electrode feed is not initiated until the arc is established by touching the electrode to the work. Alternatively, a slow run-in wire feed can be used. Attempts to start the arc by feeding the electrode into the work at normal speed usually fail.

The reason for this is that the heat developed by the limited welding amperage is insufficient to initiate melting of the electrode tip. With a constant-potential machine, a large surge of current takes place when the electrode touches the workpiece. The electrode melts back rapidly, and the arc is established readily. However, a slow run-in feed is advantageous for improving the soundness of the weld metal at starts. It also helps provide better contact tube life by limiting the starting current surge. Since the resistance heating of the aluminum electrode is much less than ferrous electrodes, guns with long contact tubes should be used to provide consistent electrical transfer.

As the gun-to-work distance is changed, a constant-potential machine will tend to maintain a constant arc length by allowing the welding amperage to vary. With a constant-current (CC) machine, larger changes in arc length will be noted, but the amperage change will be less than with a constant-potential (CP) machine. Oscillation should be minimized or avoided when using a CP power supply

with aluminum, due to the wide fluctuations in heat input that may lead to lack of fusion in deep groove and fillet welds. A drooping volt-ampere characteristic power supply (CC) is generally preferred for sound welds in aluminum when the arc is manipulated. Proper welding procedures should be developed and followed for each type of power supply. A shorter arc gives deeper penetration and is generally used for the first pass. Longer arcs are used for cover passes and welds, where deep penetration is not required. However, arc length that is too long or too short causes inadequate inert gas shielding, creating excessive weld porosity.

Power sources are available for pulsed spray welding. A pulsed, direct-current power source pulses the welding amperage from a low background value to a high peak value. The steady, background amperage is too low to produce spray transfer. The peak amperage, which is superimposed upon the background amperage at regulated intervals, is well above the spray transition amperage. Consequently, one droplet of metal is usually transferred during each pulse. The combination of the two levels of amperage produces a steady arc with axial spray transfer at average welding amperage below those required for conventional spray arc welding. Now available are synergic controllers that include the adjustment of peak and background amperage, along with voltage and pulse rate, with a single knob.

Because the heat input is lower than normal spray arc welding, this variation of GMAW is capable of welding thinner base metal than is practical with conventional spray transfer. It is useful for welding aluminum of 0.08 in. (2 mm) or less in thickness. This type of power source also makes it possible to weld groove and fillet welds having relatively poor joint fit-up in either the horizontal or vertical position.

4.2.4 Wire Feed Units. Selection of an appropriate wire feed system is important. Desirable features of a system are as follows:

(1) A constant adjustable speed drive.

(2) A slow run-in or touch-start initial wire feed speed starting system compatible with the appropriate type of power source.

(3) Radius-groove top and bottom wire drive rolls or a 60° vee feed roll with a flat pressure roll. Self-contained wire guns [Figure (7D)] may also use knurled feed rolls, but they are not recommended for other systems with long wire liners to the gun that can become clogged with aluminum shavings.

(4) Nonmetallic liners and guides for the electrode; e.g., nylon, teflon, etc.

(5) Water and gas solenoid valves.

To protect the aluminum welding wire from dirt and to reduce the incidence of weld porosity, it is desirable to have a spool enclosure. Additional protection can be achieved with an electric heater in the enclosure to minimize condensation.

4.3 Gas Tungsten Arc Welding. A nonconsumable tungsten electrode is used for gas tungsten arc welding (GTAW). Both the electrode and the molten weld pool are protected by an inert gas shield. When required, filler metal is added by hand or by a mechanical wire feeder.

Even though the tungsten electrode is nonconsumable under normal operating conditions, the weld metal can be contaminated with tungsten if the electrode is allowed to touch the molten weld metal, filler rod, or if the welding current is excessive for the electrode size. GTAW is suitable for welding aluminum in all positions. Weld beads are characteristically smooth. A typical water-cooled welding torch is shown in Figure 8. GTAW is often the only suitable process where joint accessibility is limited because a wide variety of welding torch designs are available, including miniature sizes. Also, some low-current models are air cooled and easier to manipulate than water cooled types.

4.3.1 Types of Welding Current. Aluminum can be gas tungsten arc welded using conventional sinusoidal-wave ac (60 Hz), balanced sinusoidal-wave (bwac) and square-wave ac (swac), square-wave with adjustable balance, and dc with the electrode either negative or positive. Direct current can be pulsed to provide good control of the weld pool, particularly when welding in other than the flat position.

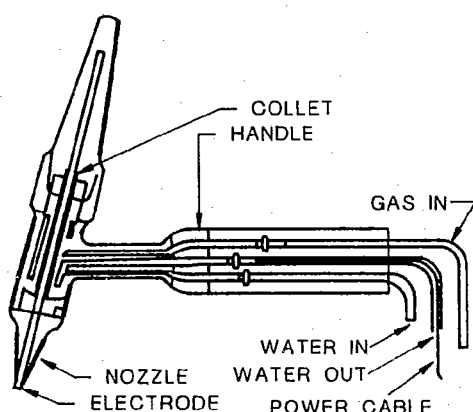


Figure 8 — Typical Water-Cooled Gas Tungsten Arc Welding Torch

Surface cleaning of the aluminum takes place when the electrode is positive, but penetration is poor. Conversely, penetration is good with a negative electrode, but there is no cleaning action. Alternating current can provide good cleaning action and acceptable penetration, particularly with swac of variable frequency and pulse width. Direct current can provide good penetration or good cleaning, but not both conditions simultaneously.

4.3.2 Electrodes. The choice of tungsten electrode depends upon the type of welding current selected for the application. With conventional ac, better arc action is obtained when the electrode has a hemispherical-shaped tip. AWS Classes EWP (pure tungsten) and EWZr (tungsten-zirconia) electrodes retain this tip shape well. Class EWTh-3 (tungsten-thoria) electrodes may also be used.¹⁴ The electrode should be tapered to facilitate melting the tip to form a hemispherical shape.

Class EWTh-1 and EWTh-2 (tungsten-thoria) electrodes are preferred for use with dc power. Both have higher emissivity, better current carrying capacity, easier starting characteristics, and longer life than do EWP electrodes. When these electrodes are used with ac on aluminum, there is an increased tendency for rectification of the arc, reduced arc cleaning action and arc stability, as well as increased loss of tungsten compared to the EWP and EWZr electrode types.

4.3.3 Shielding Gases. Argon is the most commonly used shielding gas, particularly for manual welding. Helium is used in special cases. Arc voltage characteristics with argon permit greater arc length variations with minimal effect on arc power than helium. Argon also provides better arc starting characteristics and improved cleaning action, especially with alternating current.

Helium is used primarily for machine welding with dc power. It permits welding at higher travel speed or with greater penetration than argon.

Helium-argon mixtures are sometimes used to take advantage of the higher heat inputs with helium while maintaining the favorable arc characteristics of argon. Mixtures of 25% to 75% helium will permit higher travel speeds with ac power. Cleaning action is still acceptable. A mixture of 90% He-10% Ar will provide better arc starting characteristics with dc power than pure helium.

14. Refer to ANSI/AWS A5.12-80, *Specification for Tungsten Arc Welding Electrodes*, published by the American Welding Society.

4.3.4 Alternating Current Power. When ac is used in conjunction with shielding of argon or an argon-helium mixture, the surface oxide is removed by arc action. However, this cleaning action may not be satisfactory when the mixture contains 90% helium or more, and preweld cleaning is usually necessary. Pure helium shielding is seldom used with alternating current because the arc characteristics are poor.

The oxide removal action takes place only during the portion of the ac cycle when the electrode is positive. This action tends to rectify the ac power. To assure arc initiation during this half cycle, the power source should have either a high open-circuit voltage or an auxiliary circuit to superimpose high voltage on the welding circuit. The arc should be initiated by some means other than touching the electrode to the workpiece to avoid tungsten contamination. High frequency arc starting is commonly used in this regard.

The magnitude of the current will be greater when the electrode is negative unless the power source contains appropriate electrical circuitry to balance the ac wave. For this reason, balanced-waved ac power sources are recommended for welding aluminum. Proper gas shielding and arc cleaning action are indicated by a bright weld bead with silvery borders on each side. An oxidized weld bead may be a result of an unstable arc, low welding current, poor gas shielding, or excessive arc length.

4.3.5 Direct Current, Electrode Negative Power. Gas tungsten arc welding with direct current, electrode negative (dcen) has distinct advantages compared to ac power, particularly with machine welding. The deep penetration possible with helium shielding is particularly useful for welding thick sections. Preheating is not normally required. With thin sections, dcen permits much higher travel speed than does alternating current, and the arc length should be carefully controlled when using helium shielding gas.

The surface appearance of a weld made with dcen will be dull rather than bright because the cleaning action of the electrode positive half-cycle of ac is absent. A thin oxide film accounts for this appearance, but it is easily removed by wire brushing. Thorough preweld cleaning is essential, as is interpass cleaning with multiple-pass welds.

Argon shielding may be used with dcen, but penetration will be less than with helium. Arc length control will not be so critical, and this may be beneficial when manually welding thin base metal.

4.3.6 Direct Current, Electrode Positive Power. Welding with dcep provides good surface cleaning action and permits welding of thin aluminum base metal with sufficient current to maintain a stable arc. However, the weld bead tends to be wide, and penetration is shallow. Application is limited to base metal of about 0.050 in. (1.3 mm) thickness and under, or for tack welding, because of tungsten electrode overheating. Argon shielding should be used. Helium or argon-helium mixtures would contribute to electrode overheating. Edge or square-groove joint geometries with or without filler metal may be applicable.

4.3.7 Square-Wave Alternating Current Power. Square-wave alternating current (swac) power supplies differ from conventional ac sinusoidal wave power with respect to the current wave form. The swac power source is designed to produce dc power and rapidly shift the polarity to produce a square alternating wave form of adjustable frequency available in some models. In addition, the relative percentage of electrode negative time within one cycle of current is adjustable within limits.

This type of power combines the advantages of surface cleaning associated with conventional ac power and deep penetration obtainable with dcen power. However, one is gained with some sacrifice in the other. If longer electrode-positive time is needed for acceptable cleaning, penetration will decrease with a specific welding current and frequency.

The square-wave shape enhances arc reignition during polarity reversal. Often, superimposed high frequency voltage is needed only to start the arc, rather than continuously during welding to stabilize the arc.

Welding techniques similar to those for conventional ac welding are suitable with swac welding, as is the electrode tip shape. Argon shielding is preferred, but argon-helium mixtures can provide deeper penetration at some sacrifice in cleaning action.

4.3.8 Wire Feed Units. Mechanized GTAW employs a wire feed unit for the addition of filler metal. Models range from the conventional machine-mounted type to special-purpose units. The guide that directs the filler wire into the molten weld pool is usually mounted next to the welding torch. Controls operate and regulate the wire feed. The wire is supplied on spools identical to those for gas metal arc welding bare wire electrodes.

4.4 Mechanized Welding. High welding currents and travel speeds can be used, resulting in greater productivity with this method. Mechanized welding is employed in two ways.

4.4.1 Mechanically Aided Welding. The arc welding gun is normally mounted either on a tracked or trackless pacing carriage or on a boom. Both mountings may carry the equipment alone, or may be large enough to accommodate the welder also. In either case, the welder manually regulates welding machine settings, travel speed, wire entry position, and torch position. Such mechanical aids improve efficiency, when welding long joints.

4.4.2 Machine Welding. Machine welding employs completely mechanized equipment. The welding operator monitors the welding and manually adjusts seam tracking and welding variables, such as welding current, arc voltage, wire feed rate and travel speed. Resulting weld beads are accurate and uniform within the process capability. Shipyard use of machine welding is economical for long joints in hull plates, prefabrication of panels, welding tubular and other hollow components of superstructure, hatch covers, ship-fabricated bulkheads, and similar applications. Machine welding should be considered for shipyard use wherever the work can be positioned for welding in the flat, horizontal, or vertical position.

4.5 Stud Welding. There are two types of stud welding that employ an arc to obtain fusion. These are gas shielded drawn arc and capacitor discharge stud welding. Aluminum studs can be joined to aluminum components with both types of equipment.¹⁵ Stud welding is used to join various mechanical fasteners to structural sections.

4.5.1 Arc Stud Welding. Arc stud welding equipment consists of a stud welding gun, a timing control device, a dc power source, and a gas adapter foot that holds a ceramic ferrule around the stud and conducts shielding gas to the joint. The ferrule confines the weld metal and aids in forming a fillet at the base of the welded stud.

The stud welding gun is also equipped with a dampening device to control the plunging rate of the stud at the completion of the weld time. Argon is generally used for shielding, but helium may be use-

ful with large studs to take advantage of the higher arc energy. The equipment arrangement is shown in Figure 9. This equipment is used with the stud (electrode) positive and the work negative.

An aluminum stud differs from a steel stud in that no flux is used on the welding end. A cylindrical- or cone-shaped projection is used on the base of the stud. The projection dimensions on the welding end are designed for each size of stud to give the best arc action. The projection serves to initiate the long arc used for aluminum stud welding.

Studs have weld base diameters of 1/4 to 1/2 in. (6.4 to 13 mm). Their sizes and shapes are similar to steel studs. They are commonly made of aluminum-magnesium alloys, including 5183, 5356, and 5556, that have a typical tensile strength of 40 ksi (280 MPa). These alloys have high strength, good ductility, and they are metallurgically compatible with the majority of aluminum alloys used in the shipbuilding industry.

4.5.2 Capacitor Discharge Stud Welding. With this process, dc arc power is produced by a rapid discharge of stored electrical energy with pressure applied during or immediately following the electrical discharge. The process uses an electrostatic storage system as a power source in which the weld energy is stored in capacitors.

There are three different types of capacitor discharge stud welding: initial contact, initial gap and drawn arc. They differ primarily in the manner of arc initiation. Initial contact and initial gap stud welding utilize studs having a small, specially designed projection (tip) on the welding end of the stud. Drawn arc stud welding creates a pilot arc as the stud is lifted off the workpiece by the stud gun, similar to arc stud welding.

The process is best suited for welding studs to relatively thin base metal. Neither ferrules nor shielding gas is normally required to protect the weld metal because the welding time is very short. However, argon shielding should be used with the drawn arc method because the welding time is long enough for oxidation to take place.

Studs for capacitor discharge welding commonly have bases ranging from 0.062 through 0.187 in. (1.6 through 4.75 mm) diameter. The drawn arc technique is commonly used for 1/4 through 1/2 in. (6.4 through 13 mm) diameter. Studs are commonly made from 1100, 4043, 5183, 5356, and 5556 alloys, and are readily welded to 5XXX (except 4043) and 6XXX alloys.

Arc times are significantly shorter and welding currents are much higher than those used for arc

15. Stud welding is discussed in ANSI/AWS C5.4-84, *Recommended Practices for Stud Welding*, and Vol. 2 of the *Welding Handbook*, 7th Ed.

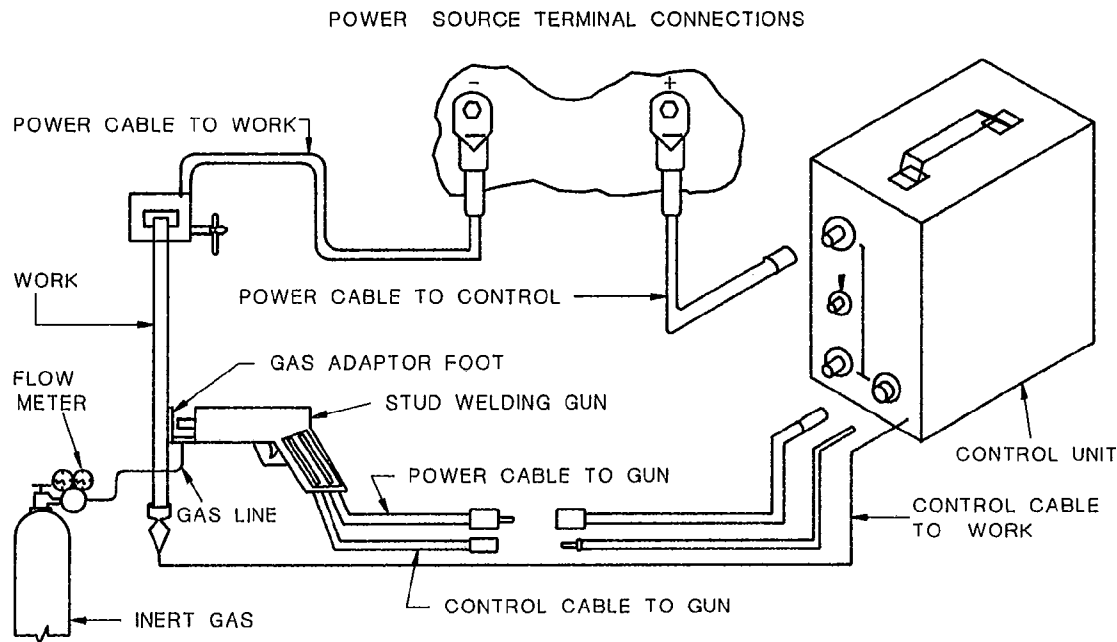


Figure 9 — Equipment Setup for Arc Stud Welding of Aluminum

stud welding. It is the very short weld time that accounts for the shallow weld penetration into the workpiece and also the small stud melt-off distance.

Depending upon stud size and type of equipment used, the peak welding current can vary from about 600 to 20 000 A. The total time to make a weld depends on the welding method used. For the drawn arc method, weld time is in the range of 6 to 15 milliseconds.

4.5.3 Quality Control. Aluminum stud welding requires attention to the following points to assure good reliability:

- (1) Correctly designed studs and proper matching of stud and base metal (reference Table 7)
- (2) Power source and welding equipment of sufficient capacity for the stud size
- (3) Surfaces that are clean and free of lubricants, oxides, and other contaminants
- (4) Proper positioning of the stud welding gun on the work surface, and correct stud lift and plunge settings

Visual inspection of aluminum stud welds for acceptance is limited because the appearance of the weld fillet does not necessarily indicate soundness. Therefore, visual inspection of aluminum stud welds is recommended only to determine complete fusion and absence of undercut around the periphery of the weld.

Aluminum studs can be tested to establish ac-

ceptable welding procedures using a bend test. If the stud bends to 15 degrees from the original axis without breaking the stud or weld, the stud welding techniques should be considered satisfactory. Production studs should not be bent and then straightened because of possible damage to them. In this case, the torque test or separate qualification test plates may be substituted.

Torque testing of threaded aluminum studs is done in the same manner as that used for steel studs. Torque is applied to a predetermined value or until the stud fails. For a particular application, the acceptable proof load should be established by suitable laboratory tests, relating applied torque to tensile loading.

5. Qualification Procedures for Welding

5.1 General. Standards for welding aluminum ship structures routinely call for qualification of the welding procedures to be used and the qualification of welders and welding operators to produce sound welds. Such qualification is recommended in every case and is mandatory for all hulls that are to be welded to codes and specifications of cognizant governmental and commercial agencies. The principal agencies are included in Appendix A.

It is essential that the builder and owner agree

upon suitable standards of welding procedure and performance. Welders and welding inspectors who are experienced and qualified in welding aluminum (preferably in marine applications) should be employed for ship structures. Most shipyards conduct training programs for welding and inspection personnel.

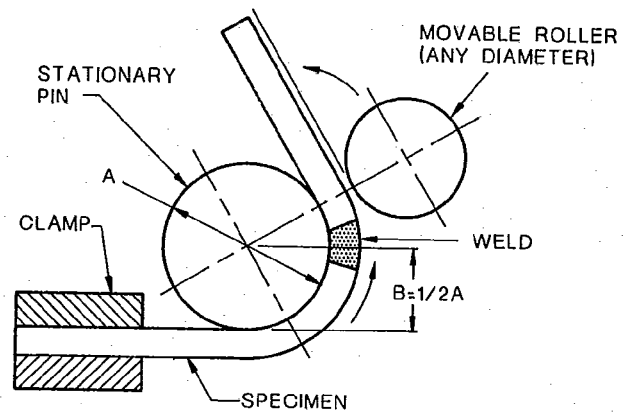
5.2 Procedure Qualification. Procedure qualification practices for welding may not be defined in the contract for the vessel to be constructed. However, the contract for a Navy or Coast Guard ship, for example, will probably refer to MIL-STD-248. This document describes in detail the procedure and performance qualification requirements for vessel construction.

In the absence of specification requirements in the contract, the Navy or Coast Guard will normally request that welding procedures be qualified in a manner similar to the requirements of either the *ASME Boiler and Pressure Vessel Code*, Section IX; the *American Bureau of Shipping Rules*; or *ANSI/AWS D1.2, Structural Welding Code — Aluminum*. These documents require that a welded test plate be prepared using the basic joint design, material preparation, welding process, procedures, equipment, plate thickness, and welding position that will be used during construction of the vessel. The weld shall be postweld heat-treated, if required by the design requirements of the vessel. Tensile or bend test specimens, or both, cut from the test weld need to meet the minimum requirements of the specification. Minimum weldment strengths for marine aluminum alloys are given in Table 8.

Weld bend tests are commonly conducted in two types of jigs.¹⁶ One is the standard plunger-type guided bend test. The other is the wrap-around guided bend jig shown in Figure 10. It is preferred for aluminum because it produces a more uniform bending across the weld metal and heat-affected zone than does the plunger type.

Welding and testing of procedure plates are usually witnessed by the designated Navy or Coast Guard inspector, or the ABS surveyor. Details of the procedures, similar to that outlined in Section IX of the *ASME Boiler and Pressure Vessel Code*, or MIL-STD-248, are presented to the surveillance agency. Upon approval by that agency, the procedure may be used in fabrication of the vessel. The

16. Refer to *Rules for Building and Classing Aluminum Vessels*, American Bureau of Shipping, or AWS B4.0, *Standard Methods for Mechanical Testing of Welds*, American Welding Society.



DIAMETER A IS SELECTED TO PRODUCE THE REQUIRED BEND RADIUS IN THE SPECIMEN.

Figure 10 — Wrap-Around Guided Bend Test Jig

ranges of base metal thickness, alloy, welding positions, and other conditions qualified by each procedure qualification are designated in the particular code specification or document.

The U.S. Navy, Coast Guard, and American Bureau of Shipping normally require that copies of procedure qualification test data and weld procedure specifications be submitted for review and approval. It should be recognized that, when this is required, production welding is not allowed to proceed prior to receiving this approval.

5.3 Typical Test Coupon. A typical set of weld test specimens consists of two reduced-section tensile test specimens and two each of root-bend and face-bend test specimens. These are obtained from a groove-weld, butt joint test plate of adequate size. Appropriate specimen locations in the test plate are designated by the qualification document.

The tensile specimens should fracture at or above the minimum specified strength (see Table 8) or as otherwise required by the applicable code. The bend specimen should bend over a designated radius with no cracks exceeding 1/8 in. (3.2 mm) in length on the convex side.

Additional tests may include visual, penetrant, radiographic inspection or microscopic examination of weld cross sections.

5.4 Performance Qualification. Welder and welding operator performance qualification may be designated to be in accordance with Section IX of the *ASME Boiler and Pressure Vessel Code*, MIL-STD-

248, Section 30 of the *Rules for Building and Classing Aluminum Vessels*, published by the American Bureau of Shipping, or ANSI/AWS D1.2 *Structural Welding Code — Aluminum*.

5.5 Record Keeping. Records of procedure and performance qualification tests for welding components covered by ABS, military, government agency, ASME, or similar specifications should be kept by the fabricator.

6. Welding Procedure and Techniques

6.1 General. The technology of fabricating welded aluminum hulls is well developed and is similar, in many respects, to that established for other marine materials. This knowledge, combined with the good formability of aluminum, enables fitters and welders to produce sound hulls exhibiting a high degree of craftsmanship.

6.2 Fitting, Aligning, and Assembling. After degreasing and heavy oxide removal from anticipated joint surfaces, the next step in vessel fabrication is to assemble flat plates and subsections for welding of the butt joints. Plates are tack welded together, welded on one side, and then turned for back chipping or gouging and welding on the other side. Some shipyards make the tack welds and the first weld on the same side; others weld the side opposite to the tack welds first. Joint edges that have been accurately measured and prepared on milling or planing machines, or by other precision cutting methods, can be easily fit-up with a minimum of fixturing.

Fit-up requirements for welded aluminum construction are generally more restrictive than those normally employed for welded steel construction. Root openings should be as small as possible, and accurately maintained during welding to ensure sound welds.

Procedures used in aligning component pieces are generally similar to those used for steel. Small aluminum parts can be hand-held in position while being tack welded. Larger components can be aligned by the use of welded strong-backs or clips, or positioned by welded tabs and come-alongs. Judicious use can be made of shims and wedges.

Edges to be welded should be maintained in alignment with a uniform root opening in accordance with the specific welding procedure. When developing welding procedures, it is important to use

small, uniform root openings to minimize distortion. Wherever practicable, a tight-fitted butt joint should be used. When mechanized welding is used, very uniform alignment and root opening is necessary for optimum weld quality.

After assembling and welding, flat-plate stiffeners and attachments are fitted and tack welded to the plates. Tack welding or fixturing may be used to hold the plates or other joint members in alignment for welding. Tack welds are used most frequently, although fixturing may be used to advantage on subassemblies or on hulls of small boats in large production runs. For complex shapes, tack welds are generally used.

All cold welding starts and oversize or unsound tack welds should be chipped out, or subsequent weld defects will occur at these places. Tack welds should be of sufficient size to hold the joint in alignment and to resist both spring back of parts and thermal stresses during welding. Tack welds should have both ends ground for incorporation into the final weld.

Major subassemblies are erected on the shipways or on the platen in accordance with the erection schedule. Although some yards fabricate subassemblies to exact dimensions and no trimming is necessary when they are fitted to the hull, it is sometimes desirable to provide excess base metal on one side of the master joint for fit-up, as shown in Figure 11. The plate can be trimmed, while in position in the ways, to mate with the adjoining section. Structural members, such as longitudinals, should extend beyond the edge of one plate for a distance of at least 12 in. (300 mm) and remain unwelded for a distance of about 12 in. (300 mm) back from that edge. The structural sections on the adjacent plate ends about 12 in. (300 mm) from the edge (see Figure 11). The structural sections can also be trimmed during fit-up. Another method used would leave the stiffeners cut back a minimum of 12 in. (300 mm) on both sides of the erection butt joint.

The final closing joint of a series of subassemblies usually requires trimming. Sometimes the joint is overlapped, and then cut and beveled for welding on the vessel. In other instances, the opening is surveyed, and the cutting for proper fit-up is done in the subassembly area. A build-up of tolerances and weld shrinkage may occur in ship construction that requires fitting a "margin" plate. The use of margin plates that are less than 8 in. (200 mm) wide should be avoided. The minimum width of margin plates will depend on the actual design and production condition, including plate thickness, frame spacing and location of welding.

As a general rule, a master butt joint should not

fall on a transverse frame. The distance of a butt joint from a frame should not be less than the sum of (1) the distance from the web of the frame section to the edge of the outstanding flange, and (2) the width of the welding gun being used. Locating the joint at a reasonable distance from the flange permits the welder to make the weld with a minimum of difficulty. Adequate access to the weld also makes repair welding easier, should it be needed.

6.3 Weld Backing. Backing is frequently used to support the molten weld metal at the root of a weld to prevent excessive melt-through. Backing may be either temporary or permanent and, in any case, it should be cleaned prior to welding.

Temporary backing is generally used for machine or automatic welding of thin sections at relatively high speeds. It can be made of aluminum, ceramic or stainless steel, and may be water-cooled. Carbon steel backing may be used when special attention is paid to prevent and remove rust. If aluminum backing is used temporarily, it can be tack welded in place and cut off after welding. Backing of other metals including hard coat anodized aluminum may be clamped in place. Copper is not recommended for backing because it may contaminate the weld and result in subsequent corrosion in service.

Temporary backing may be flat, in which case the weld should be back-gouged and welded on the second side. The backing may also be grooved to pro-

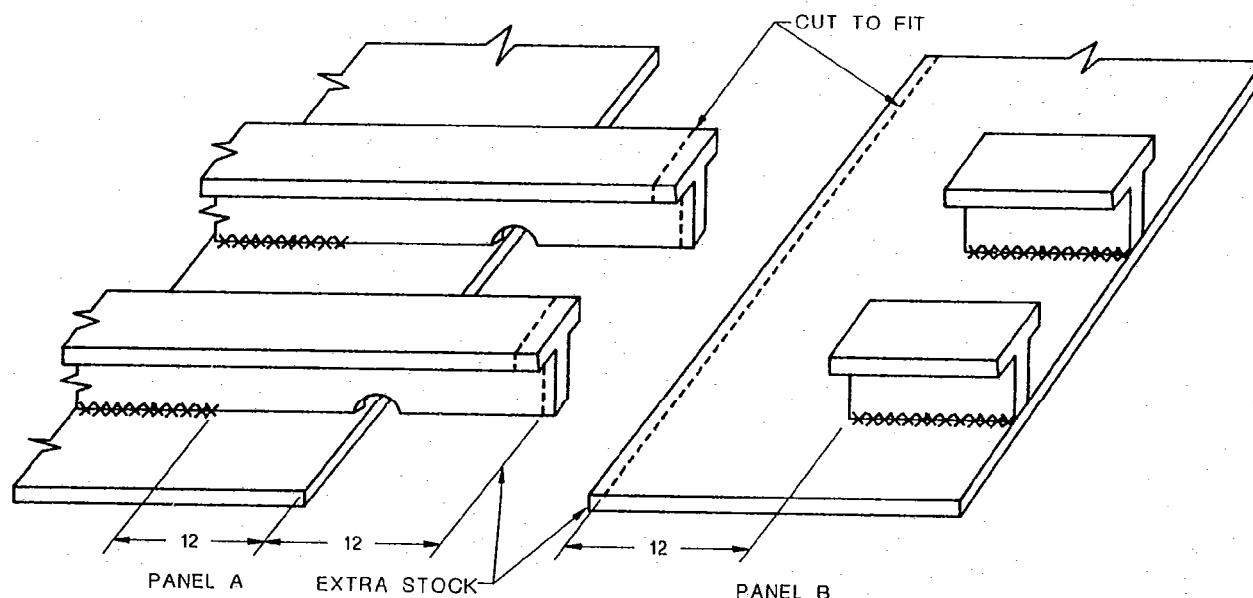
vide for root reinforcement when the weld is to be made from one side only.

Special fibre glass and ceramic backing tapes are commercially available. They are particularly useful and cost effective on nonuniform curved surfaces as well as the groove weld joints (A), (E) and (F) shown in Figure 12.

Permanent backing forms part of the joint and should be made of the same alloy as the base metal. Where the possibility of crevice corrosion exists, permanent backing should be joined to the base metal with continuous fillet welds to prevent moisture entrapment between the two. Disadvantages of permanent backing are increased weight and cost of the structures.

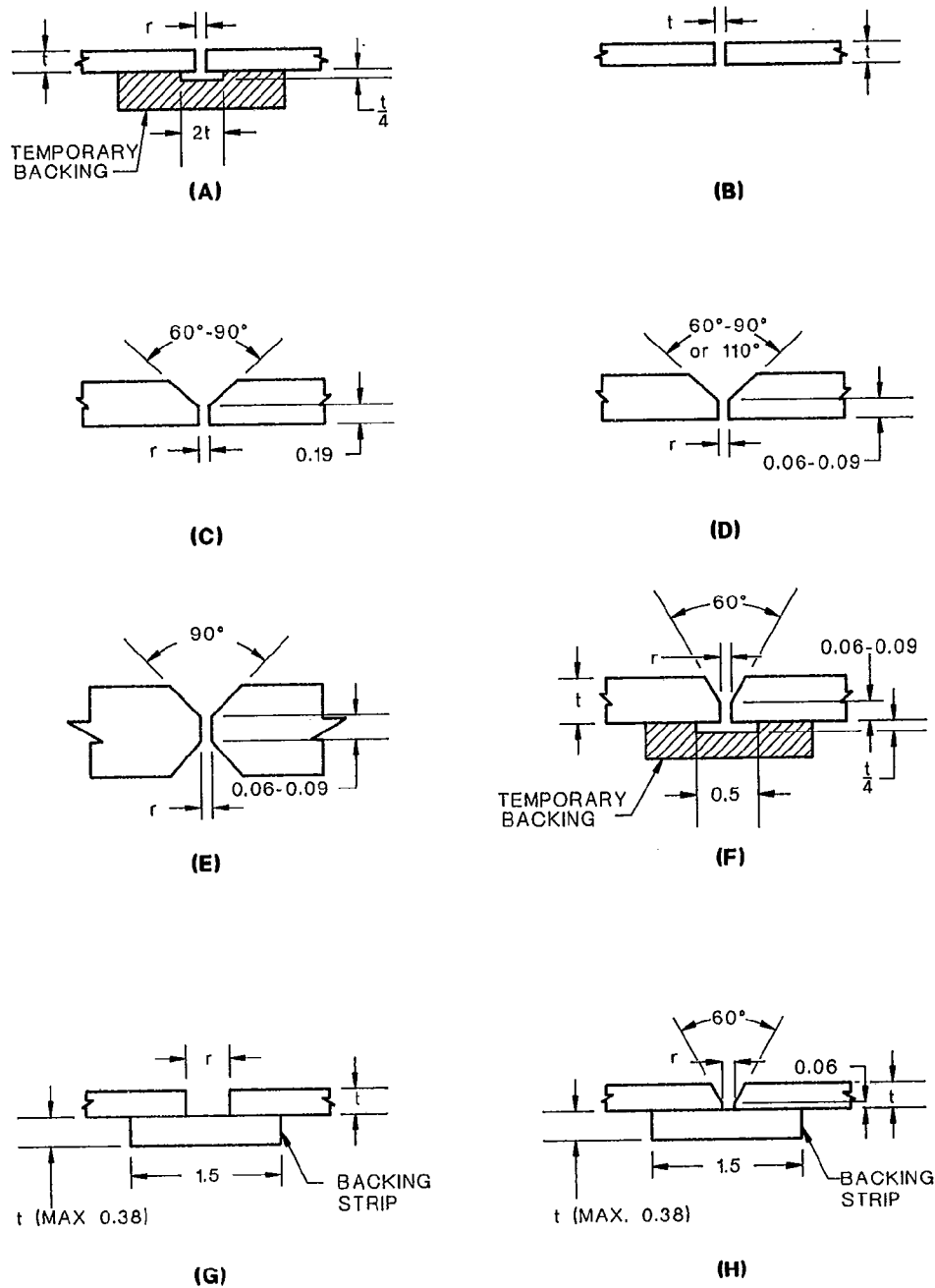
6.4 Butt Joints. Several types of butt joints are used in welded aluminum ship construction. Typical joint designs are shown in Figure 12. Joint designs (C), (D), (E) and (F) should be back-chipped to sound metal before welding the second side.

Typical procedures for gas metal arc welding of butt joints are shown in Table 10, and for gas tungsten arc welding in Table 11. For subassemblies GMA machine-welded in the flat position, square-groove welds are commonly used in thicknesses of 3/16 through 3/8 in. (4.8 through 9.5 mm). For over 3/8 in. (9.5 mm), a 1/8 to 1/4 in. (3.2 to 6.4 mm) bevel is used on each side of the joint to reduce the weld reinforcement.



NOTE: DIMENSIONS ARE IN INCHES

Figure 11 — Design of Master Weld Joints to Provide for Fit-Up in Position



NOTE: DIMENSIONS
ARE IN INCHES.

Figure 12 — Typical Joint Designs for Arc Welding of Aluminum

For semiautomatic GMA welded butt joints, a single V-groove joint with a wide root face is usually preferred. The V-groove is located on the inside of the vessel so that initial welding is done on the inside. Back gouging of the joint can be done on the outside without interference from frames, stiffeners and other obstructions. The second weld is then made on the outside of the vessel.

Automatic or machine welding is preferred to semiautomatic welding because it generally reduces the number of weld passes required and, thus, the distortion. Typical aluminum pipe welding procedures for manual GTAW are given in Tables 12 and 13, and further information and "extended land" bevel joints can be obtained by referring to ANSI/AWS D10.7, *Recommended Practices for Gas Shielded Arc Welding of Aluminum and Aluminum Alloy Pipe*.

Table 14 gives typical procedures for semiautomatic GMA welding of pipe in the horizontal rolled position. Approximate filler metal requirements for typical groove welds in aluminum are given in Appendix B.

6.5 Fillet Welds. Usually, the greatest footage of weld in ship construction consists of fillet welds that are normally employed to attach stiffeners and beams to hull, deck, and bulkhead plates. Fillet welds also are used for attaching bulkheads and for welding all attachments, such as bitts, chocks, handrails, ladders, padeyes, and other fittings, during construction.

Two important factors to consider are the size of the fillet welds¹⁷ and whether the welds are to be intermittent or continuous. Typical fillet weld procedures for gas metal arc welding of aluminum are given in Table 15, and for gas tungsten arc welding in Table 16.

Where intermittent welding is employed, weld craters at ends of beads must be avoided by reversing the direction of welding for a short distance at those points. This is done to avoid crater cracks, which may lead to failure of the weld. However, it is always recommended that the number of arc starts and stops be kept to a minimum for the technique used.

Consideration should be given to the economy of using continuous, double fillet welds rather than in-

termittent fillet welds. All factors should be weighed, including the time required to mark off an intermittent weld pattern, the actual versus theoretical length of weld, the actual versus theoretical size of the fillet weld, the normally larger fillet sizes at the ends of each intermittent weld as a result of starting and stopping and any increased quality requirements. However, double continuous fillet welds may cause greater distortion, particularly in the thinner plates. Filler metal requirements for typical fillet welds in aluminum are given in Appendix B, Figure B11.

Whether economy can be obtained is predicated, to a certain extent, on the specified fillet weld sizes. At present, there is some controversy regarding the proper fillet weld size to use. The U.S. Navy, in some cases, requires fillet weld sizes beyond normal commercial standards. For commercial work, however, the general rule is to use a continuous full fillet weld, the size of which is equal to the thickness of the thinner member joined. Sizes of double fillet welds that fully connect members of a 5000-series marine alloy at right angles are given in Figure 13. Similar data for as-welded 6061-T6 alloy are given in Figure 14. The data are based on the following conditions:

(1) Typical base metal tensile and shear strengths are used.

(2) Weld shear values used are 80% of typical.

(3) Welded connections are intended to be strong enough to force failure to occur in the web rather than in the welds, or in the base metal by shear parallel with the fusion lines of the welds.

Some ship structure designs call for a larger size of fillet weld for a distance of 18 to 24 in. (460 to 610 mm) back from the ends of stiffeners. This is often accomplished with a second weld pass in these areas.

6.6 Plug and Slot Welds. Plug and slot gas metal arc welds are primarily used for attaching plates to decks, as shown in Figure 15. Similar applications could be for doubler plates around sea chests, hatch corner reinforcements, and doubler plates on machine foundations.

Plug and slot welds can pose a problem with gas metal arc welding. The hole or slot should be large enough to properly maneuver the welding gun for complete fusion of the fillet weld placed in the corner of the joint.

Wherever possible, slot welds are recommended over plug welds. The slots should be at least 4 in. (100 mm) long and of sufficient width to permit the welder to obtain good fusion when making the fillet weld pass around the periphery of the slot.

17. The size of a fillet weld with equal legs is the leg length of the largest isosceles right triangle that can be inscribed within the weld cross section. With unequal legs, the weld size is the leg lengths of the largest right triangle that can be inscribed in the weld cross section.

Table 10
Typical Procedures for Gas Metal Arc Welding of Groove Welds in Aluminum Alloys
with Argon Shielding

Section Thickness in.	Welding Position ^a	Joint Geometry ^b	Root (r) Opening in.	No. of Weld Passes	Electrode Diameter in.	Welding Current A	Arc Voltage ^c V	Argon Flow ft ³ /hr	Travel Speed in./min
0.062	F	A	0	1	0.030	70-110	15-20	25	25-45
	F	G	0.094	1	0.030	70-110	15-20	25	25-45
0.094	F	A	0	1	0.030-0.047	90-150	18-22	30	25-45
	F,V,H,O	G	0.125	1	0.030	110-130	18-23	30	23-30
0.125	F,V,H	A	0-0.094	1	0.030-0.047	120-150	20-24	30	24-30
	F,V,H,O	G	0.188	1	0.030-0.047	110-135	19-23	30	18-28
0.188	F,V,H	B	0-0.062	1F,1R	0.030-0.047	130-175	22-26	35	24-30
	F,V,H	F	0-0.062	1	0.047	140-180	23-27	35	24-30
	O	F	0-0.062	2F	0.047	140-175	23-27	60	24-30
	F,V	H	0.094-0.188	2	0.047-0.062	140-185	23-27	35	24-30
	H,O	H	0.188	3	0.047	130-175	23-27	60	25-35
0.250	F	C-60°	0-0.094	2	0.047-0.062	175-200	24-28	40	24-30
	F	F	0-0.094	2	0.047-0.062	185-225	24-29	40	24-30
	V,H	F	0-0.094	3F,1R	0.047	165-190	25-29	45	25-35
	O	F	0.094	3F,1R	0.047-0.062	180-200	25-29	60	25-35
	F,V	H	0.125-0.250	2-3	0.047-0.062	175-225	25-29	40	24-30
	O,H	H	0.250	4-6	0.047-0.062	170-200	25-29	60	25-40
0.375	F	C-90°	0-0.094	1F,1R	0.062	225-290	26-29	50	20-30
	F	F	0-0.094	2F,1R	0.062	210-275	26-29	50	24-35
	V,H	F	0-0.094	3F,1R	0.062	190-220	26-29	55	24-30
	O	F	0-0.094	5F,1R	0.062	200-250	26-29	80	25-40
	F,V	H	0.250-0.375	4	0.062	210-290	26-29	50	24-30
	O,H	H	0.375	8-10	0.062	190-260	26-29	80	25-40
0.750	F	C-60°	0-0.094	3F,1R	0.062-0.094	340-400	26-31	60	14-20
	F	F	0-0.125	4F,1R	0.094	325-375	26-31	60	16-20
	V,H,O	F	0-0.062	8F,1R	0.062	240-300	26-30	80	24-30
	F	E	0-0.062	3F,3R	0.062	270-330	26-30	60	16-24
	V,H,O	E	0-0.062	6F,6R	0.062	230-280	26-30	80	16-24

Note: 5XXX filler alloys will use upper portion of range for current and lower portion of voltage range. 1XXX, 4XXX and 2XXX filler alloys employ the lower portion of the current range, and the upper portion of the voltage range.

a. F – flat; V – vertical; H – horizontal; O – overhead.

b. Refer to Fig. 12.

c. Voltage measured between contact tube and work.

It is not always necessary to fill the entire slot for strength. Where a smooth surface is desired or required to avoid retention of moisture and dirt, the welded slot can be filled flush with a suitable mastic filler.

6.7 Inserts and Doublers. Large openings in the hull or deck, such as hatches, scuttles, elevator shafts and doors, and also load-bearing fittings generally require reinforcement in the form of thicker plate, either as an insert or as a doubler. Generous

radii, *R*, are recommended for inserts and doublers, where applicable, as shown in Figure 16. A V-groove weld should be used to join the deck to the insert. The insert plate should be tapered to the thickness of the deck plate at the joint to avoid stress concentration at the weld. The use of insert plates is preferred to doublers because the stress concentrations inherent in fillet welds are avoided. The peripheral groove weld should have complete joint penetration to uniformly distribute the stress at the transition in plate thickness.

Table 10 — Metric
Typical Procedures for Gas Metal Arc Welding of Groove Welds in Aluminum Alloys
with Argon Shielding

Section Thickness mm	Welding Position ^a	Joint Geometry ^b	Root (r) Opening mm	No. of Weld Passes	Electrode Diameter mm	Welding Current A	Arc Voltage ^c V	Argon Flow L/min	Travel Speed mm/s
1.6	F	A	0	1	0.8	70-110	15-20	12	10.6-19.0
	F	G	2.4	1	0.8	70-110	15-20	12	10.6-19.0
2.4	F	A	0	1	0.8-1.2	90-150	18-22	14	10.6-19.0
	F,V,H,O	G	3.2	1	0.8	110-130	18-23	14	9.7-12.7
3.2	F,V,H	A	0-2.4	1	0.8-1.2	120-150	20-24	14	10.2-12.7
	F,V,H,O	G	4.8	1	0.8-1.2	110-135	19-23	14	7.6-11.8
4.8	F,V,H	B	0-1.6	1F,1R	0.8-1.2	130-175	22-26	17	10.2-12.7
	F,V,H	F	0-1.6	1	1.2	140-180	23-27	17	10.2-12.7
	O	F	0-1.6	2F	1.2	140-175	23-27	28	10.2-12.7
	F,V	H	2.4-4.8	2	1.2-1.6	140-185	23-27	17	10.2-12.7
	H,O	H	4.8	3	1.2	130-175	23-27	28	10.6-14.8
6.4	F	B	0-2.4	2	1.2-1.6	175-200	24-28	19	10.2-12.7
	F	F	0-2.4	2	1.2-1.6	185-225	24-29	19	10.2-12.7
	V,H	F	0-2.4	3F,1R	1.2	165-190	25-29	21	10.6-14.8
	O	F	0-2.4	3F,1R	1.2-1.6	180-200	25-29	28	10.6-14.8
	F,V	H	3.2-6.4	2-3	1.2-1.6	175-225	25-29	19	10.2-12.7
	O,H	H	6.4	4-6	1.2-1.6	170-200	25-29	28	10.6-16.9
9.6	F	C-90°	0-2.4	1F,1R	1.6	225-290	26-29	24	8.5-12.7
	F	F	0-2.4	2F,1R	1.6	210-275	26-29	24	10.2-14.8
	V,H	F	0-2.4	3F,1R	1.6	190-220	26-29	26	10.2-12.7
	O	F	0-2.4	5F,1R	1.6	200-250	26-29	38	10.6-16.9
	F,V	H	6.4-9.6	4	1.6	210-290	26-29	24	10.2-12.7
	O,H	H	9.6	8-10	1.6	190-260	26-29	38	10.6-16.9
19.0	F	C-60°	0-2.4	3F,1R	1.6-2.4	340-400	26-31	28	5.9-8.5
	F	F	0-3.2	4F,1R	2.4	325-375	26-31	28	6.8-8.5
	V,H,O	F	0-1.6	8F,1R	1.6	240-300	26-30	38	10.2-12.7
	F	E	0-1.6	3F,3R	1.6	270-330	26-30	28	6.8-10.2
	V,H,O	E	0-1.6	6F,6R	1.6	230-280	26-30	38	6.8-10.2

a. F – flat; V – vertical; H – horizontal; O – overhead.

b. Refer to Fig. 12.

c. Voltage measured between contact tube and work.

Note: 5XXX filler alloys will use upper portion of range for current and lower portion of voltage range. 1XXX, 4XXX and 2XXX filler alloys employ the lower portion of the current range, and the upper portion of the voltage range.

Doubler plates are normally attached by slot welding. When the doubler has been properly prepared and the faying surface cleaned, it is tack welded in position. Welding progresses, as shown in Figure 15, by first making the slot welds, then any groove welds in the doubler plates, and finally the fillet weld around the edges of the doubled section. The primary purpose of continuously welding the edges to the plate is to eliminate the possibility of crevice corrosion between the doubler and the deck plate.

6.8 Snipes and Scallops. Where snipe-type cuts are permitted in the design, they should be large enough to allow clearance for the welding gun to properly terminate the weld, as shown in Figure 17 (A). Because of the size of the welding gun nozzle for aluminum, the 3/4 in. (19 mm) snipes common in steel construction are too small for aluminum fabrication. Wherever possible, snipes of 1-1/2 in. (38 mm) or larger should be used, depending upon the depth of the member, as shown in Figure 17(B).

Table 11
Typical Procedures for Manual Gas Tungsten Arc Welding of Butt Joints in Aluminum
with AC and Argon Shielding

Section Thickness in.	Welding Position ^a	Joint Geometry ^b	Root (r) Opening in.	No. of Weld Passes	Filler Rod Diameter in.	EW-P Electrode Diameter in.	Welding Current A	Cup Diameter in.	Argon Flow ft ³ /hr	Travel Speed in./min
0.062	F,V,H	B	0-0.062	1	0.062,0.094	0.062,0.094	60-80	0.38	20	8-10
	O	B	0-0.062	1	0.094	0.062	60-75	0.38	25	8-10
0.094	F	B	0-0.094	1	0.125	0.094-0.125	95-115	0.38	20	8-10
	V,H	B	0-0.094	1	0.094,0.125	0.094	85-110	0.38	20	8-10
	O	B	0-0.094	1	0.094,0.125	0.094-0.125	90-110	0.38	25	8-10
0.125	F	B	0-0.125	1-2	0.125,0.156	0.125	125-150	0.44	20	10-12
	V,H	B	0-0.094	1-2	0.125	0.125	110-140	0.44	20	10-12
	O	B	0-0.094	1-2	0.125,0.156	0.125	115-140	0.44	25	10-12
0.188	F	D-60°	0-0.125	2	0.156,0.188	0.156,0.188	170-190	0.44-0.5	25	10-12
	V	D-60°	0-0.094	2	0.156	0.156	160-175	0.44	25	10-12
	H	D-90°	0-0.094	2	0.156	0.156	155-170	0.44	25	10-12
	O	D-110°	0-0.094	2	0.156	0.156	165-180	0.44	30	10-12
0.375	F	D-60°	0-0.125	2	0.188	0.188,0.25	220-275	0.5	30	8-10
	V	D-60°	0-0.094	2	0.188	0.188	200-240	0.5	30	8-10
	H	D-90°	0-0.094	2-3	0.156,0.188	0.156-0.188	190-225	0.5	30	8-10
	O	D-110°	0-0.094	2	0.188	0.188	210-250	0.5	35	8-10
0.38 ^c	F	D-60°	0-0.125	2	0.188,0.25	0.25	315-375	0.63	35	8-10
	F	E	0-0.094	2	0.188,0.25	0.25	340-380	0.63	35	8-10
	V	D-60°	0-0.094	3	0.188	0.188-0.25	260-300	0.63	35	8-10
	V,H,O	E	0-0.094	2	0.188	0.188-0.25	240-300	0.63	35	8-10
	H	D-90°	0-0.094	3	0.188	0.188-0.25	240-300	0.63	35	8-10
	O	D-110°	0-0.094	3	0.188	0.188-0.25	260-300	0.63	40	8-10

a. F – flat; V – vertical; H – horizontal; O – overhead.

b. See Figure 12. Angle dimension is the appropriate groove angle.

c. May be preheated.

6.9 Oil and Water Stops. Liquid-tight welded aluminum bulkheads, along with water, and oil tanks or compartments, require the use of welded stops. These consist of complete joint penetration welds, about 3 in. (76 mm) long, at intersecting members, as shown in Figure 18.

The procedure for positioning and welding of stops in aluminum is similar to that for steel. Their principal purpose is to isolate any leaks in welds that are disclosed during hydrostatic testing of watertight compartments, thus facilitating leak location and repair.

The conventional steel practice of building up rather large weld pads in corners and other locations to avoid leaks has not proved generally effective on aluminum fabrication.

The recommended repair procedure is to chip or

grind out the aluminum weld metal in the leak area, clean and dry the surfaces thoroughly, and reweld. An alternate method is to clean and dry the surfaces, remove the oxide coating, and then remelt the weld metal, preferably using the GTAW method with dcen power. However, the exact nature of the discontinuity is the key factor in selecting the repair procedure and welding method.

6.10 Coamings. Weld joint designs for protective and reinforcement coamings in aluminum hulls and decks vary with specific design details and anticipated service requirements. The designs should be developed as required. A common half-round coaming is frequently attached to the top of the shear strake with a single V-groove weld on top and a fillet weld on the underside. The groove weld is

Table 11 — Metric
Typical Procedures for Manual Gas Tungsten Arc Welding of Butt Joints in Aluminum
with AC and Argon Shielding

Section Thickness mm	Welding Position ^a	Joint Geometry ^b	Root (r) Opening mm	No. of Weld Passes	Filler Rod Diameter mm	EW-P Electrode Diameter mm	Welding Current A	Cup Diameter mm	Argon Flow L/min	Travel Speed mm/s
1.6	F,V,H	B	0-1.6	1	1.6, 2.4	1.6, 2.4	60-80	9.65	9	3.4-4.2
	O	B	0-1.6	1	2.4	1.6	60-75	9.65	12	3.4-4.2
2.4	F	B	0-2.4	1	3.2	2.4, 3.2	95-115	9.65	9	3.4-4.2
	V,H	B	0-2.4	1	2.4, 3.2	2.4	85-110	9.65	9	3.4-4.2
	O	B	0-2.4	1	2.4, 3.2	2.4, 3.2	90-110	9.65	12	3.4-4.2
3.2	F	B	0-3.2	1-2	3.2, 4.0	3.2	125-150	11.18	9	4.2-5.1
	V,H	B	0-2.4	1-2	3.2	3.2	110-140	11.18	9	4.2-5.1
	O	B	0-2.4	1-2	3.2, 4.0	3.2	115-140	11.18	12	4.2-5.1
4.8	F	D-60°	0-3.2	2	4.0, 4.8	4.0, 4.8	170-190	11.18, 12.7	12	4.2-5.1
	V	D-60°	0-2.4	2	4.0	4.0	160-175	11.18	12	4.2-5.1
	H	D-90°	0-2.4	2	4.0	4.0	155-170	11.18	12	4.2-5.1
	O	D-110°	0-2.4	2	4.0	4.0	165-180	11.18	14	4.2-5.1
6.4	F	D-60°	0-3.2	2	4.8	4.8, 6.4	220-275	12.7	14	3.4-4.2
	V	D-60°	0-2.4	2	4.8	4.8	200-240	12.7	14	3.4-4.2
	H	D-90°	0-2.4	2-3	4.0, 4.8	4.0, 4.8	190-225	12.7	14	3.4-4.2
	O	D-110°	0-2.4	2	4.8	4.8	210-250	12.7	17	3.4-4.2
9.6 ^c	F	D-60°	0-3.2	2	4.8, 6.4	6.4	315-375	16.0	17	3.4-4.2
	F	E	0-2.4	2	4.8, 6.4	6.4	340-380	16.0	17	3.4-4.2
	V	D-60°	0-2.4	3	4.8	4.8, 6.4	260-300	16.0	17	3.4-4.2
	V,H,O	E	0-2.4	2	4.8	4.8, 6.4	240-300	16.0	17	3.4-4.2
	H	D-90°	0-2.4	3	4.8	4.8, 6.4	240-300	16.0	17	3.4-4.2
	O	D-110°	0-2.4	3	4.8	4.8, 6.4	260-300	16.0	19	3.4-4.2

a. F – flat; V – vertical; H – horizontal; O – overhead.

b. See Figure 12. Angle dimension is the appropriate groove angle.

c. May be preheated.

usually ground flush to the contour of the coaming piece.

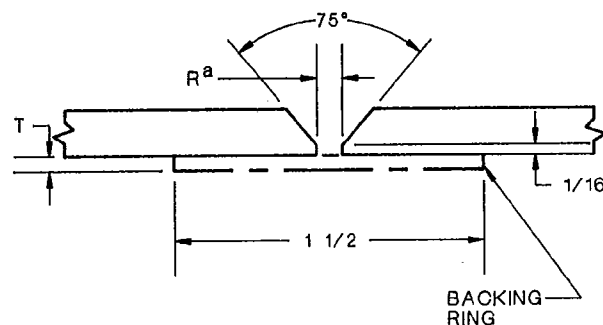
6.11 Avoiding Joint Corrosion. Properly welded joints made in marine aluminum with the correct filler metal are highly corrosion resistant. The aluminum alloys used for marine construction form a tenacious oxide film on their surface that protects the material against the corrosive environment. It is only in the event that this film is constantly removed or disturbed, that progressive oxidation can take place. For this reason, local corrosion should be expected in regions subject to extreme scrubbing action, such as that caused by turbulent flow adjacent to projections from underwater hulls, over rudders and related surfaces. These surfaces should be protected by coatings and these coatings maintained to prevent pitting.

Galvanic corrosion is probably the greatest source of corrosion damage to aluminum structures and should be constantly guarded against by using care in construction and maintenance. The same priority given by the designer to avoiding sharp interior corners, crevices, and other voids during the design and location of structural components should also be extended to welded joints and weld surfaces. Although galvanic corrosion normally occurs when moisture is in contact with two different metals to form an electrical circuit, it also can take place when members of the same alloy are involved, if a moist contaminate includes metallic salts. Good drainage should always be provided.

Smooth, rounded weld beads that are free of incomplete fusion, undercut, overlap and cracks are necessary to avoid crevices that may hold dirt and moisture. Uneven, heavily rippled or dimpled weld

Table 12
Typical Procedures for Gas Tungsten Arc Welding Aluminum Pipe in the Horizontal Rolled Position

TYPICAL PROCEDURES FOR GAS TUNGSTEN
 ARC WELDING ALUMINUM PIPE IN THE HORIZONTAL
 ROLLED POSITION



Nominal Pipe Size in.	Wall Thickness in.	Tungsten Electrode Diameter in.	Gas Nozzle Diameter in.	Welding Rod Diameter in.	Welding Current a.c. A	Argon Flow ft ³ /h	Backing Ring (T) Thickness in.	No. of Passes ^b
1	0.133	1/8	7/16	3/32	100-115	25-40	0.072	1-2
1-1/4	0.140	1/8	7/16	1/8	110-135	25-40	0.072	1-2
1-1/2	0.145	1/8	7/16	1/8	115-140	25-40	0.072	1-2
2	0.154	1/8	7/16	1/8	125-150	25-40	0.093	1-2
2-1/2	0.203	1/8	7/16	1/8	140-180	30-40	0.093	2
3	0.216	1/8	1/2	1/8-5/32	150-190	30-40	0.093	2
3-1/2	0.226	1/8	1/2	1/8-5/32	160-200	30-40	0.093	2
4	0.237	3/16	1/2	1/8-3/16	170-210	30-40	0.125	2
5	0.258	3/16	1/2	5/32-3/16	190-230	30-40	0.125	2
6	0.280	3/16	1/2	5/32-3/16	210-250	35-40	0.187	2
8	0.322	3/16	1/2	5/32-3/16	220-260	35-40	0.187	2-3
10	0.365	3/16	1/2	5/32-3/16	240-280	35-40	0.187	2-3
12	0.406	3/16	1/2	5/32-3/16	250-290	35-40	0.187	2-3

a. $R = 0$ for no backing ring or removable backing ring, 1/4 in. max for integral backing ring.

b. Root opening = 0. More passes are required when $R = 1/4$ in.

beads should be machined flush, repaired or replaced. Avoidance or correction of such potential trouble spots helps eliminate the possibility of crevice entrapment and concentration-cell corrosion.

Wherever weld beads are intermittent and exposed to moisture, frequent or continual entrapment of water occurs. If drainage is not adequate, corrosion is likely to be caused by air- or sea-borne salts dissolved in the water. This corrosion is accelerated because the wet film excludes oxygen from the aluminum surface and prevents formation of the protective aluminum oxide. All weld surfaces and crevices should be protected against moisture entrapment with a suitable joint compound or paint coating, particularly when they are located in the bilge or other confined and generally contaminated areas. In general, butt joints are preferred to lap

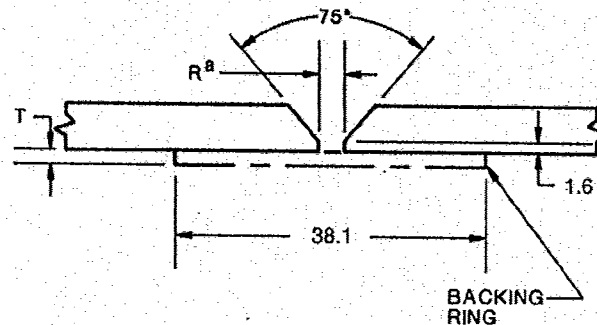
joints to avoid the possibility of crevice corrosion in the lapped area.

6.12 Strongbacks. Aluminum strongbacks of various designs are used to hold large plates, shapes or heavy assemblies, so that the joints remain in alignment during welding. Typical designs are shown in Figure 19. A strongback system employing weld studs is also very effective for use during assembly. Design and placement of strongbacks should be selected to assure adequate allowance for expansion and contraction of the work during production welding. Excessive restraint of transverse weld shrinkage is generally avoided by using an arrangement similar to those shown in Figures 19(A) and 19(B).

Strongbacks are particularly effective in maintaining a flat, smooth surface by preventing vertical

Table 12 — Metric
Typical Procedures for Gas Tungsten Arc Welding Aluminum Pipe in the Horizontal Rolled Position

TYPICAL PROCEDURES FOR GAS TUNGSTEN
 ARC WELDING ALUMINUM PIPE IN THE HORIZONTAL
 ROLLED POSITION



Nominal Pipe Size mm	Wall Thickness mm	Tungsten Electrode Diameter mm	Gas Nozzle Diameter mm	Welding Rod Diameter mm	Welding Current a.c. A	Argon Flow L/min	Backing Ring (T) Thickness mm	No. of Passes ^b
25	3.38	3.2	11.1	2.4	100-115	12-19	1.8	1-2
32	3.55	3.2	11.1	3.2	110-135	12-19	1.8	1-2
38	3.68	3.2	11.1	3.2	115-140	12-19	1.8	1-2
50	3.91	3.2	11.1	3.2	125-150	12-19	2.4	1-2
64	5.16	3.2	11.1	3.2	140-180	14-19	2.4	2
76	5.49	3.2	12.7	3.2-4.0	150-190	14-19	2.4	2
89	5.74	3.2	12.7	3.2-4.0	160-200	14-19	2.4	2
102	6.02	4.8	12.7	3.2-4.8	170-210	14-19	3.2	2
127	6.55	4.8	12.7	4.0-4.8	190-230	14-19	3.2	2
152	7.11	4.8	12.7	4.0-4.8	210-250	17-19	4.8	2
203	8.18	4.8	12.7	4.0-4.8	220-260	17-19	4.8	2-3
254	9.27	4.8	12.7	4.0-4.8	240-280	17-19	4.8	2-3
305	10.31	4.8	12.7	4.0-4.8	250-290	17-19	4.8	2-3

- a. $R = 0$ for no backing ring or removable backing ring, 6.4 mm max for integral backing ring.
 b. Root opening = O . More passes are required when $R = 6.4$ mm.

or angular distortion at groove welds in heavy plate. Sometimes, it is adequate to tack weld one side of the strongback only; the pressure alone exerted on the other plate being sufficient. T-joints can be held in alignment with temporary braces, as shown in Figure 19(D).

Although steel strongbacks are sometimes knocked off with a hammer, this practice is not recommended for aluminum. Aluminum strongbacks should be removed by chipping or other cutting to avoid base metal scarring, which would require repair. Similar holding devices are clips, wedges, and saddles that are used to hold stiffeners to deck sections.

6.13 Clamping. Small clamps, clips, weights, shims, and mechanical, or pneumatic hold-down

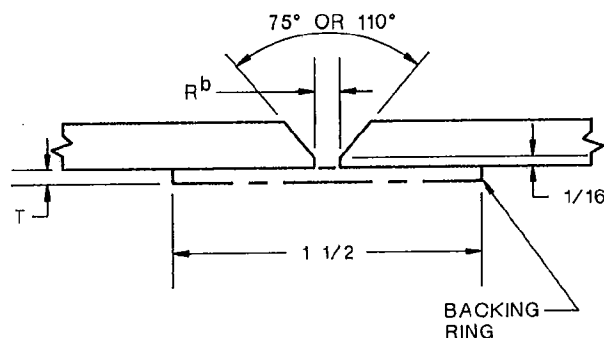
fixtures, ranging in size from hand-held to crane-manipulated, are employed to hold parts in alignment for welding. Piping and railings of all types usually are held for tack welding by standard pipe-alignment clamps.

6.14 Tack Weld Placement and Size. Placement of aluminum tack welds is similar to the practices used for steel ship structures. Tack welding is done by the GMAW or GTAW process. GTAW may be used for tack welding thin sections, and GMAW for thick sections. A qualified production tack welder should make the tack welds.

The tack welds should be of sufficient length and soundness, including tapering the starts and stops, so that they can remain as part of the production weld. Normally, tack welds are 2 to 3 in. (50 to 75

Table 13
Procedures for Gas Tungsten Arc Welding Aluminum Pipe in the Horizontal Fixed Position

PROCEDURES FOR GAS TUNGSTEN ARC
 WELDING ALUMINUM PIPE IN THE HORIZONTAL
 FIXED POSITION



Nominal Pipe Size in.	Wall Thickness in.	Tungsten Electrode Diameter in.	Gas Nozzle Diameter in.	Welding Rod Diameter in.	Welding Current a.c. A	Argon Flow ft ³ /h	Backing Ring (T) Thickness in.	No. of Passes ^c
1	0.133	1/8	1/2	3/32	90-110	30-80	0.072	1-2
1-1/4	0.140	1/8	1/2	1/8	100-120	30-80	0.072	1-2
1-1/2	0.145	1/8	1/2	1/8	110-130	30-80	0.072	1-2
2	0.154	1/8	1/2	1/8	120-140	30-80	0.093	1-2
2-1/2	0.203	1/8	1/2	1/8	130-150	30-80	0.093	2
3	0.216	1/8	1/2	1/8	145-165	30-80	0.093	2
3-1/2	0.226	1/8	1/2	1/8	150-170	30-80	0.093	2
4	0.237	3/16	1/2	1/8-3/16	160-180	35-80	0.125	2
5	0.258	3/16	1/2	5/32-3/16	180-190	35-80	0.125	2
6	0.280	3/16	1/2	5/32-3/16	195-205	50-80	0.187	2
8	0.322	3/16	1/2	5/32-3/16	210-220	50-80	0.187	2-3
10	0.365	3/16	1/2	5/32-3/16	230-240	50-80	0.187	2-3
12	0.406	3/16	1/2	5/32-3/16	245-255	50-80	0.187	2-3

a. 110° angle required on bottom 90° of pipe; can be applied to full 360°.

b. R = 0 for no backing ring or removable backing ring, 1/4 in. max for integral backing ring.

c. Greater number of passes are required for bottom 90° of weld, and when $R \leq 1/4$ in. with integral backing.

mm) long and spaced 4 to 6 in. (100 to 150 mm) apart for sections 3/8 in. (9.5 mm) thick and under, and 3 to 6 in. (75 to 150 mm) long, spaced 6 to 12 in. (150 to 300 mm) apart for thicker sections. However, the number of tack welds used should be the minimum required to maintain joint alignment. Intersecting joints should be tack welded within 12 to 15 in. (300 to 375 mm) of their intersection.

For both fillet and groove welds, it is important to keep tack weld beads as small as possible, consistent with the required tack weld strength. This permits production of sound welds and smooth beads by machine and automatic welding without chipping out the tack welds as welding progresses along the joint.

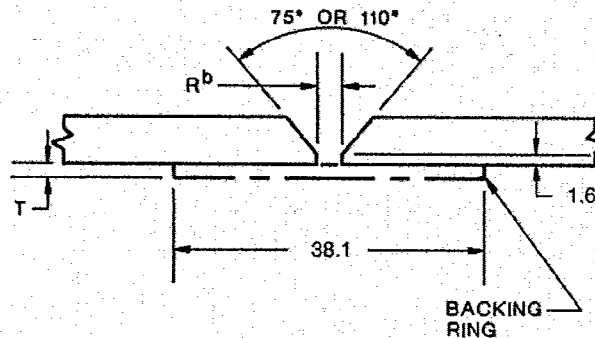
Manual welding of tack welded joints may be accomplished in a similar manner. Tapering or chipping out both ends of tack welds prior to welding is recommended. Tack welds that are cracked, or are otherwise of poor quality, should always be removed or repaired prior to making the weld.

6.15 Residual Welding Stresses and Distortion.

The heat of welding causes expansion and contraction of the base metal and some shrinkage at the joint where the metal has melted and resolidified. The thermal expansion coefficient of aluminum is about twice that of steel, with a melting point of about half that of steel, and the thermal conductivity is greater. The total amount of thermal expansion

Table 13 — Metric
Procedures for Gas Tungsten Arc Welding Aluminum Pipe in the Horizontal Fixed Position

PROCEDURES FOR GAS TUNGSTEN ARC
 WELDING ALUMINUM PIPE IN THE HORIZONTAL
 FIXED POSITION



Nominal Pipe Size mm	Wall Thickness mm	Tungsten Electrode Diameter mm	Gas Nozzle Diameter mm	Welding Rod Diameter mm	Welding Current a.c. A	Argon Flow L/min	Backing Ring (T) Thickness mm	No. of Passes ^c
25	3.38	3.2	12.7	2.4	90-110	14-38	1.8	1-2
32	3.55	3.2	12.7	3.2	100-120	14-38	1.8	1-2
38	3.68	3.2	12.7	3.2	110-130	14-38	1.8	1-2
50	3.91	3.2	12.7	3.2	120-140	14-38	2.4	1-2
64	5.16	3.2	12.7	3.2	130-150	14-38	2.4	2
76	5.49	3.2	12.7	3.2	145-165	14-38	2.4	2
89	5.74	3.2	12.7	3.2	150-170	14-38	2.4	2
102	6.02	4.8	12.7	3.2-4.8	160-180	17-38	3.2	2
127	6.55	4.8	12.7	4.0-4.8	180-190	17-38	3.2	2
152	7.11	4.8	12.7	4.0-4.8	195-205	24-38	4.8	2
203	8.18	4.8	12.7	4.0-4.8	210-220	24-38	4.8	2-3
254	9.27	4.8	12.7	4.0-4.8	230-240	24-38	4.8	2-3
305	10.31	4.8	12.7	4.0-4.8	245-255	24-38	4.8	2-3

a. 110° angle required on bottom 90° of pipe; can be applied to full 360°.

b. R = 0 for no backing ring or removable backing ring, 6.4 mm max for integral backing ring.

c. Greater number of passes are required for bottom 90° of weld, and when $R \leq 6.4$ mm with integral backing.

sion varies inversely with the speed of welding. A rule of thumb is to apply or design the welding fixtures so that plate alignment will accommodate twice the dimensional change normally expected for welding a similar steel component.

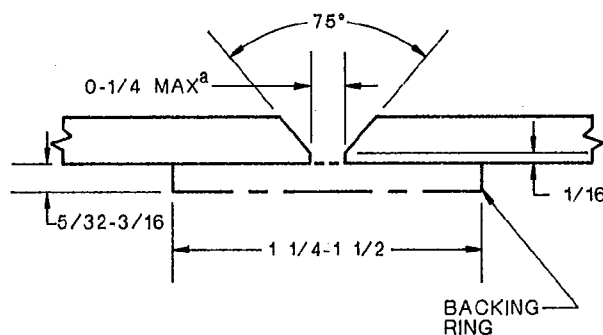
Some shipyards insist that stiffeners be welded to decks and bulkheads in the flat-assembly-bay area using a backstep welding sequence outward from the center of each stiffener, as described later. Where production warrants the investment, shipbuilders employ multiple, machine-mounted welding heads to weld simultaneously all stiffeners to a panel from one end to the other.

Welding of stiffeners to panels causes an overall shrinkage of the center portion of the panel. This frequently causes the periphery of the panel to warp

into large waves, which are most pronounced when the panel is relatively thin. However, attempts to clamp the outer edges to stiffeners are generally unsuccessful, because the warps instantly appear when the clamps are released. However, two adjacent subassembly panels similarly welded will have approximately the same amount of shrinkage within the panel. When these two sections are fitted and welded, the weld shrinkage of the joint compensates to some extent for the excess length at the edges.

The cost of correcting distortion can be significant. Marine aluminum does respond to flame heating with subsequent water quench shrinking, but it should be used only on heavy sections with controlled procedures. Thin sections should not be heat straightened. Some procedures used to remove un-

Table 14
Typical Procedures for Gas Metal Arc Welding Aluminum Pipe in the Horizontal Rolled Position



Nominal Pipe Size in.	Wall Thickness in.	Electrode Diameter in.	Approx. Welding Current, dcep, Amp	Argon Flow ft ³ /h	No. of Passes ^b
4	0.237	3/64	200	45	2
5	0.258	3/64	215	45	2
6	0.280	3/64	225	45	2
8	0.322	1/16	225	50	3
10	0.365	1/16	225	50	3
12	0.406	1/16	250	50	3

a. Root opening = 0 for no backing or removable backing ring, and 1/4 in. for any permanent backing.

b. For root opening = 0. More passes are required when the root opening $\leq 1/4$ in..

wanted distortion in aluminum assemblies include slotting and rewelding, weld-bead overlay, and the welding of additional stiffeners. Such welding techniques used for shrinking metal are quite expensive. Additional stiffeners, that are employed to correct for distortion, increase the weight and cost of the ship needlessly. Prevention of distortion by following controlled procedures and sequence is, of course, much more satisfactory and economical than any correctional procedure.

6.16 Welding Sequence. Planning the optimum welding sequence to minimize distortion and meet specified tolerances varies with the assembly to be welded, the thickness of the base metals, the fixturing and experience available at the shipyard, and the type of welding employed. The goal in making the plan is to minimize distortion of the completed subassembly, hull, or entire ship structure. While no specific formula encompassing all factors and applying to all assemblies is available, the following general practices have proved helpful to many builders.

(1) In large panels consisting of a number of plates, the butt seams should be welded before the panel seams. In that way, the shrinkage caused by

the many smaller joints has taken place prior to final alignment and welding of the long panel seams, as shown in Figures 20 and 21.

(2) Welding of panels constructed of multiple plates should progress from the center toward the outer edges.

(3) Starting at the center of a seam and welding outward with a backstep sequence has proven helpful in specific instances.

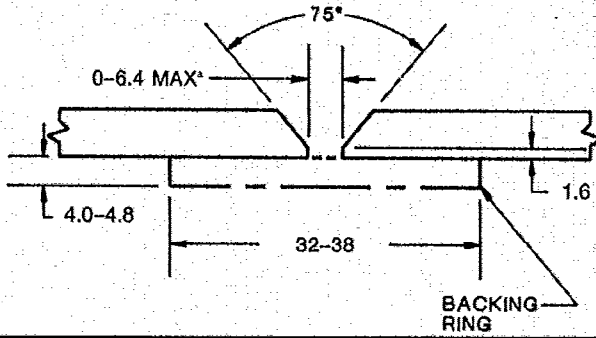
Figure 20 shows the generally accepted welding sequence at the intersection of groove welds in plating.

When the third weld is made in *proper* sequence, the plates on either side are still relatively free to draw together. It is essential for both T- and cross-joints, that the weld be completed at each butt before continuing the welding at the seam, which is perpendicular to the butts.

When the concept shown in Figure 22 is applied to a plate structure, the order of welding is as shown in Figure 20. On a broader scale, the sequence for a staggered butt arrangement takes on an orderly form that is easy to follow, as shown in Figure 21. There are several joints that can be welded at the same time, as indicated by the numbering system.

Figure 23 shows the same basic arrangements as in Figure 20 with the addition of internal framing or

Table 14 — Metric
Typical Procedures for Gas Metal Arc Welding Aluminum Pipe in the Horizontal Rolled Position



Nominal Pipe Size mm	Wall Thickness mm	Electrode Diameter mm	Approx. welding Current, dcep, Amp	Argon Flow L/min	No. of Passes ^b
102	6.02	1.2	200	21	2
127	6.55	1.2	215	21	2
152	7.11	1.2	225	21	2
203	8.18	1.6	225	24	3
254	9.27	1.6	225	24	3
305	10.31	1.6	250	24	3

a. Root opening = 0 for no backing or removable backing ring, and 6.4 mm for any permanent backing.

b. For root opening = 0. More passes are required when the root opening ≤ 6.4 mm.

stiffeners. As mentioned previously, the internal framing and other supports should be welded only to within about 12 in. (300 mm) of panel edges. After the butt joint between the panels is welded, the unwelded portions of the internal structures can be aligned and welded. Figure 24 shows this principle applied to the assembly of large plate panels. If the internal members were first welded completely out to the panel edges, they would offer rather severe restraint to the shrinkage of the tie-in groove welds.

6.17 Angular Distortion. In addition to the linear dimensional changes resulting from the characteristic expansion and contraction of the weld, angular distortion about the weld axis may occur when joining sections that are relatively free to move. The rotation amounts to approximately two degrees per weld pass. Angular distortion can be minimized by symmetrical joint design and welding procedures, welding with minimum heat input, and avoiding deposition of excess filler metal. Angular distortion normally is not a problem when welding relatively large and thick sections, where proper use is made of strongbacks to provide control.

6.18 Interpass Temperature. While the mechanical properties of the 5000 series aluminum alloys are

not so adversely affected by the heat of welding as are those of the heat treatable 6061 alloy, it is always desirable to limit the size of the heat-affected zones. Also, to avoid possible hot cracking of aluminum weld metal, the interpass temperature should be maintained at a level suitable for the specific alloy. Overheated weld metal results in large grain size and high shrinkage stresses.

A generally observed rule is not to exceed an interpass temperature of 150°F (66°C); the weld should be cool enough to touch briefly with the hand. Out-of-position welds, particularly, are apt to be of poor quality if the interpass temperature exceeds 150°F (66°C). Typical aluminum alloys used for marine application are also subject to corrosion through exfoliation, when heated long enough in the sensitizing range of 200-500°F (93-260°C).

6.19 Welding Stress Relief. As previously pointed out, the best method of controlling welding stresses is through the use of the appropriate welding process, welding conditions, filler metal, weld sequence for the particular section thickness, joint design, and assembly sequence. Residual stresses in welded assemblies can be as high as the yield strength of the metal when consideration is not given to the above.

Post heating at a temperature of 450° to 525°F

Table 15
Typical Procedures for Gas Metal Arc Welding of Fillet Welds in Aluminum Alloys with Argon Shielding

Section Thickness in.	Welding Position ^a	No. of Passes ^b	Electrode Diameter in.	Welding Current dcep A	Arc Voltage V	Argon Flow ft ³ /h	Travel Speed in./min
0.094	F,V,H,O	1	0.030	100-130	18-22	30	24-30
0.125	F	1	0.030-0.047	125-150	20-24	30	24-30
	V,H	1	0.030	110-130	19-23	30	24-30
	O	1	0.030-0.047	115-150	20-24	40	24-40
0.188	F	1	0.047	180-210	22-26	30	24-30
	V,H	1	0.030-0.047	130-175	21-25	35	24-30
	O	1	0.030-0.047	130-190	22-26	45	24-30
0.250	F	1	0.047-0.062	170-240	24-28	40	24-30
	V,H	1	0.047	170-210	23-27	45	24-30
	O	1	0.047-0.062	190-220	24-28	60	24-30
0.375	F	1	0.062	240-300	26-29	50	18-25
	H,V	3	0.062	190-240	24-27	60	24-30
	O	3	0.062	200-240	25-28	85	24-30
0.750	F	4	0.094	360-380	26-30	60	18-25
	H,V	4-6	0.062	260-310	25-29	70	24-30
	O	10	0.062	275-310	25-29	85	24-30

Note: 5XXX filler alloys will use upper portion of range for current, and lower portion of voltage range. 1XXX, 4XXX, and 2XXX filler alloys employ the lower portion of the current range, and the upper portion of the voltage range.

a. F – flat; V – vertical; H – horizontal; O – overhead.

b. Number of weld passes for minimum leg size fillet weld only.

(232° to 274°C) will materially reduce the residual welding stresses with little reduction in the strength of wrought 5000 series alloys. As stated previously, alloys that contain 3% or more of magnesium should not be heated for extended periods of time because they may become sensitized to stress and exfoliation corrosion. Therefore, the total heating time for such alloys should not exceed about 30 minutes.

Thermal stress relief methods for heat treatable alloys, such as 6061-T6, generally result in as much or greater decrease in mechanical properties as in the residual stress levels. Therefore, thermal stress relief is used only when a heat treatable alloy weldment can subsequently be solution treated and aged to restore mechanical properties. The manufacturer's recommendation for thermal treatment should be followed.

Mechanical peening of weld metal is often preferred over thermal stress relief to effect limited redistribution of weld stresses. Peening may be accomplished by shot peening with a multiple-point peening gun or with specially designed flapper

wheels. Generally, the depth of cold work by shot peening is greater than that obtainable with a multiple-point gun. Peening of aluminum weld metal should not be attempted, however, until careful inspection has revealed no surface weld defects, such as incomplete fusion or cracks. Such defects could be covered-up by the peening operation and thus left undetected.

6.20 Inspection of Welds

6.20.1 Visual. Visual inspection of aluminum welds is the first and most important quality control procedure. Inspectors should be well versed in aluminum welding so that they can properly evaluate the appearance of welds. Considerations relative to visual inspection are as follows:

(1) Groove weld beads should be smooth and properly contoured, with a minimum amount of undercut as allowed by the design agency.

(2) Welds may exhibit some surface porosity, but the presence of large or gross surface porosity usually is cause for rejection.

Table 15 — Metric
Typical Procedures for Gas Metal Arc Welding of Fillet Welds in Aluminum Alloys with Argon Shielding

Section Thickness mm	Welding Position ^a	No. of Passes ^b	Electrode Diameter mm	Welding Current DCEP A	Arc Voltage V	Argon Flow L/min	Travel Speed mm/min
2.4	F,V,H,O	1	0.8	00-130	18-22	14	10.2-12.7
3.2	F	1	0.8-1.2	125-150	20-24	14	10.2-12.7
	V,H	1	0.8	110-130	19-23	14	10.2-12.7
	O	1	0.8-1.2	115-150	20-24	19	10.2-16.9
4.8	F	1	1.2	180-210	22-26	14	10.2-12.7
	V,H	1	0.8-1.2	130-175	21-25	17	10.2-12.7
	O	1	0.8-1.2	130-190	22-26	21	10.2-12.7
6.4	F	1	1.2-1.6	170-240	24-28	19	10.2-12.7
	V,H	1	1.2	170-210	23-27	21	10.2-12.7
	O	1	1.2-1.6	190-220	24-28	28	10.1-12.7
9.6	F	1	1.6	240-300	26-29	24	7.6-10.6
	H,V	3	1.6	190-240	24-27	28	10.2-12.7
	O	3	1.6	200-240	25-28	40	10.2-12.7
19.0 ^c	F	4	2.4	360-380	26-30	28	7.6-10.6
	H,V	4-6	1.6	260-310	25-29	33	10.2-12.7
	O	10	1.6	275-310	25-29	40	10.2-12.7

a. F – flat; V – vertical; H – horizontal; O – overhead.

b. Number of weld passes for minimum leg size fillet weld only.

(3) Excessive melt-through, overlap, incomplete fusion, and visible inclusions are obvious defects.

(4) Crater cracks in any location, including tack welds, root passes of welds, and at starts and stops of final production welds, are defects.

Inspectors should use a low-power (3X) magnifying glass to aid in visual examination of doubtful weld areas.

6.20.2 Radiographic. One of the better methods of determining weld quality is radiographic inspection. However, because some cracks and incomplete fusion may escape detection due to the relative positions of the defect and the X-ray source, inspection requires professional radiographers and interpretation. Industry-wide radiographic standards of aluminum weld quality have been established for commercial marine work. For example, radiographs made in accordance with *ABS Rules for Nondestructive Inspection of Hull Welds*, which show any of the following discontinuities, indicate unacceptable welds that need to be repaired:

- (1) Any type of crack
- (2) Incomplete fusion exceeding allowable lengths or aggregate amount per unit length of weld

(3) Incomplete penetration exceeding allowable lengths or aggregate amounts per unit length of weld

(4) Porosity or tungsten inclusions exceeding the amounts indicated in the applicable construction standard

The amount of radiography required on a vessel is determined by the contract, the judgment of the fabricator, or both.

Low kilovoltage (150 kV) portable X-ray equipment is readily available from a number of manufacturers. Generally, radioisotope sources are not used on aluminum because the film image of discontinuities lacks contrast, compared with that obtainable with an X-ray machine. This makes detection of discontinuities more difficult. The isotopes Ytterbium 160 and Iridium 192 are used on aluminum for specific applications. The latter is particularly useful for aluminum thicknesses above 3 in. (76 mm), which is a practical maximum for 150 kV X-ray machines.

6.20.3 Ultrasonic. Ultrasonic inspection may be used on aluminum and is particularly advantageous for detecting cracks and incomplete fusion. Its adoption and use normally require initial justifica-

Table 16
Typical Procedures for Manual Gas Tungsten Arc Welding of Fillet Welds in Aluminum
with AC and Argon Shielding

Section Thickness in.	Welding Position ^a	No. of Weld Passes	Filler Rod Diameter in.	EW-P Electrode Diameter in.	Welding Current A	Gas Cup Diameter in.	Argon Flow ft ³ /h	Travel Speed in./min
0.062	F,H,V	1	0.062,0.094	0.062-0.094	70-110	0.38	16	8-10
	O	1	0.062,0.094	0.062-0.094	65-90	0.38	20	8-10
0.094	F	1	0.094,0.125	0.125-0.156	110-145	0.38	18	8-10
	H,V	1	0.094	0.094-0.125	90-125	0.38	18	8-10
	O	1	0.094	0.094-0.125	110-135	0.38	20	8-10
0.125	F	1	0.125	0.125-0.156	135-175	0.44	20	10-12
	H,V	1	0.125	0.094-0.125	115-145	0.38	20	8-10
	O	1	0.125	0.094-0.125	125-155	0.44	25	8-10
0.188	F	1	0.156	0.156-0.188	190-245	0.5	25	8-10
	H,V	1	0.156	0.156-0.188	175-210	0.5	25	8-10
	O	1	0.156	0.156-0.188	185-225	0.5	30	8-10
0.250	F	1	0.188	0.188-0.25	240-295	0.5	30	8-10
	H,V	1	0.188	0.188	220-265	0.5	30	8-10
	O	1	0.188	0.188	230-275	0.5	35	8-10
0.375 ^b	F	2	0.188	0.25	325-375	0.63	35	8-10
	V	2	0.188	0.188-0.25	280-315	0.63	35	8-10
	H	3	0.188	0.188-0.25	270-300	0.63	35	8-10
	O	3	0.188	0.188-0.25	290-335	0.63	40	8-10

a. F – flat; H – horizontal; V – vertical; O – overhead.

b. May be preheated.

tion for a specific job by X-ray and, perhaps, metallographic sectioning.

6.20.4 Penetrant. Dye-penetrant or fluorescent-penetrant inspection may be used after welding is completed. However, it is not recommended on castings or unfinished weld joints where subsequent welding may be done. This is due to the difficulty of removing the penetrant solution from pores and crevices. Subsequent weld passes on such contaminated surfaces are likely to have excessive porosity caused by hydrocarbons in the residual dye, moisture, or by both. If used for final inspection, the entire surface that was inspected should be thoroughly cleaned of residual dye before any repair welding is attempted.

6.21 Repair of Welds. Repairing of welds can be time consuming if not done properly. It is vitally important to accurately determine the nature and exact location of a defect as indicated by X-ray or other means of inspection. The most important de-

cision on a butt joint is to determine the side of the weld that the defect is nearest to. Ultrasonic and angulation X-ray inspection techniques can assist in locating a defect more precisely.

The normal method of metal removal is with a chipping gun. The operator should remove defective metal until sound metal is reached. A split chip is indicative of incomplete fusion. High levels of porosity are easily detected when sharp knife-edged chisels are used.

Primary problems with chipping as a means of weld-metal removal for repair welding are the following:

- (1) Failure to follow the weld seam
- (2) Failure to remove all defective material to the proper depth
- (3) Chipping a narrow, deep groove that makes production of a sound repair weld difficult

Metal can also be removed by some high-speed milling tools, such as routers, or proprietary equipment, such as hand-held milling tools. A principal drawback with the use of this type of equipment is

Table 16 — Metric
Typical Procedures for Manual Gas Tungsten Arc Welding of Fillet Welds in Aluminum
with AC and Argon Shielding

Section Thickness mm	Welding Position ^a	No. of Weld Passes	Filler Rod Diameter mm	EW-P Electrode Diameter mm	Welding Current A	Gas Cup Diameter mm	Argon Flow L/min	Travel Speed mm/s
1.6	F,H,V O	1	1.6, 2.4	1.6, 2.4	70-110	9.6	8	3.4-4.2
		1	1.6, 2.4	1.6, 2.4	65-90	9.6	9	3.4-4.2
2.4	F	1	2.4, 3.2	3.2-4.0	110-145	9.6	8	3.4-4.2
	H,V	1	2.4	2.4-3.2	90-125	9.6	8	3.4-4.2
	O	1	2.4	2.4-3.2	110-135	9.6	9	3.4-4.2
3.2	F	1	3.2	3.2-4.0	135-175	11.2	9	4.2-5.1
	H,V	1	3.2	2.4-3.2	115-145	9.6	9	3.4-4.2
	O	1	3.2	2.4-3.2	125-155	11.2	12	3.4-4.2
4.8	F	1	4.0	4.0-4.8	190-245	12.7	12	3.4-4.2
	H,V	1	4.0	4.0-4.8	175-210	12.7	12	3.4-4.2
	O	1	4.0	4.0-4.8	185-225	12.7	14	3.4-4.2
6.4	F	1	4.8	4.8-6.4	240-295	12.7	14	3.4-4.2
	H,V	1	4.8	4.8	220-265	12.7	14	3.4-4.2
	O	1	4.8	4.8	230-275	12.7	17	3.4-4.2
9.6	F	2	4.8	6.4	325-375	16.0	17	3.4-4.2
	V	2	4.8	4.8-6.4	280-315	16.0	17	3.4-4.2
	H	3	4.8	4.8-6.4	270-300	16.0	17	3.4-4.2
	O	3	4.8	4.8-6.4	290-335	16.0	19	3.4-4.2

a. F – flat; H – horizontal; V – vertical; O – overhead.

b. May be preheated.

guiding a high-speed tool so that it follows the weld seam. Also, it should be adjusted so that the depth of cut reaches sound material. An additional problem is that it is impractical to examine chips or grindings visually to determine whether the joint has been cleaned to sound metal. Inspection of a milled surface for defects may be difficult because the cutter may produce a “finish” or relatively fine cutting pattern. A technique gaining acceptance to remove defective welds is plasma arc gouging.

Grooves should taper gradually to the surface at both ends, with a generous radius at the bottom of the excavation. Incomplete fusion may occur at these locations if the taper is too steep.

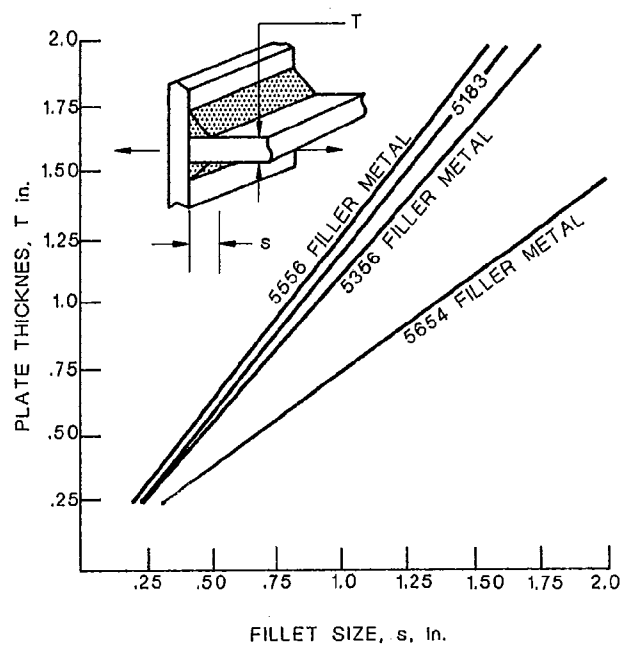
Cleaning joints prior to repair welding is important. Care should be taken while using chemical cleaners and deoxidizers so that the liquid is not trapped within the joint itself. After a welded joint has been chipped or milled for repair, it is desirable to weld the repair area during the same working day to avoid the entrapment of debris, dust, and moisture. In some instances, it is practical to temporarily cover the joint with a nonresidue-leaving tape in or-

der to exclude debris. Scheduling can also be helpful, like welding the top side of groove welds and longitudinals first to minimize dirt entrapment.

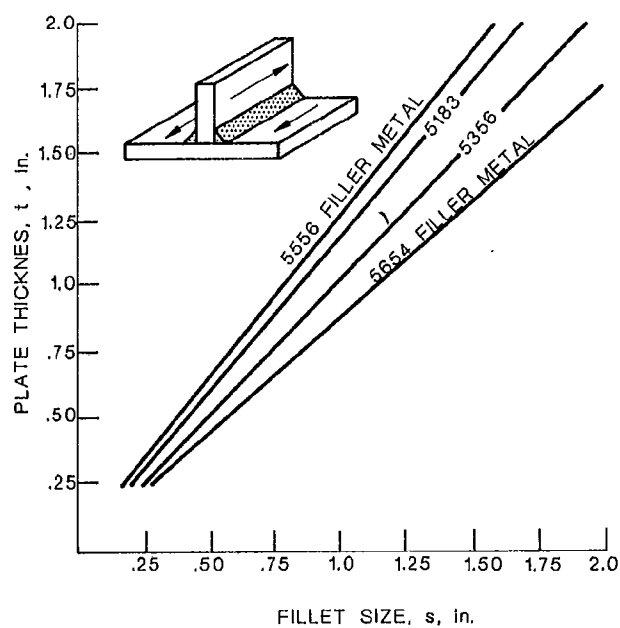
Two critical conditions that may be encountered in repair welding are incomplete fusion at the start of the repair weld, and an unacceptable crater condition at the end of a short repair weld bead. These can be readily prevented by using starting and stopping wedges at the ends of the area to be repaired, as shown in Figure 25. The wedge blocks are cut off after welding, and the face of the weld dressed to match the remainder of the weld.

In the case of fillet welds, the necessity for repair is generally determined by visual inspection. Usually, defective fillet welds contain cracks, undercut, overlap or insufficient weld metal. Cracks and overlaps should be chipped out, and the joint rewelded and reexamined. Undercutting and deficient weld metal frequently can be repaired by depositing one or more weld beads in the defective area.

Doing it right the first time is most important with aluminum alloys because of the difficulty in making sound repairs.

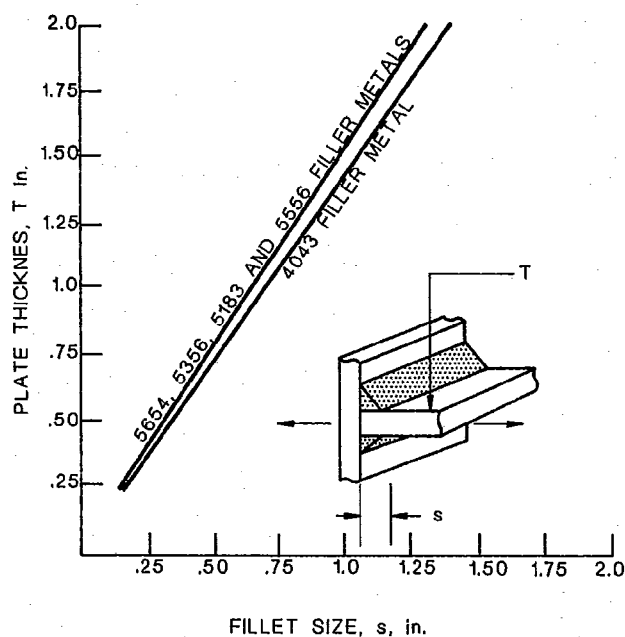
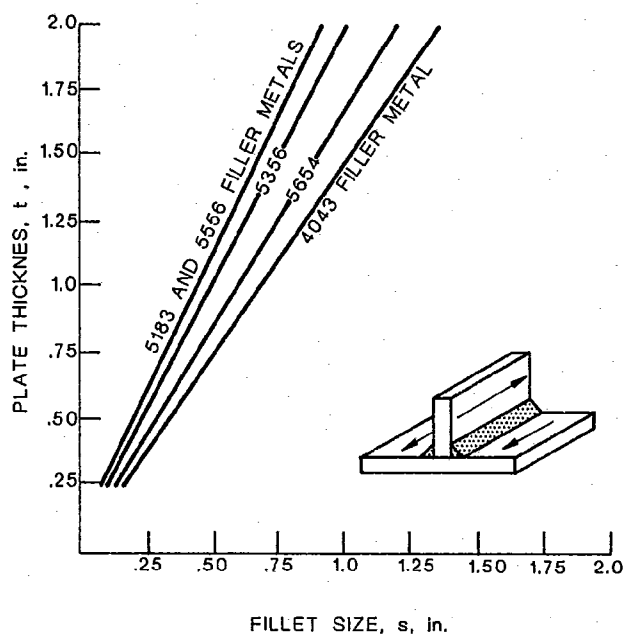


(A) LOADING IN TRANSVERSE SHEAR



(B) LOADING IN LONGITUDINAL SHEAR

Figure 13 — Sizes of Double Fillet Welds to Fully Connect As-Welded 5086-H116 Members at Right Angles

**(A) LOADING IN TRANSVERSE SHEAR****(B) LOADING IN LONGITUDINAL SHEAR****Figure 14 — Size of Double Fillet Welds to Fully Connect As-Welded 6061-T6 Members at Right Angles**

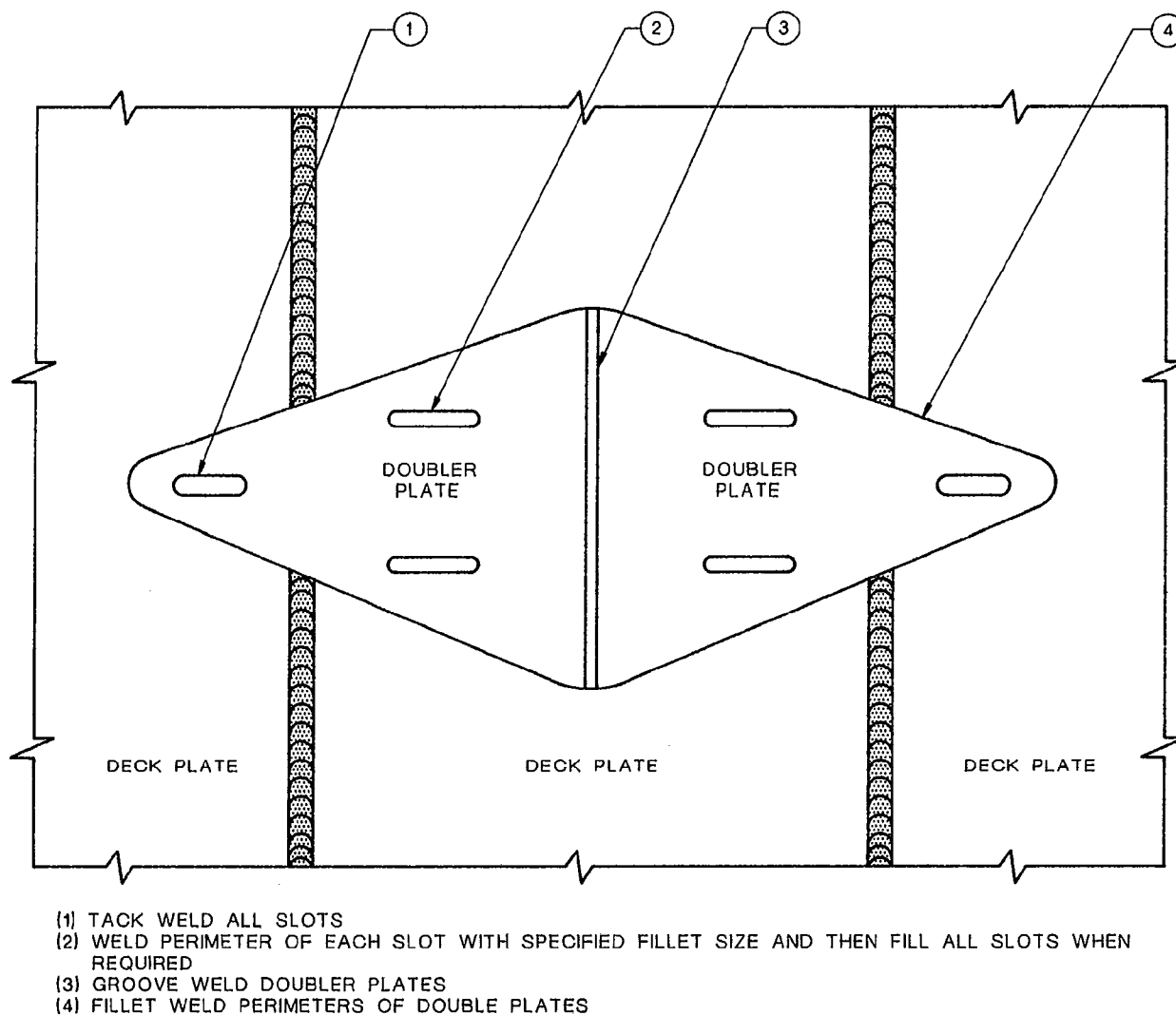


Figure 15 — Welding Sequence for Large Doubler Plate

All weld repair in aluminum requires completely clean surfaces free of oil, grease, thick oxide film, and imbedded particles of any type. Either GMAW or GTAW is suitable for weld repairs. When welding on hull plates below the waterline, preheat or high welding heat input is necessary to compensate for the chilling effect of the water.

6.22 Metal Straightening. Straightening of aluminum plates or other members using spot heating with oxyfuel gas torches followed by quick water

spray quenching (as is used with steel) is not generally recommended. However, metal straightening, when rigidly controlled, can be used successfully on heavier thicknesses. For welded seams that are too badly out of fair, one commonly used straightening method is to cut the seams apart. Strongbacks are applied to pull the metal out past fair. The seams are then rewelded with a balanced sequence, so that the resulting joint is straight. Excessive distortion sometimes occurs at the intersection of four welds at a common point, as intersecting groove welds.

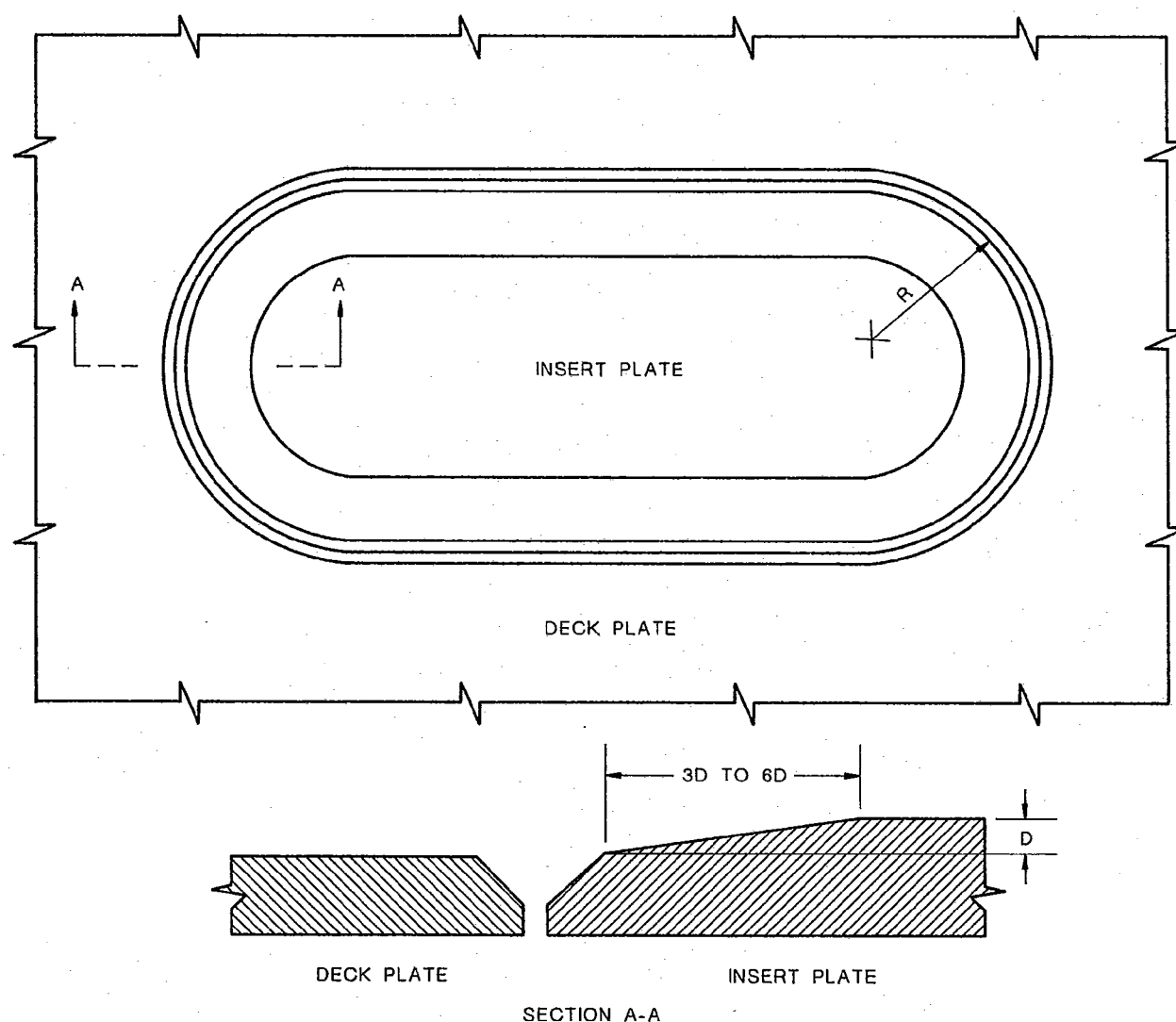


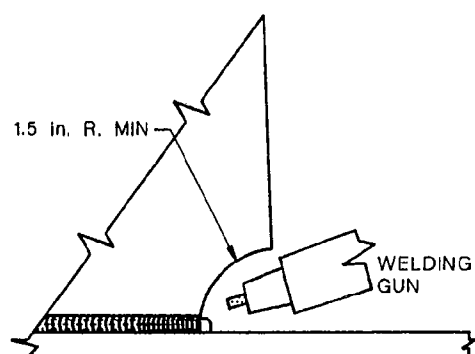
Figure 16 — General Design of an Insert Plate

For welded assemblies, deck or other panel structures of thick plate, where an unbalanced welding procedure has caused bowing or local warping of members, straightening may be effected by placing additional weld beads on the concave side of the member. An example is shown in Figure 26. The specific weld bead pattern and welding sequence to be used should be established by tests.

6.23 Repair Welding of Aluminum Hulls. Virtually any part of an aluminum hull or other ship struc-

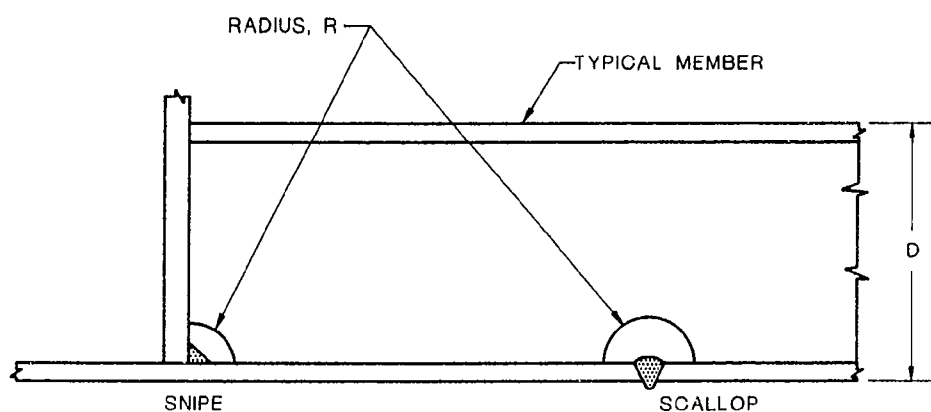
ture, which can be freed of oil and moisture, can be repaired by welding at dockside. Proper grounding of welding equipment is essential to protect the hull from greatly accelerated electrolytic corrosion during welding, particularly when the craft is in salt water. Recommended welding machine grounding is discussed later.

Relatively large damaged panels or sections can be cut out easily and replaced because the light weight of aluminum permits handling of large prefabricated components with conventional dock



RADIUS SNIPE ALLOWS ACCESS
FOR GUN TO COMPLETE WELD WITHOUT
CRATER FORMATION

(A)



DEPTH OF MEMBER, D, in.	RADIUS, R, in.
LESS THAN 6 (152mm)	1.5 (38mm)
6 TO 9 (152 TO 229mm)	2 (51mm)
GREATER THAN 9 (229mm)	3 (76mm)

(B)

Figure 17 — Proper Design of Snipes and Scallop

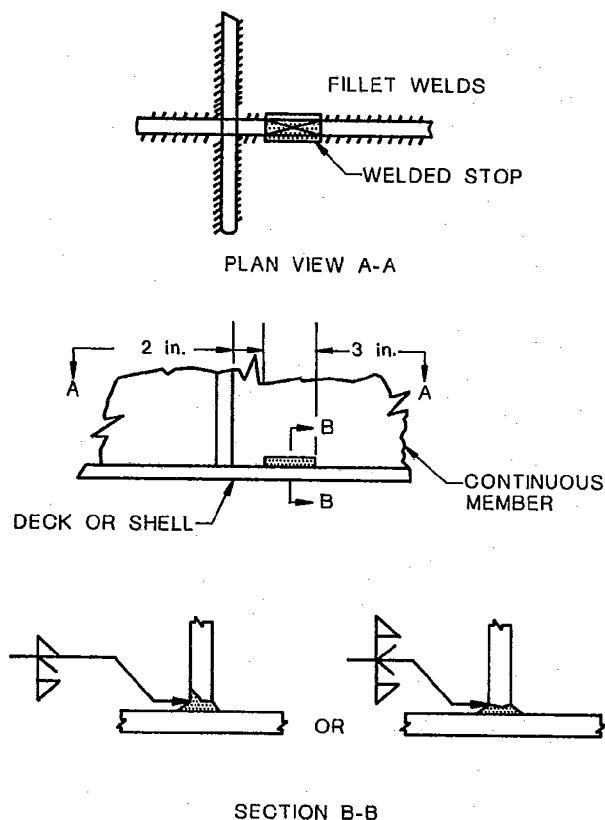


Figure 18 — Welded Oil or Water Stop at Intersecting Members

cranes and trucks. The alloy composition of the aluminum sections to be repaired or replaced should be determined, if practical. However, the 5000 series marine alloys are so universally employed for aluminum hulls that it is likely the alloy in question is one of these. Also, one of the commonly used filler metals for this series, such as 5356, may be used. This filler metal also may be used for welding 6061 alloy. However, use of the correct filler metal to produce optimum weld properties is always recommended where the composition of the base metal is known or can be determined. Either the GTAW or GMAW process may be used.

Proper preparation of aluminum surfaces to be repair-welded is essential. The principal steps to be taken are as follows:

- (1) The damaged sections of all components should be removed.
- (2) The original weld metal in new weld areas should be removed to provide the correct plate edge shape and contour.
- (3) Patches and reinforcements should be fabricated and formed to obtain proper close fit-up.

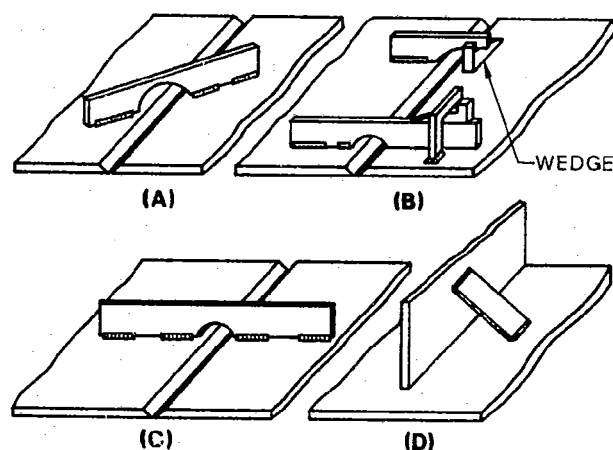


Figure 19 — Typical Strongbacks for Maintaining Alignment During Welding

- (4) All weld joint surfaces should be solvent cleaned, filed, and brushed.
- (5) All surfaces in the weld area should be dried.
- (6) The patch should be positioned and clamped for tack welding.
- (7) The patch should be tack welded in place.
- (8) Tack welds should be chipped out as required.
- (9) The proper weld sequence should be followed to minimize residual stress.

All permanent boatyard repairs should be equivalent to the original construction. For extensive repairs, original specification and "as built" drawings should be obtained from the builder by the repair yard.

Repairs of cracks or other defects in a weld are made by chipping out the defective weld to sound metal and repair welding, as described previously. If seams in watertight compartments are improperly repaired, unfused areas within the weld metal are likely to cause leakage over a period of time.

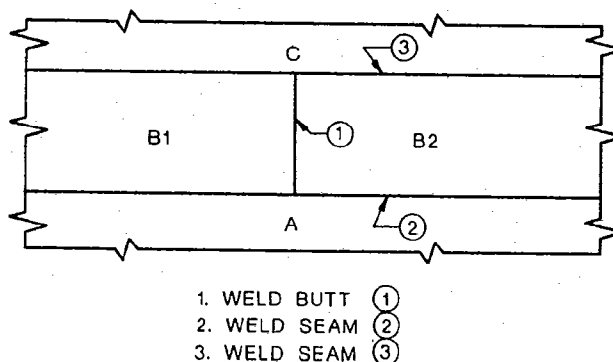


Figure 20 — Welding Sequence for Plate Butt and Adjacent Seams

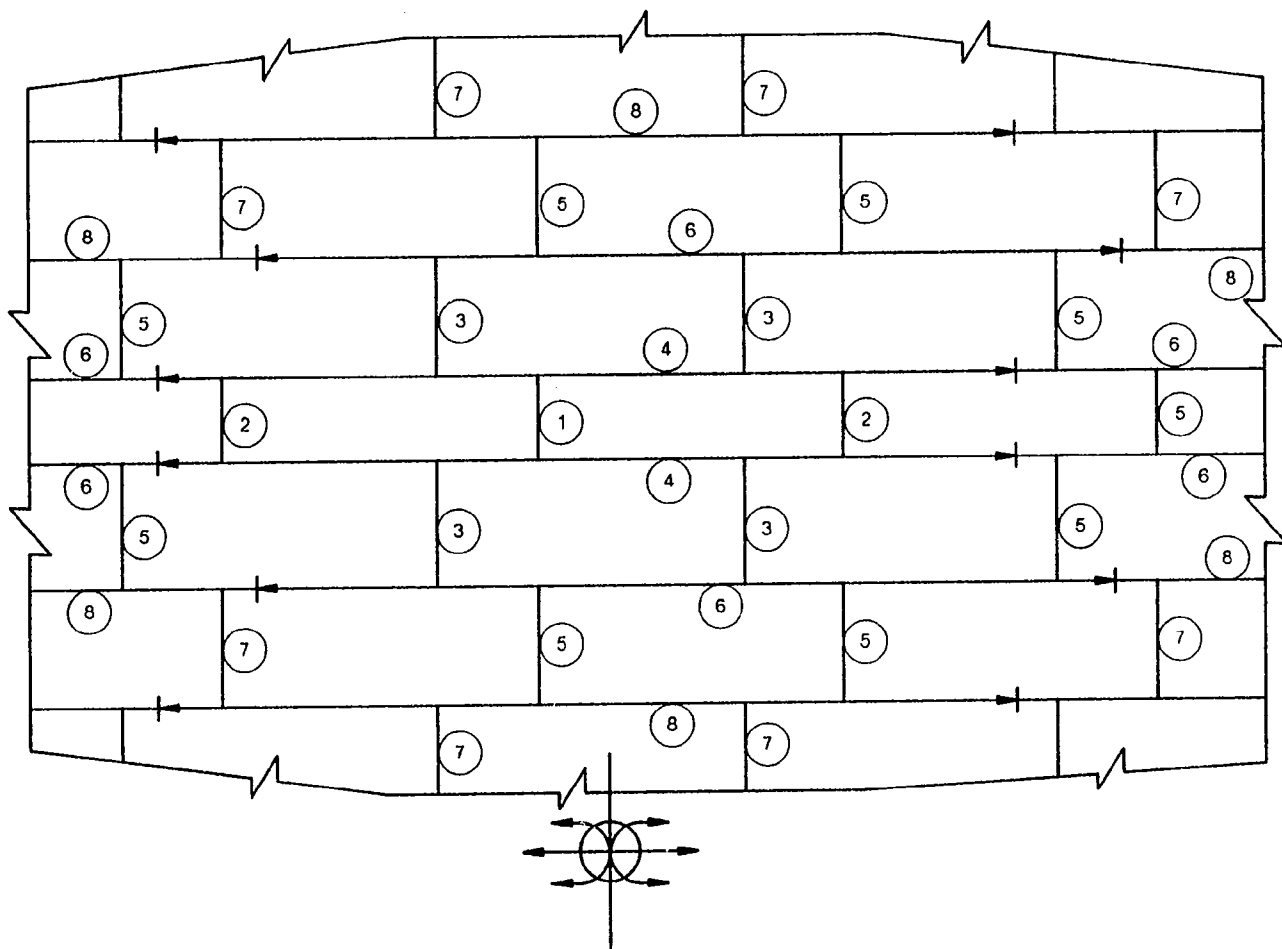
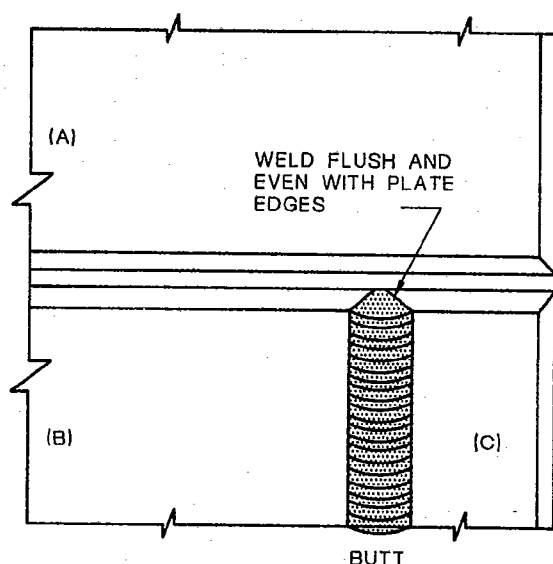


Figure 21 — Typical Welding Sequence for Plate Butts and Seams where Butts are Staggered

Small cracks can develop at the sites of such internal voids. Welding over defects should be avoided, as cracks can propagate from these areas.

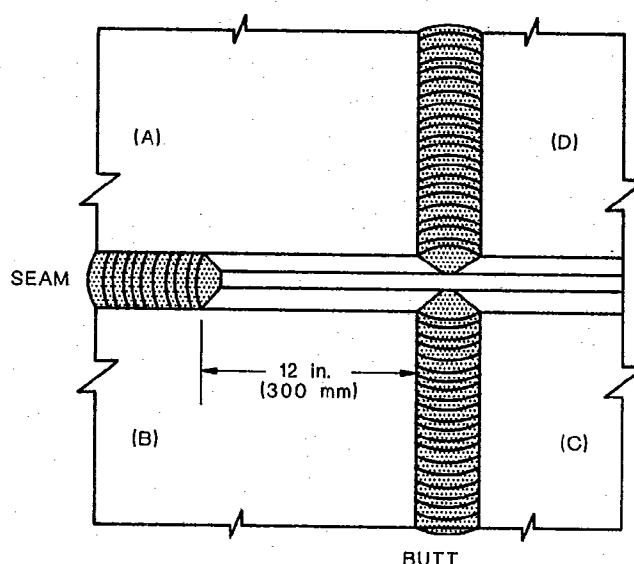
Where damage is encountered or extensive repairs are required, replacement of entire panels or a larger section than that actually affected is recommended. Such sections may be removed with plasma arc cutting or with a sabre saw, leaving large-radius corners. Edges of the opening end of

new cut-to-size sections are prepared according to the thickness of the joint and welding processes to be used. If the plate thickness of the patch is greater than the original plate, all edges should be tapered to the thickness of the adjacent plate (see Figure 16). The patch or insert should be welded in place from both sides, if possible. If not, full penetration welds should be made using removable or permanent backing.



1. WELD BUTT BETWEEN (B) AND (C)
2. WELD SEAM

(A) STAGGERED BUTTS



1. WELD SEAM BETWEEN (A) AND (B) TO WITHIN 12 in. (300mm) OF BUTT JOINT
2. WELD BUTT BETWEEN (B) AND (C)
3. WELD BUTT BETWEEN (A) AND (D)
4. COMPLETE WELDING SEAM

(B) ALIGNED BUTTS

Figure 22 — Welding Sequence at the Intersection of Plate Butts and Seams

When it is necessary to weld sections under the restrained conditions usually encountered in repair jobs, the sequence should be similar to that shown in Figure 27. All adjacent seams in the existing structure should be cut back about 12 in. (300 mm) from the opening to prevent or reduce restraint. Likewise, the framing of the old structure should be released for a distance of about 12 in. (300 mm) from the opening. Welds should not be started or stopped at a corner.

Relatively minor cracks in base metal may be repaired by welding. Chipping to remove the crack prior to welding is recommended in all cases. Preheating of the base metal adjacent to the crack is suggested. Use of drilled holes at either end of the crack, as shown in Figure 28, to prevent extension is optional for aluminum. Welding should start on the base metal at each end of the repair and terminate at the midpoint. The second weld should be fused completely with the first and the crater filled. The backstep method should be used on longer cracks.

6.24 Welding Power Connections. The possibility of electrolytic corrosion of aluminum hulls in water

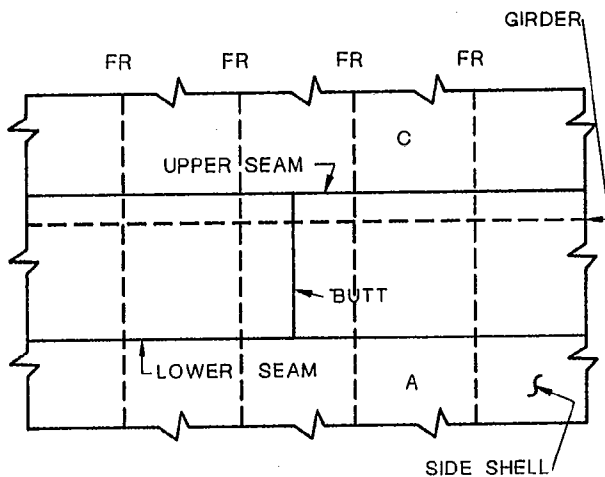
caused by welding and associated operations, can be overcome by proper connection of the power leads from the welding machines and accessory equipment.¹⁸ The arc welding machines, electrode and work leads, and associated control equipment should be installed on the craft where the welding is to be done. A welding machine on one craft with the work lead connected to that craft should not be used to perform welding on another craft alongside.

If it is not possible to install the welding machine on board, it should be installed on shore in a location as close as possible to the craft. A shore-based welding machine work lead should not be connected to an earth ground. It should be clamped directly to the work on the craft where the welding is being done. Care should be taken to ensure that there is no intermediate contact of the electrode and

18. Based on the following published material:

(1) U.S. Navy NAVSHIP NOTE 4700 (1969), derived from *Care, Maintenance, Repair, and Operation Manual for U.S. Navy Aluminum Boats* (1968), by Sub-Committee on Marine Applications, The Aluminum Association.

(2) Roger, T. Howard, Marine Corrosion, Appendix 3, *Earthing of Welding Machines*, pp. 284-287.



- (1) WELD FRAMES (FR) AND GIRDER TO PLATES WITHIN 12 in. (305 mm) OF ALL UNWELDED BUTTS AND SEAMS.
- (2) WELD BUTT COMPLETE.
- (3) WELD UNWELDED PORTION OF GIRDER IN WAY OF BUTT.
- (4) WELD LOWER SEAM TO POINT 12 in. (305 mm) FROM NEXT BUTT.
- (5) WELD UNWELDED PORTION OF FRAMES IN WAY OF LOWER SEAM.
- (6) WELD UPPER SEAM TO POINT 12 in. (305 mm) FROM NEXT BUTT.
- (7) WELD UNWELDED PORTION OF FRAMES IN WAY OF UPPER SEAM.

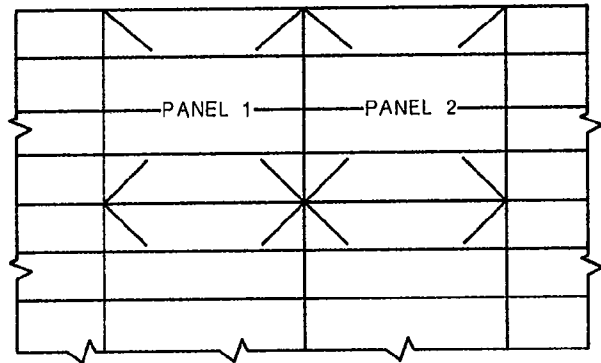
Figure 23 — Typical Welding Sequence for Plate Butt and Adjacent Seams where Internal Framing is Attached.

work lead cables between the welding machine and the craft.

No work lead connections should be made between the craft and the shore or between adjacent craft for welding. Care should be taken to prevent cables from hanging or sagging in the water between the craft and shore. It is essential that no welding current flows through the sea water to or away from the metal hull; the ship should not be part of an electrolytic cell.

Separate welding machines should be used when welding on more than one ship at dockside. The work lead from each machine should be connected only to the work on the one ship being served. If it is essential to weld on two or more ships using a single welding machine, separate work leads may be run from the shore-based welding machine to each ship, but this arrangement is not recommended. It is preferred to connect a single work lead or cable only to the craft being welded.

In addition to employing a correctly isolated welding circuit, as previously described, the follow-



- (1) PANELS 1 AND 2 ARE COMPLETE WITH INTERNALS WELDED TO WITHIN 12 in. (305mm) OF EDGES OF PANEL.
- (2) WELD PANELS TOGETHER FOLLOWING THE SAME GENERAL SEQUENCE AS INDICATED IN FIGS. 22 AND 23.

Figure 24 — Typical Welding Sequence for Large Subassembled Plate Panels

ing conditions should be checked to ensure corrosion protection from stray welding current:

(1) Both electrode and work lead cables should be of adequate size to carry the maximum welding current to be used. See Figures 29 and 30.

(2) Care should be taken to make certain that mooring lines do not accidentally ground the power source because they may act as electrical conductors.

(3) A work lead of adequate length should be used so that it can be clamped as closely as possible to the welding site. Even if the circuit is isolated on the one ship, some current may flow through the water alongside if the work lead is clamped to the vessel a long way from the welding site.

(4) Inspect all cable connections regularly to ensure they are clean and tight. A salt-laden atmos-

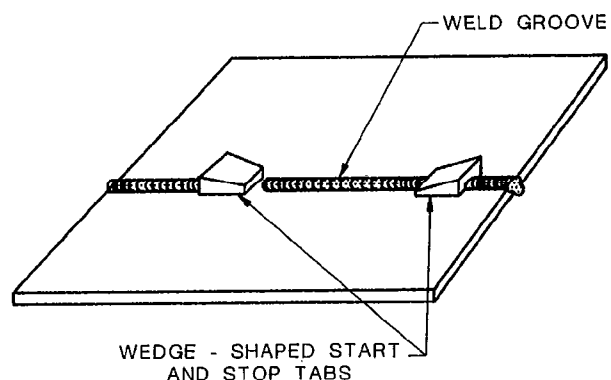


Figure 25 — Placement of Starting and Stopping Tabs at the Ends of a Repair Weld Groove

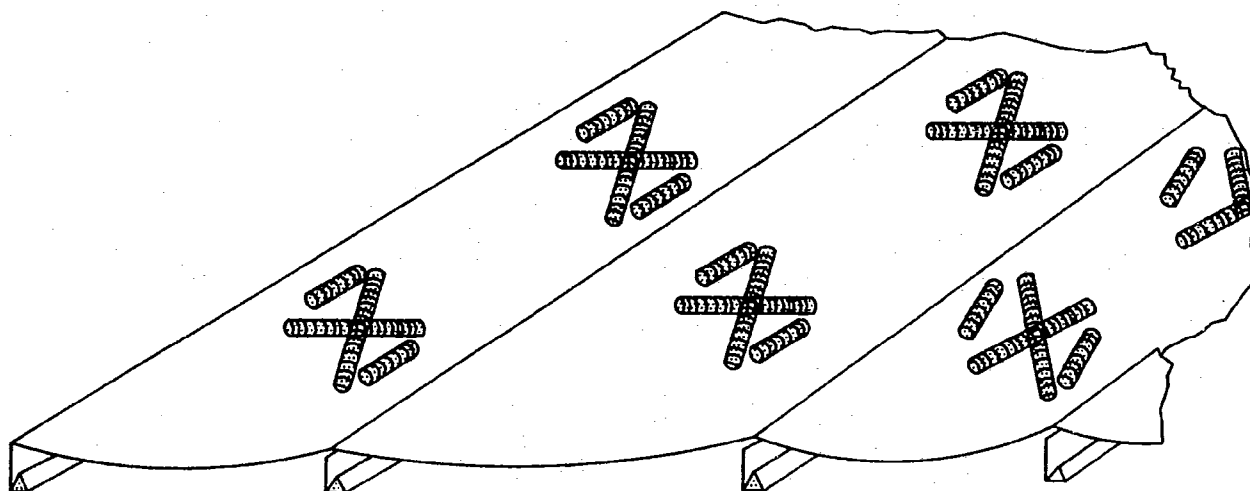


Figure 26 — Correction of Distortion in a Panel by Welding on the Concave Side, Using a Predetermined Pattern

phers may corrode any electrical contact, and cable movement may loosen it.

For best electrical connections, the aluminum surface should be ground or sanded to remove the oxide, and bolted or clamped lugs with an electrical sealer should be used.

7. Safety

7.1 Introduction. In welding, safety precautions always apply to the process being used, the equipment, the welder's physical and mental condition, the type and condition of the welder's clothing, shop or yard conditions, and other factors. Welding safety also is affected by the metal being welded which may generate hazardous fumes and gases.

7.2 Fumes and Gases. Many welding, cutting and allied processes produce fumes and gases which may be harmful to health. Fumes are solid particles which originate from welding consumables, the base metal, and any coatings present on the base metal. Gases are produced during the welding process or may be produced by the effects of process radiation on the surrounding environment. The amount and composition of these fumes and gases depend upon the composition of the filler metal and base metal, welding process, current level, arc length, and other factors.

The possible effects of over-exposure range from irritation of eyes, skin, and respiratory system to more severe complications. Effects may

occur immediately or at some later time. Fumes can cause symptoms such as nausea, headaches, dizziness, and metal fume fever. The possibility of more serious health effects exists when especially toxic metals are involved. In confined spaces, the gases might displace breathing air and cause asphyxiation.

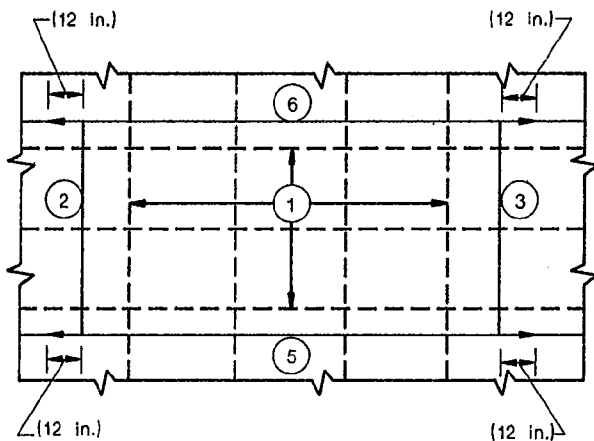
Enough ventilation, exhaust at the arc, or both, should be used to keep fumes and gases from the breathing zone and general area. In some cases, natural air movement will provide enough ventilation. Where ventilation may be questionable, air sampling should be used to determine if corrective measures should be applied.

The following sources should be referred to for more detailed information on fumes and gases produced by the various welding processes:

(1) The permissible exposure limits required by OSHA can be found at CFR Title 29, Chapter XVII, Part 1910. The *OSHA General Industry Standards* are available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

(2) The recommended threshold limit values for these fumes and gases may be found in *Threshold Limit Values for Chemical Substances and Physical Agents in the Workroom Environment* published by the American Conference of Governmental Industrial Hygienists (ACGIH), 6500 Glenway Avenue, Building D-5, Cincinnati, Ohio 45211.

(3) The results of an AWS funded study are available in the report entitled *Fumes and Gases in the Welding Environment*.



NOTE THAT A RELEASE LENGTH OF 12 in. (305mm) IS PROVIDED IN THE HORIZONTAL SEAMS AT EACH CORNER OF THE INSERT PLATE.

- (1) WELD FRAMING TO WITHIN 12 in. (305mm) OF UNWELDED BUTTS AND SEAMS.
- (2) WELD VERTICAL BUTT ② COMPLETE.
- (3) WELD VERTICAL BUTT ③ COMPLETE.
- (4) WELD UNWELDED FRAMING IN WAY OF VERTICAL BUTTS.
- (5) WELD HORIZONTAL SEAM ⑤ INCLUDING RELEASE LENGTHS.
- (6) WELD HORIZONTAL SEAM ⑥ INCLUDING RELEASE LENGTHS.
- (7) WELD UNWELDED FRAMING IN WAY OF HORIZONTAL SEAMS.

Figure 27 — Welding Sequence for Side Shell Plate Repair

7.3 Radiation. Welding, cutting and allied operations may produce radiant energy (radiation) harmful to health.

Radiant energy may be ionizing (such as X-rays) or nonionizing (such as ultraviolet, visible light, or infrared). Radiation can produce a variety of effects such as skin burns and eye damage, depending on the radiant energy's wavelength and intensity, if excessive exposure occurs.

The intensity and wavelengths of nonionizing radiant energy produced depend on many factors such as the process, welding parameters, electrode and base metal composition, fluxes, and any coating or plating on the base metal. Most arc welding and cutting processes (except submerged arc when used properly), laser welding and torch welding, cutting, brazing, or soldering can produce sufficient quantities of nonionizing radiation to make precautionary measures necessary.

Protection from possible harmful effects caused by nonionizing radiant energy from welding include the following measures:

- (1) The welding arcs should not be observed directly but through welding filter plates which meet

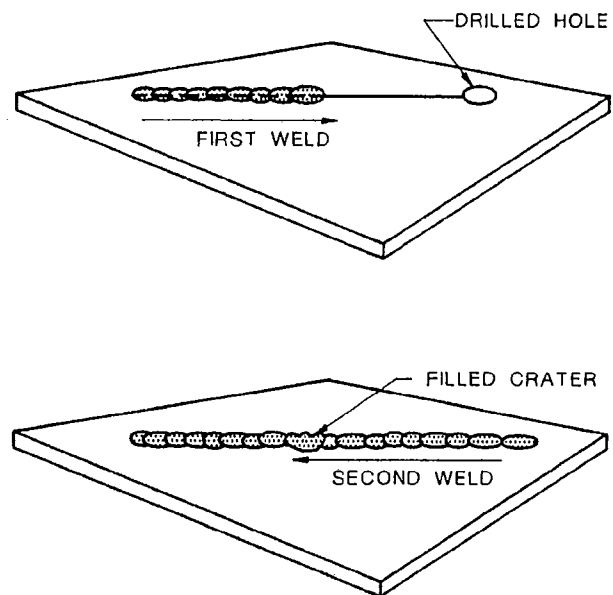


Figure 28 — Technique for Repairing a Crack by Welding

the requirements of Z87.1, *Practice for Occupational and Educational Eye and Face Protection*, published by American National Standards Institute.

(2) Exposed skin should be protected with adequate gloves and clothing as specified in ANSI Z49.1, *Safety in Welding and Cutting*, published by the American Welding Society.

(3) One should beware of reflections from welding arcs, and all persons should be protected from intense reflections. (Note: paints using pigments of substantially zinc oxide or titanium dioxide have a low reflectance for ultraviolet radiation.)

(4) One should avoid exposing passersby to welding operations by the use of screens, curtains, or adequate distance from aisles, walkways, etc.

(5) Safety glasses with UV protective side shields have been shown to provide some beneficial protection from ultraviolet radiation produced by welding arcs.

7.4 Electrical Hazards. Electric shock can kill. However, it can be avoided. Live electrical parts should not be touched. The manufacturer's instructions and recommended safe practices should be read and understood. Faulty installation, improper grounding, and incorrect operation and maintenance of electrical equipment are all sources of danger.

All electrical equipment and the workpieces should be grounded. The work lead is not a ground

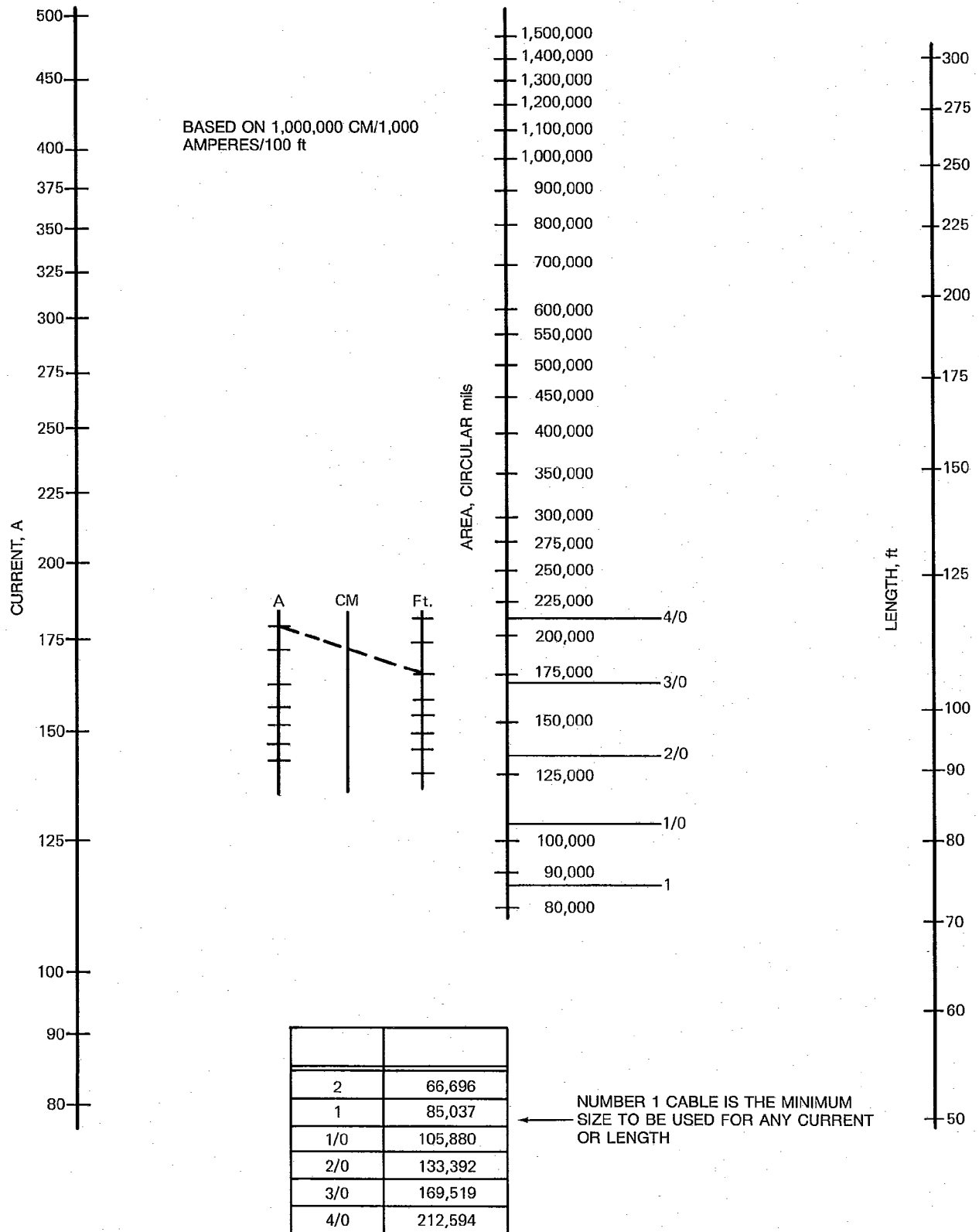


Figure 29 — Nomograph for Copper Ground Cable Size

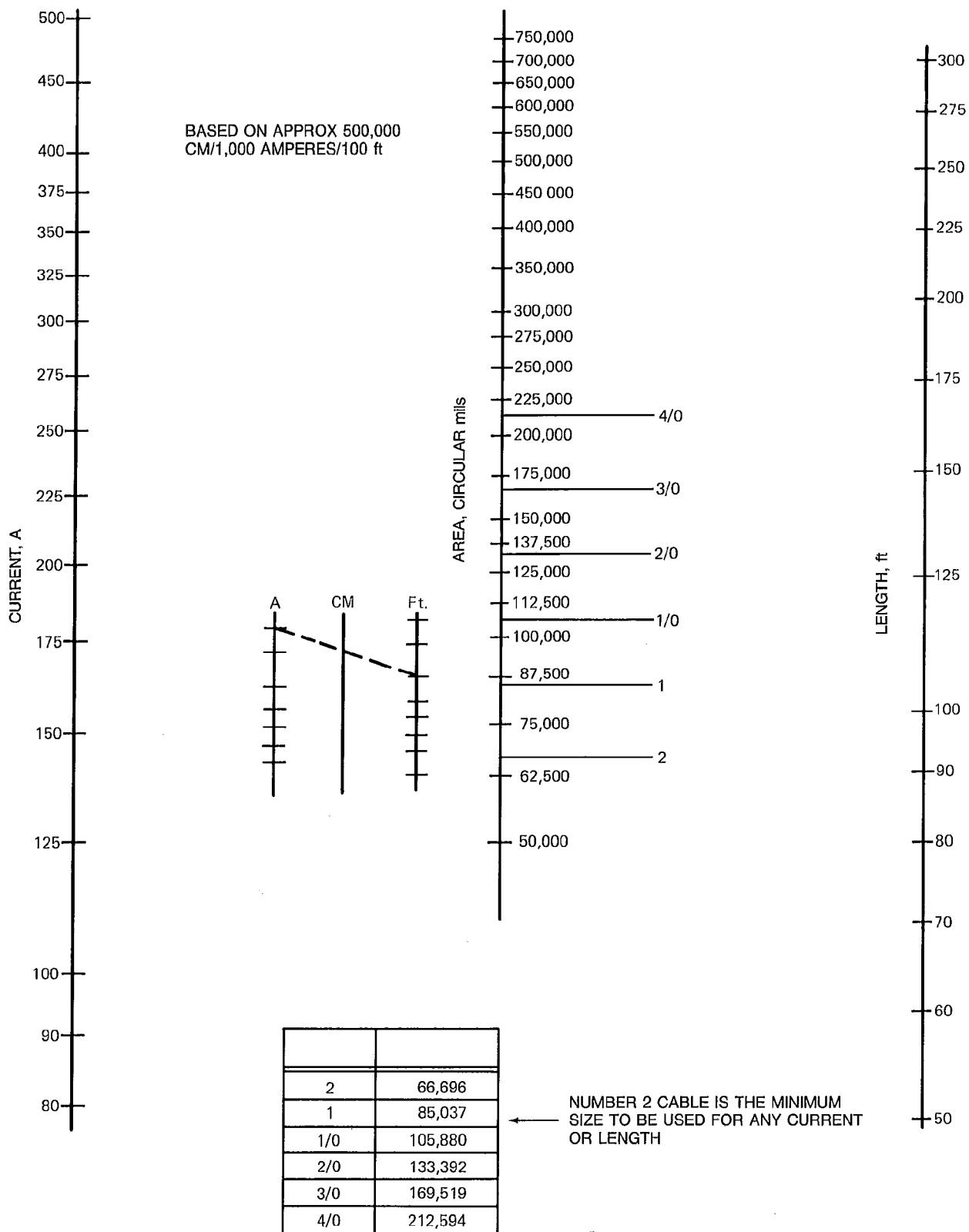


Figure 30 — Nomograph for Copper Electrode Lead Cable Size

lead. It is used only to complete the welding circuit. A separate connection is required to ground the workpiece. The work lead should not be mistaken for a ground connection.

The correct cable size should be used, since sustained overloading may cause cable failure and result in possible electrical shock or fire hazard. All electrical connections should be tight, clean and dry. Poor connections can overheat and even melt. Further, they can produce dangerous arcs and sparks. Water, grease or dirt should not be allowed to accumulate on plugs, sockets, or electrical units. Moisture can conduct electricity. To prevent shock, the work area, equipment, and clothing should be kept dry at all times. Dry gloves and rubber soled shoes should be worn, or one should stand on a dry board or insulated platform.

Cables and connectors should be kept in good condition. Improper or worn electrical connections may set up conditions that could cause electrical shock or short circuits. Worn, damaged, or bare cables should not be used. Open circuit voltage should be avoided.

When several welders are working with arcs of different polarities, or when a number of alternating current machines are being used, the open circuit voltages can be additive. The added voltages increase the severity of the shock hazard.

In case of electric shock, the power should first be turned off. If the rescuer must resort to pulling the victim from the live contact, nonconducting materials should be used. If the victim is not breathing, cardiopulmonary resuscitation (CPR) should be administered as soon as contact with the electrical source is broken. A physician should be called and CPR should be continued until breathing has been restored, or until a physician has arrived. Electrical burns should be treated as thermal burns; that is, clean, cold (iced) compresses should be applied. Contamination should be prevented and the burns should be covered with a clean, dry dressing. A physician should be called.

7.5 Fire Prevention. Molten metal, sparks, slag, and hot work surfaces are produced by welding, cutting and allied processes. These can cause fire or explosion if precautionary measures are not followed.

Many of the fires associated with welding, cutting and applied processes have been caused by sparks which can travel up to 35 ft (11 m) in a horizontal direction from the work area. Sparks can pass through or become lodged in cracks, clothing, pipe holes and other small openings in floors or partitions. (Note: sparks and molten metal can travel greater distances when falling.)

Typical combustible materials commonly involved in fires are floors, partitions, roofs, and building contents such as wood, paper, clothing, plastics, chemical and flammable liquids and gases. Outdoors, the combustible materials involved are dry leaves, grass and brush. Explosions have occurred where welding or cutting has been performed in spaces containing flammable gases, vapors, liquids or dusts.

All combustible material should be removed from the work area. Where possible, the work should be moved to a location well away from combustible materials. If neither action is possible, combustibles should be protected with a cover of fire resistant material. All combustible materials should be moved and made safe for a radius of 35 ft (11 m) around the work area. All open doorways, windows, cracks and other openings should be covered or blocked with fire resistant material. If possible, the work area should be enclosed with portable fire resistant screens.

Combustible walls, ceilings, etc. should be protected from sparks and heat with fire resistant covers. If work is to be performed on a metal wall, ceiling, etc., ignition of combustibles on the other side should be prevented by moving the combustibles to a safe location. If this cannot be done, someone should be designated to serve as a fire watch, equipped with a fire extinguisher during the welding operation and for one half-hour after welding is completed.

Welding or cutting should not be performed on material having a combustible coating or combustible internal structure, as in walls or ceilings, without an approved method for eliminating the hazard. Hot slag should be disposed of in containers holding combustible material. A fire extinguisher should be kept nearby. A thorough examination for evidence of fire should be made. Easily visible smoke or flame may not be present for some time after the fire has started.

Overloading and improper sizing can cause overheating of electrical equipment. All electrical equipment and wiring should be installed properly with recommended circuit protection.

The work cable should be connected to the work as close to the welding area as practical. Work cables connected to locations some distance from the welding area increase the possibility of the welding current passing through lifting chains, crane cables or other alternate circuits. This can create fire hazards or overheat lifting chains or cables until they fail.

Welding or cutting should not be done in atmospheres containing dangerously reactive or flamma-

ble gases, vapors, liquids or dust. Heat should not be applied to a container that has held an unknown substance or a combustible material whose contents when heated can produce flammable or explosive vapors. Heat should not be applied to a workpiece covered by an unknown substance or whose coating can produce flammable, toxic or reactive vapors when heated. Adequate procedures should be developed and proper equipment used to do the job safely. Adequate ventilation should be provided in work areas to prevent accumulation of flammable gases, vapors or dusts. Containers should be cleaned and purged before applying heat.

Closed containers, including castings, should be vented before preheating, welding or cutting. Venting will prevent the buildup of pressure and possible explosion due to the heating and the resultant expansion of gases.

7.6 OSHA Regulations. The OSHA regulations that govern safety practices are found in the *Code of Federal Regulations*, Title 29, Chapter XVII, Part 1915, "Safety and Health Regulations for Ship Repairing." Subpart D deals with "Welding, Cutting, and Heating" in situations involving ship repairing, and Title 29 CFR 1910.252-Subpart Q "Welding, Cutting and Brazing for General Industry" covers the general industry. These regulations are supplemented by the following publications:

National Electric Code National Fire Protection Association.

Oxygen-Fuel Gas Systems for Welding and Cutting NFPA No. 51, National Fire Protection Association.

Practice for Occupational and Educational Eye and Face Protection ANSI Z87.1, American National Standards Institute.

Safety in Welding and Cutting ANSI Z49.1, American Welding Society.

Standard for Fire Prevention in the Use of Cutting and Welding Processes NFPA No. 51B, National Fire Protection Association.

Standard Welding Terms and Definitions AWS A3.0, American Welding Society.

Threshold Limit Values American Conference of Governmental Industrial Hygienists.

Metric Conversion Factors

1 in. = 25.4 mm

1 in./min = 25.4 mm/min and 0.423 mm/s

1 ft/min = 305 mm/min and 5.1 mm/s

1 lb = 0.45 kg

1 ft³/h = 0.0283 m³/h and 0.472 L/min

1 psi = 6.89 kPa

1 ksi = 6.89 MPa

t^c = 0.556 (t^F-32)

Appendix A

Codes and Other Standards

(This Appendix is not a part of ANSI/AWS D3.7-90, *Guide for Aluminum Hull Welding*, but is included for information purposes only.)

Issuing Agencies

Agencies that publish codes, specifications, recommended practices, materials standards, and welding tests applicable to welded aluminum ship structure are as follows:

The Aluminum Association, Inc.
900 19th Street, N.W.
Washington, D.C. 20006

American Bureau of Shipping
45 Eisenhower Drive
Paramus, New Jersey 07652

American Conference of Governmental Industrial Hygienists
6500 Glenway Avenue — Building D-5
Cincinnati, Ohio 45211

American National Standards Institute
1430 Broadway
New York, New York 10018

American Society for Testing and Materials
1916 Race Street
Philadelphia, Pennsylvania 19103

American Society of Mechanical Engineers
345 East 47th Street
New York, New York 10017

American Welding Society
550 N.W. LeJeune Road
P.O. Box 351040
Miami, Florida 33135

National Fire Protection Association, Inc.
Batterymarch Park
Quincy, Massachusetts 02269

Naval Publications and Forms Center
Philadelphia, Pennsylvania

Society of Naval Architects and Marine Engineers
74 Trinity Place
New York, New York 10006

United States Coast Guard
2100 Second Street, S.W.
Washington, DC 20593-0001

United States Navy
Naval Sea Systems Command
NAVSEA 05M
Washington, DC 20762

Standards

Pertinent governmental and commercial standards and references are given in the following list.

Federal

QQ-A-200/4	Aluminum Alloy 5083, Bar, Rod, Shapes, Tube and Wire, Extruded
QQ-A-200/5	Aluminum Alloy 5086, Bar, Rod, Shapes, Tube and Wire, Extruded
QQ-A-200/6	Aluminum Alloy 5454, Bar, Rod, Shapes, Tube and Wire, Extruded
QQ-A-200/7	Aluminum Alloy 5456, Bar, Rod, Shapes, Tube and Wire, Extruded
QQ-A-225/7	Aluminum Alloy 5052, Bar, Rod, and Wire;

	Rolled, Drawn, or Cold Finished	MIL-W-45210	Welding, Resistance, Spot; Weldable Aluminum Alloys
QQ-A-250/6	Aluminum Alloy 5083, Plate and Sheet	MIL-W-45211	Welding, Stud, Aluminum
QQ-A-250/8	Aluminum Alloy 5052, Plate and Sheet	MIL-R-45774	Radiographic Inspection, Weld Soundness Standards
QQ-A-250/9	Aluminum Alloy 5456, Plate and Sheet		
QQ-A-250/10	Aluminum Alloy 5454, Plate and Sheet	NAVSEA 0900-LP-006-3010	Ultrasonic Inspection Procedure and Acceptance Standards for Hull Structure, Production and Repair Welds
WW-T-700/5	Tube, Aluminum Alloy, Drawn, Seamless, 5086		
Military			
MIL-STD-248	Welding and Brazing Procedure and Performance Qualification	NAVSEA 0900-LP-003-8000	Surface Inspection Acceptance Standards for Metals
MIL-STD-0022	Welded Joint Design	NAVSEA 0900-LP-003-9000	Radiograph Standards for Production and Repair Welds
MIL-STD-1595	Qualification of Aircraft, Missile and Aerospace Fusion Welders	U.S. Coast Guard	Title 46, Code of Federal Regulations
MIL-STD-1689	Fabrication, Welding, and Inspection of Ships Structure	U.S. Coast Guard	Rules for Nondestructive Inspection of Hull Welds
		Industrial	
MIL-W-6858	Spot and Seam Welding of Aluminum, Magnesium, Non-Hardening Steels, Nickel and Titanium	ASME Boiler and Pressure Vessel Code, Section IX	Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators
MIL-F-6939	Gas Welding Flux for Aluminum and Aluminum Alloys	ANSI B96.1	Standard for Welded Aluminum Alloy Storage Tanks
MIL-W-8604	Process for Welding of Aluminum Alloys	American Bureau of Shipping	ABS Rules for Building and Classing Aluminum Vessels
MIL-W-10430	Preparation for Delivery of Welding Rods and Electrodes	AWS A5.01	Filler Metal Procurement Guidelines
MIL-E-15597	Welding Electrodes (covered)	AWS A5.10	Specification for Bare Aluminum and Aluminum Alloy Welding Electrodes and Rods
MIL-W-22248	Weldments, Aluminum and Aluminum Alloys	AWS B2.1	Standard for Welding Procedure and Performance Qualification
MIL-W-45205	Welding Aluminum Alloys, Excluding Armor		
MIL-W-45206	Welding Aluminum Alloy Armor	AWS C5.5	Recommended Practices

	for Gas Tungsten Arc Welding		Procedures and Welders for Piping and Tubing
AWS C5.6	Recommended Practices for Gas Metal Arc Welding	AWS QC1	Standard for Qualification and Certification of Welding Inspectors
AWS D1.2	Structural Welding Code — Aluminum		
AWS D10.7	Recommended Practices for Gas-Shielded-Arc Welding of Aluminum and Aluminum Alloy Pipe	Other Publications by the D3 Committee on Marine Construction:	
		ANSI/AWS D3.5	Guide for Steel Hull Welding
AWS D10.9	Standard for Qualification of Welding	ANSI/AWS D3.6	Specification for Underwater Welding

Appendix B

Quantity of Filler Metal Required for Welded Joints in Aluminum Made By GMAW and GTAW Processes

(This Appendix is not a part of ANSI/AWS D3.7-90, *Guide for Aluminum Hull Welding*, but is included for information purposes only.)

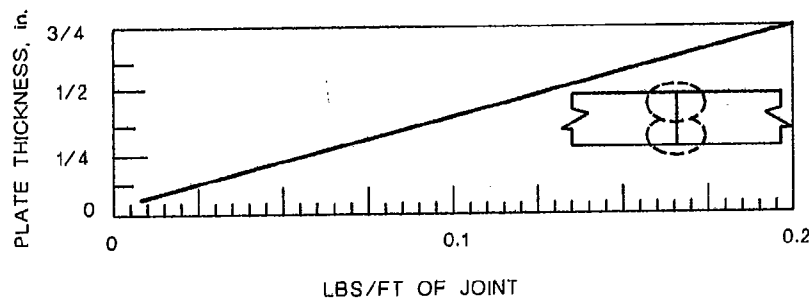


Figure B1 — Double-Square-Groove Welds, Convex Beads

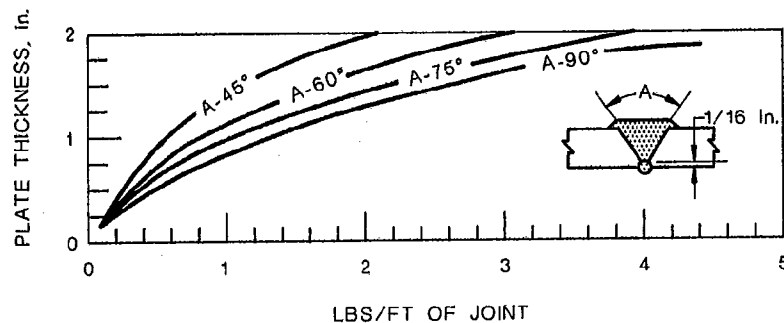


Figure B2 — Single-V-Groove Welds, No Root Opening, Welded Flush

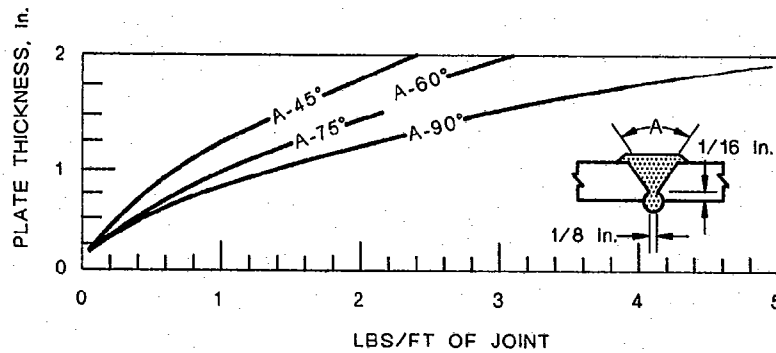


Figure B3 — Single-V-Groove Welds, 1/8-in. (3.2 mm) Root Opening, Welded Flush

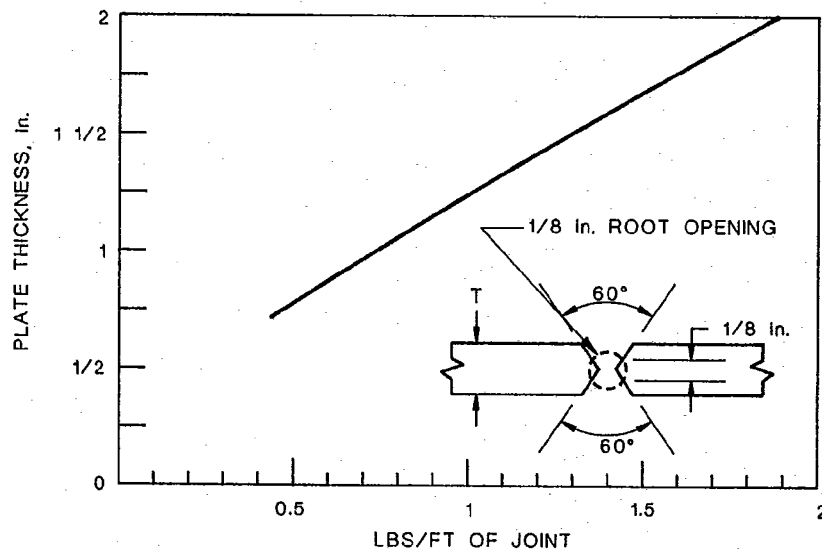


Figure B4 — Double-V-Groove Welds

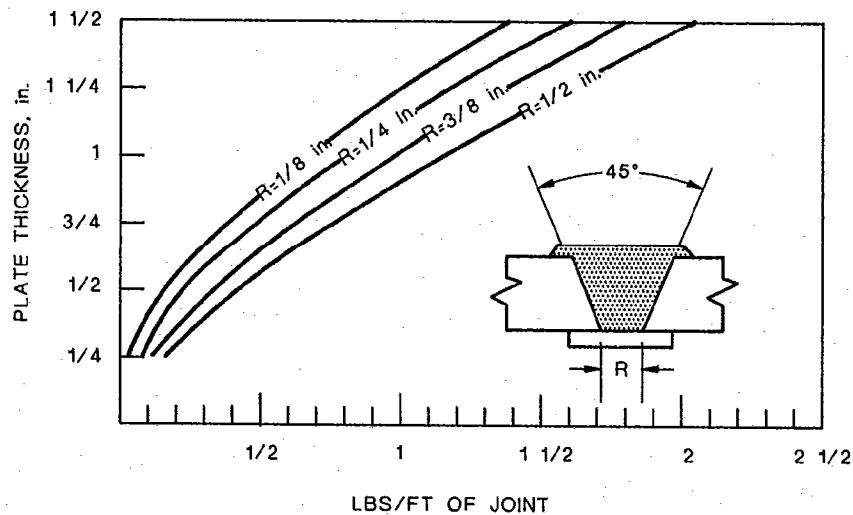


Figure B5 — Single-V-Groove Welds, 45° Groove Angle, with Backing Strip

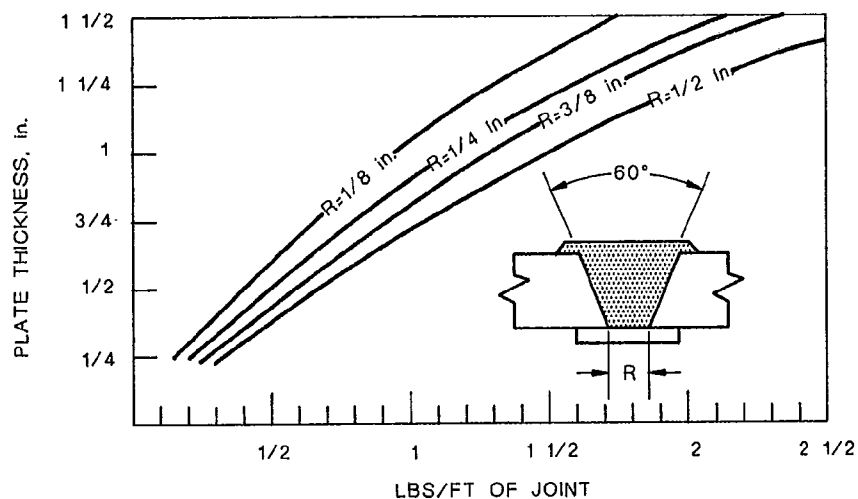


Figure B6 — Single-V-Groove Welds, 60° Groove Angle, with Backing Strip

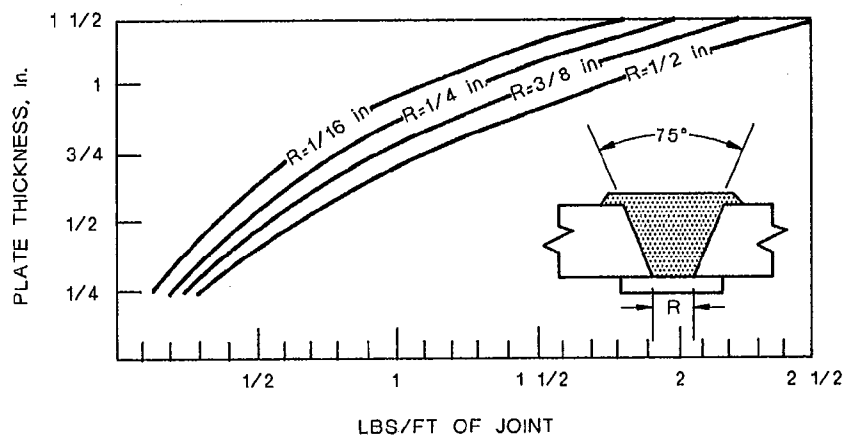


Figure B7 — Single-V-Groove Welds, 75° Groove Angle, with Backing Strip

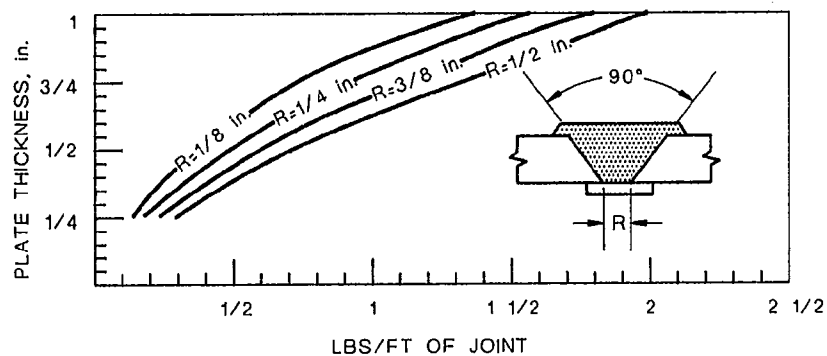


Figure B8 — Single-V-Groove Welds, 90° Groove Angle, with Backing Strip

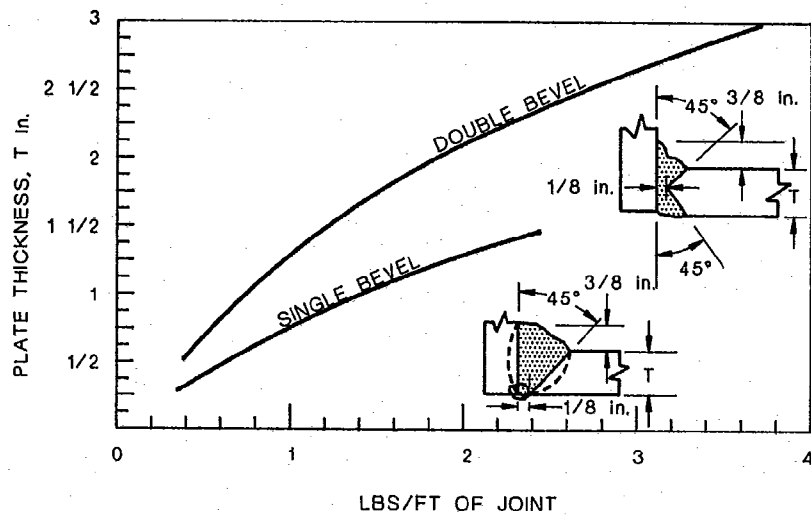


Figure B9 — Single and Double-Bevel Groove Welds

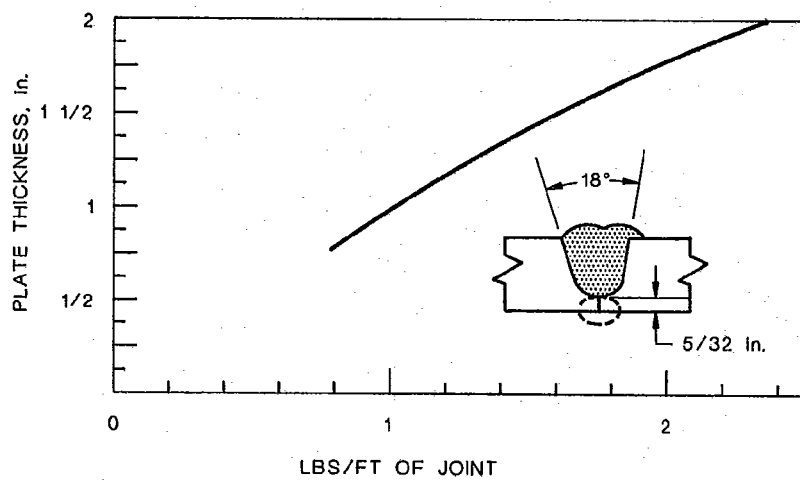


Figure B10 — Single-U-Groove Welds

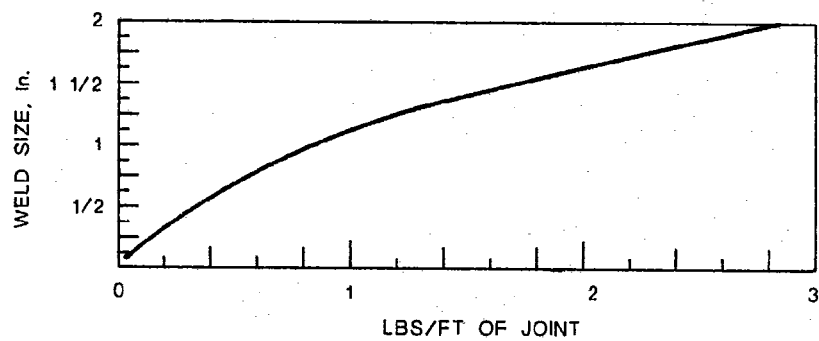


Figure B11 — Fillet Welds with Equal Leg Lengths