

Guide for Aluminum Hull Welding



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hull welding, aluminum hulls, boats,
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Guide for **Aluminum Hull Welding**

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Prepared by
AWS D3 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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Dedication

Paul B. Dickerson

1926–2004

The AWS D3 Committee on Welding in Marine Construction dedicates this edition of AWS D3.7, *Guide for Aluminum Hull Welding*, to the memory of Paul B. Dickerson. Paul was an AWS Fellow and contributed unselfishly to several technical committees of the American Welding Society. His knowledge of aluminum alloy welding was prodigious, and Paul freely shared this knowledge with anyone that needed his help. Paul will be greatly missed by his family, friends, peers, and associates.

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Foreword

(This Foreword is not a part of AWS D3.7:2004, *Guide for Aluminum Hull Welding*, but is included for informational 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 procedures 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 aluminum hulls, boats, crafts and ships 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*. The first revision was ANSI/AWS D3.7-90.

This second revision, D3.7:2004, includes recent advances in welding equipment and techniques along with the inclusion of approximate mathematical equivalents in the International System of Units (SI).

Comments and suggestions for the improvement of this standard are welcome. They should be sent to the Secretary, AWS D3 Committee on Welding in Marine Construction, American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126.

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Guide for Aluminum Hull Welding

1. General

1.1 Scope. This standard makes sole use of U.S. Customary Units. Approximate mathematical equivalents in the International System of Units (SI) are provided for comparison in parentheses or in appropriate columns in tables and figures.

This guide provides 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 1/8 in. (3.2 mm) thick and greater. 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 1950s. 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).¹ The first inert gas welding process to be developed was gas tungsten arc welding which is sometimes referred to as TIG welding. Introduced in 1941, this process uses a non-consumable 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.

1.2.2 Gas Metal Arc Welding (GMAW).² The second process, gas metal arc welding, which is sometimes

referred to as MIG welding, 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.

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 residual chlorides from the flux 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 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. Refer to AWS C5.5/C5.5M, *Recommended Practices for Gas Tungsten Arc Welding*, and the *Welding Handbook*, Vol. 2, 8th Ed. 73–108.

2. Refer to AWS C5.6, *Recommended Practices for Gas Metal Arc Welding*, and the *Welding Handbook*, Vol. 2, 8th Ed. 109–156.

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 Welding 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 Annex A, together with pertinent codes, specifications, and regulations.

2. Aluminum Hull Materials

2.1 General. In the early 1950s, 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 ksi–42 ksi (170 MPa–290 MPa), and their minimum yield strengths from 15 ksi–25 ksi (100 MPa–170 MPa). The 5000 series marine alloys have excellent corrosion resistance and retain good weld strength without postweld thermal treatment.

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 nonheat 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 lower strength.

Where operating temperatures in excess of 150°F (65°C) are anticipated, 5454 alloy is used to avoid the problem of stress corrosion cracking found in aluminum alloys with higher magnesium content. It is useful in stack enclosures 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 5086³ is recommended for most marine construction. 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 5083³ and 5456 are also employed for commercial marine construction. Designated as Grade “B,” non-heat 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 non-heat 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:

- (1) H1 Strain Hardened
- (2) H2 Strain Hardened and Partially Annealed
- (3) H3 Strain Hardened followed by Stabilization

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

- (1) 1 is 1/8 hard

- (2) 2 is 1/4 hard
- (3) 4 is 1/2 hard
- (4) 6 is 3/4 hard
- (5) 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 tempers provide the most desirable combination of mechanical properties and corrosion resistance 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. Federal specification QQ-A-250 describes the requirements for the H116 temper for 5083, 5086, and 5456 alloys.

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 properties, 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:

- (1) T1 cooled from an elevated temperature process and naturally aged to a substantially stable condition
- (2) T2 cooled from an elevated temperature process, cold worked, and naturally aged to a substantially stable condition
- (3) T3 solution heat-treated, cold-worked, and naturally aged to a substantially stable condition
- (4) T4 solution heat-treated and naturally aged to a substantially stable condition
- (5) T5 cooled from an elevated temperature process and then artificially aged
- (6) T6 solution heat-treated and then artificially aged
- (7) T7 solution heat-treated and stabilized
- (8) T8 solution heat-treated, cold worked, and then artificially aged
- (9) T9 solution heat-treated, artificially aged, and then cold worked
- (10) 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

3. The International Organization for Standardization (ISO) equivalent for 5083 and 5086 alloys are AlMg4.5Mn0.7 and AlM4, respectively.

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 T4 or T6 temper or a variation thereof.

2.4 Aluminum Product Forms.⁴ All product forms of aluminum are used in marine construction, including plate, extrusions, forgings, and castings. 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 in.–0.249 in. (0.15 mm–6.4 mm) thick is called sheet. (The term *strip* is not used for aluminum.) 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 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 sheet and 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.

4. Information on wrought 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.

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

Typical of the many extruded aluminum shapes that have been used for marine construction are those shown in Figure 1. Minimum mechanical properties of extruded marine aluminum 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. Three aluminum alloys commonly employed for marine structural components are 5083, 6061, and 6151. Minimum mechanical properties of forged aluminum alloys are given in Table 4.⁷

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.

Minimum mechanical properties of cast aluminum alloys for marine use are given in Table 5.⁸

2.5 Welding Filler Metals. Aluminum alloy filler metals are supplied as wire electrodes on spools or in coils, and as welding rods.⁹ General availability includes spools with nominal weights of 1, 16, 20, 30, 125, and 165 lb (0.45, 6.8, 9.1, 14.6, 56, and 80 kg). The same alloys are also available as 36 in. (0.91 m) straight lengths in packages of 5, 10, 25, and 50 lb (2.3, 4.5, 11, and 23 kg). Sizes range from 0.030 in.–3/16 in. (0.8 mm–4 mm) diameter for spooled electrode, and 1/16 in.–1/4 in. (1.6 mm through 6.4 mm) diameter for straight length 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. ANSI/AWS A5.01, “*Filler Metal Procurement Guidelines*,” should be consulted for defining lot size and any testing desired by the purchaser. Although not the only cause of weld porosity, the hydrated surface of the filler metal can be a major cause.

6. Additional extrusion alloy data are given in ASTM B 221, *Standard Specification for Aluminum Alloy Extruded Bar, Rod, Wire, Shape, and Tube*.

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

8. Additional data for sand, die, permanent mold, and investment castings are given in ASTM Standard Specification B 26, B 85, B 108, and B 618, respectively. Also aluminum casting information is provided in “Standards for Aluminum Sand and Permanent Mold Castings” published by the Aluminum Association, Inc.

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

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

Composition (Weight Percent) ^{(1),(2)}											
Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others		Al
									Each	Totals	
5082	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	0.10	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

Notes:

(1) Single values are maximum limits.

(2) Registered with the Aluminum Association.

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

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

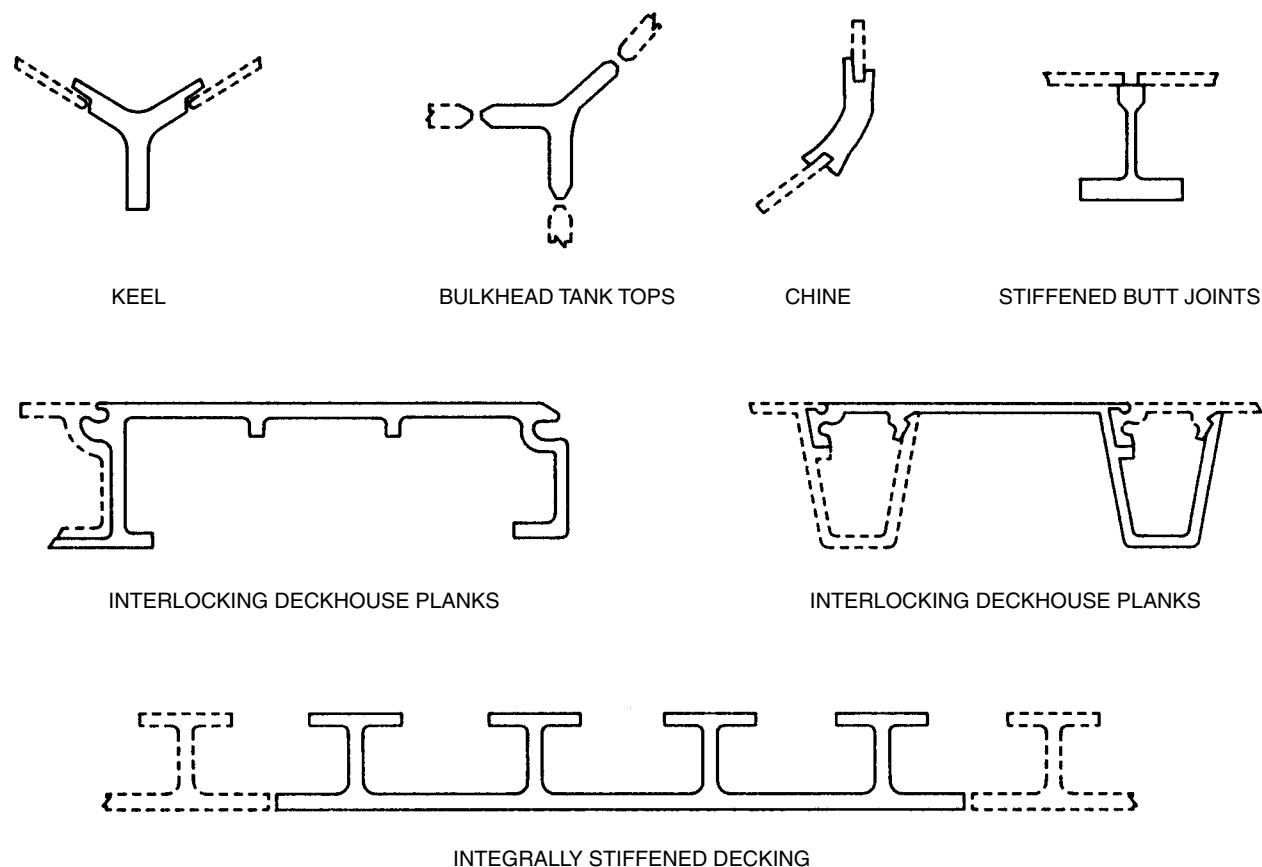


Figure 1—Typical Extrusion Shapes for Shipbuilding Applications

Table 3
Minimum Mechanical Properties of Extruded Marine Aluminum Alloys

Alloy	Temper	Minimum Strength				Minimum Elongation % in 2 in. (51 mm)
		Ultimate		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
			Ultimate		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	Long Transverse	38	260	35	240	5
6151	T6	Longitudinal	44	300	37	250	10
		Long Transverse	44	300	37	250	6

Note:

(1) D is the specimen diameter.

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

Alloy	Temper	Product	Minimum Strength ⁽¹⁾				Minimum Elongation % in 2 in. (51 mm)
			Ultimate		Yield		
			ksi	MPa	ksi	MPa	
356.0	T6	Permanent mold casting	33	230	22	150	3
A356.0	T6	Sand casting	34	230	24	170	3.5
A356.0	T61	Permanent mold casting	37	250	26	180	5
514.0	F	Sand casting	22	150	9	60	6
520.0	T4	Sand casting	42	290	22	150	12
535.0	F	Sand casting	35	240	18	120	9

Note:

(1) Values represent properties obtained from separately cast test bars.

Table 6
Chemical Compositions of Aluminum Welding Filler Metals

Composition, Weight Percent ⁽¹⁾											
Filler Metal	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others ⁽²⁾		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	[Note (3)]	[Note (3)]	0.05	0.01	3.1–3.9	0.15–0.35	0.20	0.05–0.15	0.05	0.15	Remainder

Notes:

(1) Single values are maximum.

(2) Beryllium: 0.0003% maximum.

(3) Silicon + iron: 0.45% maximum.

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 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 applications that require volumetric NDT, it is good practice to perform a fillet weld break test and to examine the fractured surface for excessive porosity. An overhead fillet weld break test is best for determining wire quality. Any contamination on the wire will show as porosity in the weld. 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. The aluminum welding filler metal selection guide are given in Table 7 and rates suggested filler metals for welding wrought and cast aluminum alloys to themselves 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 Annex 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 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.

Table 7
Aluminum Welding Filler Metal Selection Guide

Base Metal	Filler Metal	Characteristics ⁽¹⁾						
		WSDCT ⁽²⁾	WSDCT	WSDCT	WSDCT	WSDCT	WSDCT	WSDCT
		WSDCT ⁽²⁾	WSDCT	WSDCT	WSDCT	WSDCT	WSDCT	WSDCT
356.0 A356.0	4043	ABAAA	—	—	ABBA—	ABBAA	AAAAA	AAAAA
	5356	BABB—	—	—	AAAB—	AAAB—	—	—
6061	4043	ADCAA	—	—	ADCA—	ADCBA	ACBAA	
6063	5183	BABC—	AABA—	AABA—	BABC—	BABC—	BAAC—	
6151	5356	BBAC—	ABAA—	ABAA—	BBAC—	BBAC—	BBAC—	
6351	5554	CCABA	BCAA—	BCAA—	CCAB—	CCAAA	CBABB	
	5556	BABC—	AABA—	AABA—	BABC—	BABC—	BAAC—	
	5654	CCAB—	BCAA—	BCAA—	CCAB—	CCAB—	CBAB—	
5454	4043	ADCCA	—	—	—	—	—	
	5183	AAAB—	AABB—	AABB—	AABB—	AABB—	AABB—	
	5356	ABAB—	ABAB—	ABAB—	ABAB—	ABAB—	ABAB—	
	5554	CCAAA	BCAA—	BCAA—	BCAA—	BCAAA	BCAAA	
	5556	AABB—	AABB—	AABB—	AABB—	AABB—	AABB—	
	5654	BCAB—	—	—	BCAA—	BCAB—	BCAB—	
514.0 520.0 535.0	4043	ADCC—	—	—	—	—	—	
	5183	AABB—	AABA—	AABA—	AABB—	AABB—	AABB—	
	5356	ABAB—	ABAA—	ABAA—	ABAB—	ABAB—	ABAB—	
	5554	CCAA—	BCAA—	BCAA—	BCAA—	BCAA—	BCAA—	
	5556	AABB—	AABA—	AABA—	AABB—	AABB—	AABB—	
	5654	BCAA—	BCAA—	BCAA—	BCAA—	BCAA—	BCAA—	
5086	5183	AABA—	AABA—	AABA—	AABA—	AABA—	AABA—	
	5356	ABAA—	ABAA—	ABAA—	ABAA—	ABAA—	ABAA—	
	5554	CCAA—	—	—	—	—	—	
	5556	AABA—	AABA—	AABA—	AABA—	AABA—	AABA—	
	5654	BCAA—	—	—	—	—	—	
5083 5456	5183	AABA—	AABA—	AABA—	AABA—	AABA—	AABA—	
	5356	ABAA—	A-AA—	A-AA—	A-AA—	A-AA—	A-AA—	
	5554	CCAA—	—	—	—	—	—	
	5556	AABA—	AABA—	AABA—	AABA—	AABA—	AABA—	
	5654	BCAA—	—	—	—	—	—	
5052	4043	ADCBA	—	—	—	—	—	
	5183	AABC—	—	—	—	—	—	
	5356	ABAC—	—	—	—	—	—	
	5554	CCAAA	—	—	—	—	—	
	5556	AABC—	—	—	—	—	—	
	5654	BCAB—	—	—	—	—	—	

Notes:

(1) 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.

(2) 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 (6°C).

Table 8
Minimum As-Welded Mechanical Properties of Gas-Shielded Arc Welds
in Marine Aluminum Alloys (U.S. Customary Units)

Alloy and Temper	Product and Thickness Range, in.	Property ⁽¹⁾						
		Tension		Compression	Shear		Bearing	
		F _{tuw} ⁽²⁾ ksi	F _{tyw} ⁽³⁾ ksi	F _{cyw} ⁽⁴⁾ ksi	F _{suw} ⁽⁵⁾ ksi	F _{syw} ⁽⁶⁾ ksi	F _{buw} ⁽⁷⁾ ksi	F _{bysw} ⁽⁸⁾ ksi
5052-H32, H34	All	25	13	13	16	7.5	50	19
5083-H111	Extrusions	39	21	20	23	12	78	32
-H321	Sheet & Plate 0.188–1.500	40	24	24	24	14	80	36
-H321	Plate, 1.501–3.000	39	23	23	24	13	78	34
-H323, H343	Sheet	40	24	24	24	14	80	36
5086-H111	Extrusions	35	18	17	21	10	70	28
-H112	Plate, 0.250–0.499	35	17	17	21	9.5	70	28
-H112	Plate, 0.500–1.000	35	16	16	21	9	70	28
-H112	Plate, 1.001–2.000	35	14	14	21	8	70	28
-H116, H32, H34	Sheet & Plate	35	19	19	21	11	70	28
5454-H111	Extrusions	31	16	15	19	9.5	62	24
-H112	Extrusions	31	12	12	19	7	62	24
-H32, H34	Sheet & Plate	31	16	16	19	9.5	62	24
5456-H116, H321	Sheet & Plate	42	26	24	25	15	84	38
5456-H111, H321	Extrusions 0.188–1.500	41	24	22	24	14	82	38
-H116, H321	Plate, 1.501–3.000	41	24	23	25	14	82	36
-H323, H343	Sheet	42	26	26	25	15	84	38
6061-T6, T651 ⁽⁹⁾	All ⁽⁹⁾	24	20	20	15	12	50	30
-T6, T651 ⁽¹⁰⁾	Over 0.375 ⁽¹⁰⁾	24	15	15	15	9	50	30
6063-T5, T52	All	17	11	11	11	6.5	34	22
6151-T6 ⁽⁹⁾	All ⁽⁹⁾	24	20	20	15	12	50	30
-T6 ⁽¹⁰⁾	Over 0.375 ⁽¹⁰⁾	24	15	15	15	9	50	30
6351-T5k	All ⁽⁹⁾	24	20	12	50	12	50	30
-T5 ⁽¹⁰⁾	Over 0.375 ⁽¹⁰⁾	24	15	15	15	9	50	30
356.0-T6	Castings	23						
A356.0-T6	Castings	23						
514.0-F	Castings	22						
535.0-F	Castings	35						

Notes:

- (1) Welding filler metals are those recommended in Table 7.
- (2) Ultimate tensile strength across a butt joint. Strengths are AWS and ASME weld qualification test values.
- (3) Yield strength across a butt joint, 0.2% offset in a 10 in. gage length.
- (4) Compressive yield strength across a butt joint, 0.2% offset in a 10 in. gage length.
- (5) Ultimate shear strength within 1 in. of a weld.
- (6) Yield strength in shear within 1 in. of a weld.
- (7) Ultimate bearing strength within 1 in. of a weld.
- (8) Bearing yield strength within 1 in. of a weld.
- (9) For all thicknesses when welded with 5183, 5356, or 5556 filler metal, and for thicknesses of 0.275 in. and under when welded with 4043, 5554, or 5654 filler metal.
- (10) Apply when welded with 4043, 5554, or 5654 filler metals.

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

Alloy and Temper	Product and Thickness Range, in.	Property ⁽¹⁾						
		Tension		Compression	Shear		Bearing	
		F _{tuw} ⁽²⁾ MPa	F _{tyw} ⁽³⁾ MPa	F _{cyw} ⁽⁴⁾ MPa	F _{suw} ⁽⁵⁾ MPa	F _{syw} ⁽⁶⁾ MPa	F _{buw} ⁽⁷⁾ MPa	F _{byw} ⁽⁸⁾ MPa
5052-H32, H34	All	172	90	90	110	51	345	131
5083-H111	Extrusions	269	145	138	159	83	538	221
-H321	Sheet & Plate 0.188–1.500	276	165	165	165	96	552	248
-H321	Plate, 1.501–3.000	269	159	159	165	90	538	234
-H323, H343	Sheet	276	165	165	165	96	552	248
5086-H111	Extrusions	241	124	117	145	69	483	193
-H112	Plate, 0.250–0.499	241	117	117	145	65	483	193
-H112	Plate, 0.500–1.000	241	110	110	145	62	483	193
-H112	Plate, 1.001–2.000	241	96	96	145	55	483	193
-H116, H32, H34	Sheet & Plate	241	131	131	145	76	483	193
5454-H111	Extrusions	214	110	103	131	65	427	165
-H112	Extrusions	214	83	83	131	117	427	165
-H32, H34	Sheet & Plate	214	110	110	131	65	427	165
5456-H116, H321	Sheet & Plate	290	179	165	172	103	579	262
5456-H111, H321	Extrusions	283	165	152	165	96	565	262
-H116, H321	Plate, 0.188–1.500	283	165	159	172	96	565	248
-H323, H343	Sheet	290	179	179	172	103	579	262
6061-T6, T651 ⁽⁹⁾	All ⁽⁹⁾	165	138	138	103	83	345	207
-T6, T651 ⁽¹⁰⁾	Over 0.375 ⁽¹⁰⁾	165	103	103	103	62	345	207
6063-T5, T52	All	117	76	76	76	45	234	152
6151-T6 ⁽⁹⁾	All ⁽⁹⁾	165	138	138	103	83	345	207
-T6 ⁽¹⁰⁾	Over 0.375 ⁽¹⁰⁾	165	103	103	103	62	345	207
6351-T5 ⁽⁹⁾	All ⁽⁹⁾	165	138	138	103	83	345	207
-T5 ⁽¹⁰⁾	Over 0.375 ⁽¹⁰⁾	165	103	103	103	62	345	207
356.0-T6	Castings	159						
A356.0-T6	Castings	159						
514.0-F	Castings	152						
535.0-F	Castings	241						

Notes:

- (1) Welding filler metals are those recommended in Table 7.
- (2) Ultimate tensile strength across a butt joint. Strengths are AWS and ASME weld qualification test values.
- (3) Yield strength across a butt joint, 0.2% offset in a 250 mm gage length.
- (4) Compressive yield strength across a butt joint, 0.2% offset in a 250 mm gage length.
- (5) Ultimate shear strength within 25 mm of a weld.
- (6) Yield strength in shear within 25 mm of a weld.
- (7) Ultimate bearing strength within 25 mm of a weld.
- (8) Bearing yield strength within 25 mm of a weld.
- (9) For all thicknesses when welded with 5183, 5356, or 5556 filler metal, and for thicknesses of 9.52 mm and under when welded with 4043, 5554, or 5654 filler metal.
- (10) Apply when welded with 4043, 5554, or 5654 filler metals.

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 The process may be adaptable to cutting thick aluminum plate and complex plate shapes. 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.

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.

¹⁰ For additional information on machining, refer to the *ASM Handbook*, Vol. 16: Machining, ASM International, Metals Park, Ohio, 1989: 761–804.

¹¹ Plasma arc cutting is described in the *Welding Handbook*, Vol 2, 8th Ed., 329–350, and also in AWS C5.2, *Recommended Practices for Plasma Arc Cutting*.

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 2–4 teeth per in. (0.8–1.6 teeth per cm) 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.

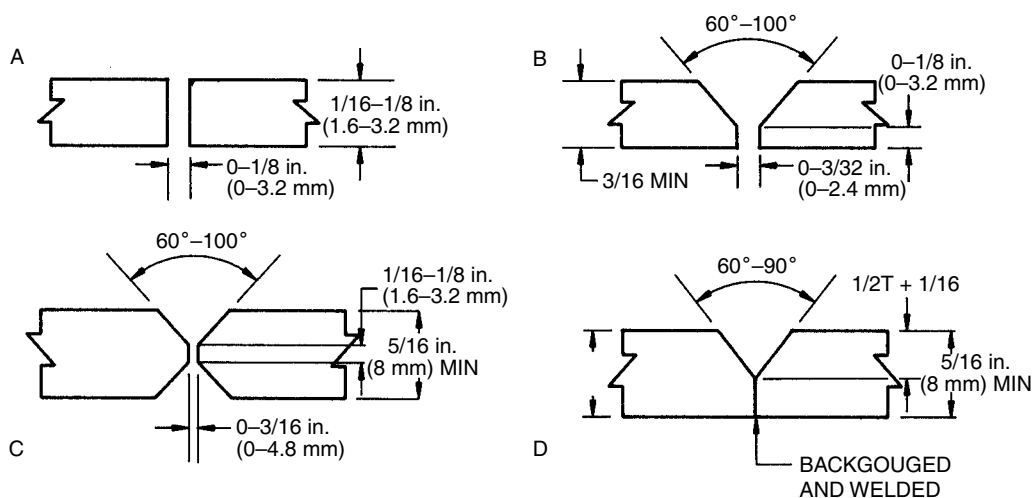
Hand-held or stationary circular saws that are fitted with high-speed steel blades are run at 8000 surface ft/min (2400 m/min) or faster, and at 4000–6000 surface ft/min (1200–1800 m/min) with other tool steel blades. Carbide tipped blades are particularly suitable where lubrication on the blade is not allowed. The carbide blade speeds should be a minimum of 10 000 surface ft./min. 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 saber 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 to remove entrapped oxide, contaminants or lubricants at folds.

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 to eliminate entrapped oxide or contaminants at folds.

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.



General Note: Joint spacing is increased in A and B when a permanent backing is used.

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

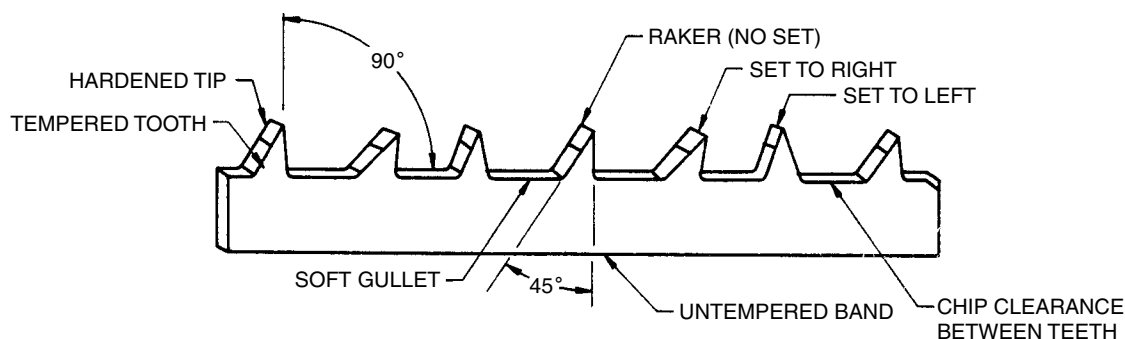


Figure 3—Typical Band Saw Blade Design for Aluminum

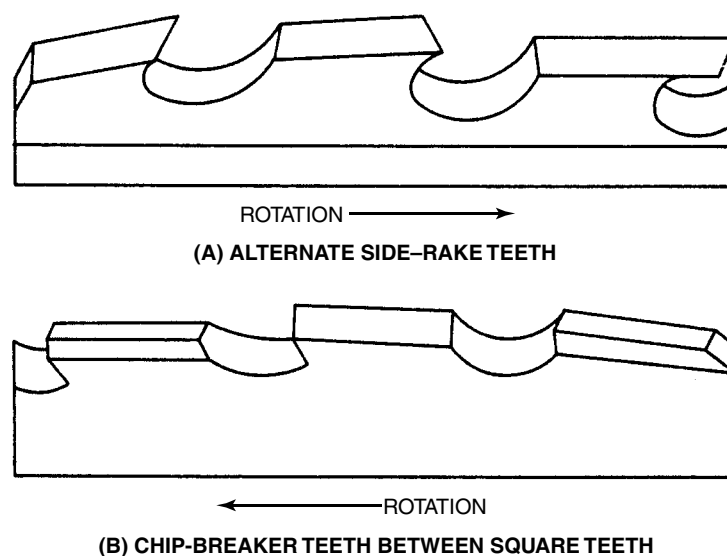


Figure 4—Teeth Arrangements for Circular Saws for Aluminum

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.

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.

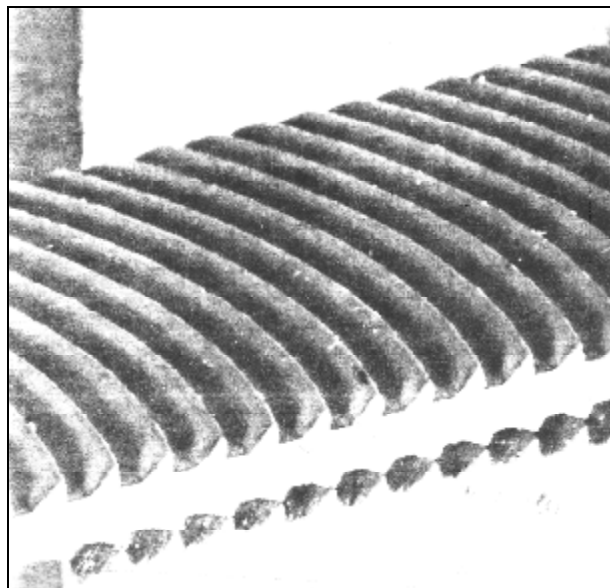


Figure 5—Vixon File for Aluminum

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, however a final solvent clean is sometimes desirable if a residue of the binder is left on the joint.

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 Backgouging. Backgouging 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. With the proper torch and nozzle, plasma gouging can be successfully employed for back gouging the non-heat treatable aluminum alloys.

Backgouging can also be accomplished using portable power saws with small cutters or portable milling cutters. Die and disk grinders with appropriate wheels are also used.

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.