

ANSI/AWS D3.5-93R
An American National Standard

Guide for Steel Hull Welding



American Welding Society



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An American National Standard

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Guide for **Steel Hull Welding**

Superseding AWS D3.5-85

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 to users in the marine construction industry as to the best practical methods to weld steel hulls for ships, barges, mobile offshore drilling units, and other marine vessels. This guide provides information on steel plates, shapes, castings, and forgings; their selection; and their weldability. It discusses welding processes and proper design for welding. Hull construction is presented in terms of preparation of materials, erection and fitting, and control of distortion. Qualification of procedures and personnel are outlined, and inspection methods are discussed. A common shipyard problem, stray current protection, is discussed as is the health and safety of the work force. Supplementary nonmandatory appendices are provided for informational purposes.



American Welding Society

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



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Personnel

AWS Committee on Welding in Marine Construction

<i>A. T. Sheppard, Chairman</i>	Tri-State Steel Construction, Incorporated
<i>K. Masubuchi, Vice-Chairman</i>	Massachusetts Institute of Technology
<i>F. X. Neary, Secretary</i>	American Welding Society
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<i>C. E. Grubbs</i>	Global Divers
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<i>R. A. Manley</i>	Bechtel Group, Incorporated
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<i>D. N. Reznik</i>	American Bureau of Shipping
<i>D. L. Simmons</i>	Bath Iron Works Corporation
<i>T. C. West</i>	Welding Engineering Services

AWS Subcommittee on Steel Hull Welding

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<i>S. A. Collins</i>	Bath Iron Works Corporation
<i>O. J. Davis</i>	Ingalls Shipbuilding
<i>A. W. Johnson</i>	A. W. Johnson and Associates
<i>L. G. Kvidahl*</i>	Ingalls Shipbuilding Company
<i>S. E. Pollard</i>	Machinists, Incorporated
<i>D. N. Reznik</i>	American Bureau of Shipping
<i>J. P. Wilkinson, III</i>	American Bureau of Shipping
<i>J. P. Stafford*</i>	Petrocon Engineering, Inc.
<i>P. R. Slimmon*</i>	Bethlehem Steel Corporation

*Advisor

Foreword

(This Foreword is not a part of ANSI/AWS D3.5-93, *Guide for Steel Hull Welding*, but is included for information purposes only.)

This guide is for reference in the construction of steel hulls by welding. It has been compiled to aid welders and supervisory personnel as well as design and construction engineers.

The first all-welded ships were built just before World War II. During that war, over 4000 welded ships, including the Liberty ships and T2 tankers, were constructed under emergency conditions. When some of these ships experienced major structural failures of the brittle-cleavage type, both government and industry undertook immediate and intensive investigation and research. Most major failures started either in a defective groove weld in the deck or bottom shell, or at a sharp structural intersection such as a square hatch corner, or some other abrupt change in structural cross-section, or lack of geometric continuity in the structure. Once started, the cracks progressed through the base metal and extended for considerable distances, in some cases across the deck and completely around the ship.

Attention was focused primarily on the influence of notches, weld quality, and the inherent notch toughness characteristics of steel and weld metal regarding both crack initiation and crack propagation. As a result of the ship research, steels having greater notch toughness were specified by regulatory agencies, and special steels having superior notch toughness were developed and specified for use in highly stressed areas. Design details were improved, and main hull welds were subjected to subsurface inspection by radiographic and ultrasonic methods.

To summarize this early research and development and to make appropriate recommendations relative to welding, the American Welding Society published D3.5-62, *Hull Welding Manual*. Because of revisions to the regulatory agencies' requirements, major developments in welding equipment and shipyard facilities, and the increased use of higher strength and superior notch-tough steels in shipbuilding, AWS D3.5-76, *Guide for Steel Hull Welding*, was prepared to replace the earlier manual. The ANSI/AWS D3.5-85 and ANSI/AWS D3.5-93 are updates of the previous Guide. The welding of aluminum in ship construction is covered in ANSI/AWS D3.7-89, *Guide for Aluminum Hull Welding*.

Much commercial building in shipyards includes special purpose ships and mobile offshore drilling units. Tankers over 30 times larger than the T2 tankers have been built. Today's container ships are as large as the largest ocean liners and have the unusual feature of having most of their strength decks open to facilitate container stowage. The large LNG (liquefied natural gas) carriers transport liquid cargo at approximately -260°F (-160°C).

For further specific details relating to welding, refer to the rules of regulatory agencies, recommendations of the steel and welding equipment manufacturers, and other related publications.

Comments and suggestions regarding this guide are welcome. These comments should be sent to the Secretary, AWS Committee on Welding in Marine Construction, American Welding Society, 550 N.W. LeJeune Road, P.O. Box 351040, Miami, Florida 33135.

Official interpretations of any of the technical requirements of this standard may be obtained by sending a request, in writing, to the Managing Director, Technical Services Division, American Welding Society. A formal reply will be issued after it has been reviewed by the appropriate personnel following established procedures.

Table of Contents

	Page No.
<i>Personnel</i>	iii
<i>Foreword</i>	iv
<i>List of Tables</i>	vii
<i>List of Figures</i>	vii
1. Materials	1
1.1 Steel Manufacturing Processes	1
1.2 Higher Strength Steels	5
1.3 Notch Toughness Properties of Steel	5
1.4 Notch Toughness of Weld Metal and Heat-Affected Zone	8
1.5 Fatigue	10
1.6 Specifications for Steel	13
1.7 Specifications for Welding Consumables	15
1.8 Selection of Materials	15
1.9 Weld Cracking	15
1.10 Service Performance of Welds	17
1.11 Welding of Higher Strength and Low-Temperature Service Steels	19
1.12 Welding of Clad Steel	19
1.13 Explosion Bonded Transition Joints	20
2. Welding Processes	20
2.1 Introduction	20
2.2 Shielded Metal Arc Welding (SMAW)	20
2.3 Submerged Arc Welding (SAW)	22
2.4 Gas Metal Arc Welding (GMAW)	23
2.5 Flux Cored Arc Welding (FCAW)	25
2.6 Electroslag Welding (ESW) and Electrogas Welding (EGW)	27
2.7 Stud Welding	27
2.8 Thermit Welding	30
2.9 Removable Backing Materials for Welding	30
3. Design	31
3.1 Introduction	31
3.2 Main Strength Members	31
3.3 Secondary Strength Members	32
3.4 Design Details	32
3.5 Details for Manual Welding	35
4. Hull Construction	43
4.1 Introduction	43
4.2 Preparation of Material	43
4.3 Erection and Fitting	44
4.4 Welding Sequence	46
4.5 Weld Distortion	46
4.6 Stress Relief	54
4.7 Preheat	57
4.8 Barge Construction for Inland Waterways	57

5. Inspection and Qualification	60
5.1 Introduction	60
5.2 Welding Procedure Qualifications	60
5.3 Welder Qualification	60
5.4 Inspection Methods	61
5.5 Welding Defects	63
5.6 Repair of Defects	65
5.7 Air Carbon Arc Process	65
6. Stray Current Protection	67
6.1 Underwater Corrosion	67
6.2 Current Flow	67
6.3 Welding Equipment Requirements	67
6.4 Grounding (Work) Connections	67
6.5 Special Precautions	74
7. Safety	77
7.1 Introduction	77
7.2 Fumes and Gases	77
7.3 Radiation	77
7.4 Electrical Hazards	78
7.5 Fire Prevention	78
7.6 OSHA Regulations	79
Appendix A — Codes and Specifications	81
Appendix B — Glossary	83
Appendix C — Safety	89
Appendix D — Mill Plate Tests and Inspection Procedures	97
Alpha-Numerical Document Title Reference — by Source	106
AWS Marine Welding Document List	(Inside Back Cover)

List of Tables

Table		Page No.
1A	American Bureau of Shipping, Requirements for Ordinary Strength Hull Structural Steel, Grades A, B, D, E, DS, CS, 2 in. (51 mm) and Under	9
1B	American Bureau of Shipping, Requirements for Ordinary Strength Hull Structural Steel, Over 2 in. (51 mm)	10
2A	American Bureau of Shipping, Requirements for Higher Strength Hull Structural Steel, Grades AH32, DH32, EH32, AH36, DH36, and EH36, 2 in. (51 mm) and Under	11
2B	American Bureau of Shipping Requirements for Higher Strength Hull Structural Steel, Over 2 in. (51 mm)	12
2C	American Bureau of Shipping, Normalizing Heat Treatment Requirements for Higher Strength Hull Structural Steels	12
3	Thickness Limitations for ABS Steel Grades	14
4	Specifications for Filler Metals — Steel	16
5	Applicable Filler Metal (ABS Grade and AWS Classification) Base Plate Combinations	21
6	Carbon and Low Alloy Steel Solid or Composite Electrodes and Rods	26
7	Carbon and Low Alloy Steel Flux Cored Electrodes (Wires)	28
8	Equivalent Fillet Weld Leg Size Factors for Skewed T-Joints	43
9	Weld Shrink Allowances	55

List of Figures

Figure		Page No.
1	Schematic Temperature Versus Deformation Plot Showing Differences Between Conventional Hot-Rolling and Control-Rolling	5
2A	Standard Charpy V-Notch Test Specimen	7
2B	Typical Charpy V-Notch Transition Temperature Curve for ABS Grade D Steel	7
3	Typical Charpy V-Notch Transition Temperature Curves for Several Grades of Steel	8
4	Tempering Passes	19
5	Typical Detail for Groove Welding Clad Plating	20
6	One Type of Gravity Feed Welding	22
7	Typical Joint Details and Backing Material Positioning for One-Side Submerged Arc Welding	24
8	Automatic Fillet Welding of Stiffeners to Plate Panel — Welds are Being Made Simultaneously on Both Sides of Stiffener	25
9	Vertical Electroslag and Electrode Gas Welding	29
10	Consumable Guide Tube Welding	30
11	Typical Joint Details for One-Side Welding	31
12	Most Highly Stressed Areas of Hull Girder	32
13	Load-Elongation and Transition Temperature Curves for Specimens With Oxygen-Cut Edges	33
14	Ending of Bulwark Fashion Plate Welded to Top of Sheerstrake	34
15	Original Design of Hatch Corner on Liberty Ship	35
16	Design of Hatch Corner on Victory Ship	35

17	Typical Hatch Corner in Way of Container Guides on Container Ship	36
18	Typical Elliptical Hatch Corner	36
19	Bilge Keel Endings	36
20	Stress Concentration at Intersecting Planes Eased by Brackets	37
21	Typical Weld Details for Welding From One Side Only, Permanent Backing	38
22	Two Methods of Edge Preparation for Groove Welds Near Plate Laps	39
23	Transition From Riveting to Welding in Flush Seam	40
24	Transition From Riveting to Welding in Lap Seam	40
25	Welded Water- or Oil-Stops at Intersecting Members	41
26	Welded Stops at Riveted Seam Lap	41
27	Scallops	42
28	Details for Skewed T-Joints	42
29	Typical Strongbacks	45
30	Cutout of Member to Permit Passage of Inboard Sliding Shoe and Cables	46
31	Correction of Poor Fit-Up	47
32	Welding Sequence at Intersection of Butt and Seam	48
33	Welding Sequence for Plate Butt and Adjacent Seams	48
34	Typical Welding Sequence For Plate Butts and Seams Where Butts are Staggered	49
35	Typical Welding Sequence for Plate Butts and Seams Where Butts are in Line	49
36	Typical Welding Sequence for Plate Butt and Adjacent Seams Where Internal Framing is Attached	50
37	Typical Welding Sequence for Large Subassembled Plate Panels	50
38	Welding Sequence for Side Shell Plate Repair	50
39	Closure of Small and Large Openings	51
40	Residual Welding Stresses	52
41	Typical Distortion of Welded Joints	53
42	Angular Deflection Due to Welding Stiffeners to Plate (The Washboard Effect)	53
43	Angular Distortion Tendencies in Making Groove Welds	53
44	Natural Buckling Deflection	53
45	Permissible Unfairness in Steel Welded Structures as Used for Guidance by U.S. Navy	56
46	Control of Distortion in Thin Plate By Intermittent Welding	56
47	Coil Storage (Top) and Uncoiling Operation (Bottom)	58
48	Barge Construction Showing a Side Shell Unit (at right) in Horizontal Position Ready to be Erected Into Final Vertical Position	59
49	Typical Weldment Cracks	64
50	Air Carbon Arc Torch	66
51	Air Carbon Arc Torch Mounted on Carriage for Flat Work	68
52	Potential Source of Direct Currents Causing Corrosion Due to Accidental or Unintentional Ground on Vessel	68
53	Equivalent Circuit for Improperly Connected Generator or Rectifier	68
54	Nomograph for Copper Ground (Work Lead) Wire Size	69
55	Nomograph for Copper Electrode Lead Cable Size	70
56	Hookup for Single Ship at Pier	71
57	Hookup for Two Ships at Pier	72
58	Hookup for Ships Afloat (Sheet 1 of 2 Sheets)	73
59	Hookup for Ships Afloat (Sheet 2 of 2 Sheets)	73
60	Hookup for Ship in Floating Docks or ARD or LSD	74
61	Hookup for Ships in Dry or Graving Dock	75
62	Grounding (Work Lead) Connections on Steel Surface Ships	76

Appendix D

D-1	Dynamic Tear Test Specimen, Anvil Supports and Striker	99
D-2	Tensile Coupon Sampling	100
D-3	Yield Stress Defined	100

	Page No.
D-4 Allowable Reduction in Tensile Coupon Elongation if Coupon Thickness is Less Than 5/16 Inch or More Than 3-1/2 Inch	100
D-5 Charpy Coupon Testing	101
D-6 Drop-Weight Test Setup to Determine Nil-Ductility (ASTM 208)	102
D-7 Drop Weight Tear Test (ASTM E436)	103
D-8 ASTM A770 Through Thickness Tensile Coupons	103
D-9 UT A435 Minimum Acceptance Criteria and Marking Requirement	105
D-10 A578 Minimum Acceptance Criteria and Marking Requirement	105

Guide for Steel Hull Welding

1. Materials

This section deals with the manufacture and heat treating of steel, properties of steel, specifications for steel and welding consumables, and the weldability of steel.¹

1.1 Steel Manufacturing Processes. Ship steel is made primarily in basic oxygen furnaces (BOF), open-hearth furnaces, and electric furnaces. There are only a few open-hearth furnaces operating today. Electric furnaces are used to make high-alloy specialty steels, steels for castings, and in conjunction with continuous casters they are used to make small to medium sized shapes and some flat rolled products.

1.1.1 Plates and Shapes. Plates are rolled in one of three types of rolling mills to produce sheared plates, universal mill plates, and continuous strip.

Sheared plates are rolled on mills which have horizontal rolls only, and are produced with irregular edges and ends which must be cut or sheared on all sides to produce a rectangular plate. Sheared plates are rolled in both directions by rotating the slab at the roughing stand of the mill. This process, called *cross rolling*, provides the plate with more uniform longitudinal and transverse properties, and sheared plates are usually specified where stringent mechanical properties are required.

Universal mill plates are rolled on mills with both horizontal and vertical rolls. The vertical rolls provide the plate with a rolled edge which does not require cutting to

establish its width. Universal mill plates are not cross-rolled, and as a result, the plates may have slightly lower ductility in the transverse direction. These plates are used where a finished edge is desirable.

Continuous strip mill plates are made on a hot strip mill and can be furnished in coils or as flat rectangular products. These plates are used primarily for structural applications, cold-formed shapes, or on automated barge construction lines. Hot strip mill plates may have directional properties between those of the sheared mill and universal mill products.

Structural shapes are usually rolled on a mill similar to a universal plate mill.

1.1.2 Chemistry. Steel is essentially a combination of iron, manganese and carbon. The carbon content normally ranges between 0.05–1.00%, while the manganese content range is 0.25–1.00%. Many other elements are added in relatively small amounts to vary the mechanical characteristics of the steel.

Plate steels generally fall in the category of either a carbon steel or an alloy steel. Carbon steels comprise those grades where no minimum content is specified or required for aluminum, boron, chromium, cobalt, columbium (niobium), molybdenum, nickel, titanium, tungsten, vanadium, or zirconium, or any other element added to obtain a desired alloying effect. When specified, minimum copper does not exceed 0.40%. The maximum content specified for any of the following elements shall not exceed the percentages noted: manganese 1.65, silicon 0.60, copper 0.60.

Alloy steels comprise those grades which exceed the above limits, plus any grade to which any element other than those mentioned above is added for the purpose of achieving a specific alloying effect. Carbon steels usually have a lower base price than alloy steels and therefore are much more widely applied.

For structural applications, plates normally do not exceed 0.30% carbon and 1.50% manganese.

1. Some of the information contained in this section comes from the following sources:

American Bureau of Shipping. *Rules for building and classing steel vessels*. Parau, NJ: American Bureau of Shipping, 1990.

Bethlehem Steel Corp., *Plate selection guide, Book 1*. Bethlehem, PA: Bethlehem Steel Corporation, 1985.

1.1.2.1 Effects of Elements. The effects of the commonly specified chemical elements on the properties of hot-rolled and heat-treated carbon and alloy plates are discussed here by considering the various elements individually. In practice, however, the effect of any particular element will often depend on the quantities of other elements also present in the steel. For example, the total effect of a combination of alloying elements on the hardenability of a steel is usually greater than the sum of their individual contributions. This type of interrelation should be taken into account whenever a change in a specified analysis is evaluated.

Carbon is the principal hardening element in steel, with each additional increment of carbon increasing the hardness and tensile strength of steel in the as-rolled or normalized condition. For plate steels, the carbon level is generally less than 0.30%. For improved ductility, weldability, and toughness, carbon levels below 0.20% are preferred. A compromise must be maintained between higher carbon level required for tensile properties and lower carbon levels associated with improved ductility, weldability, and toughness.

Manganese is present in all commercial steels and contributes significantly to strength and hardness in much the same manner, but to a lesser extent, as does carbon. Its effectiveness depends largely upon, and is directly proportional to, the carbon content of the steel. Another important characteristic of manganese in steel is its ability to decrease the critical cooling rate during hardening, thereby increasing the hardenability. The effect of manganese in this respect is greater than that of any of the other commonly used alloying elements.

Manganese is an active deoxidizer, and shows less tendency to segregate within the ingot than do most other elements. Its presence in a steel is also highly beneficial to surface quality in that it tends to combine with sulfur, thereby minimizing the formation of iron sulfide, the causative factor of hot-shortness, or susceptibility to cracking and tearing at rolling temperatures.

Phosphorus is generally considered an impurity except where its beneficial effect on machinability and resistance to atmospheric corrosion is desired. While phosphorus increases strength and hardness to about the same degree as carbon, it also tends to decrease ductility and toughness, or impact strength, particularly for steel in the quenched-and-tempered condition. The phosphorus content of most steels is therefore kept below specified maxima, which range up to 0.04%.

In the free-machining steels, however, specified phosphorus content may run as high as 0.12%. This is attained by adding phosphorus to the ladle, commonly termed *rephosphorizing*.

Sulfur is generally considered an undesirable element except where machinability is an important consideration and resulfurized steels may be ordered. Whereas sulfides

in steel act as effective chip-breakers to improve machinability, they also serve to decrease transverse ductility and impact strength. Moreover, increasing sulfur impairs weldability and has adverse effects on surface quality.

Manufacturers can produce plates with a maximum 0.010% sulfur with sulfide shape control. By controlling sulfur level, significant improvements in mechanical properties are possible. Impact properties improve. Ductility increases, especially in the through-thickness direction. Weldability and formability also improve.

Silicon is one of the principal deoxidizers used in the manufacture of both carbon and alloy steels, and depending on the type of steel, can be present in varying amounts up to 0.40% as a result of deoxidation. Silicon is also a ferrite strengthener and is sometimes added as an alloying element up to approximately 0.5% in plate steels.

Nickel is one of the fundamental steel-alloying elements. When present in appreciable amounts, it provides improved toughness, particularly at low temperatures. Nickel lowers the critical temperatures of steel, widens the temperature range for effective quenching and tempering, and retards the decomposition of austenite. In addition, nickel does not form carbides or other compounds which might be difficult to dissolve during heating for austenitizing. All these factors contribute to easier and more successful thermal treatment. Because of the tight adherent scale formed on reheating nickel-containing steels, the surface quality of plates with nickel is somewhat poorer than those without nickel.

Chromium is used in constructional alloy steels primarily to increase hardenability, provide improved abrasion resistance, and to promote carburization. Of the common alloying elements, chromium is surpassed only by manganese and molybdenum in its effect on hardenability. Chromium significantly increases the corrosion resistance of some alloys.

Chromium forms the most stable carbide of any of the more common alloying elements, giving high-carbon-chromium steels exceptional wear resistance. And, because its carbide is relatively stable at elevated temperatures, chromium is frequently added to steels used for high-temperature applications.

Molybdenum exhibits a greater effect on hardenability per unit added than any other commonly specified alloying element except manganese or boron. It is a nonoxidizing element, making it highly useful in the melting of steels where close hardenability control is desired.

Molybdenum is unique in the degree to which it increases the high-temperature tensile and creep strengths of steel. Its use also reduces the susceptibility to temper brittleness.

Vanadium is widely used as a strengthening agent in steels. Vanadium additions are normally 0.10% or lower. Vanadium-bearing steels are strengthened by both precipitation hardening and refining the ferrite grain size. Pre-

precipitation of vanadium carbide and nitride particles in ferrite can provide a marked increase in strength. Thermo-mechanical processing, for example controlled rolling, increases the effectiveness of vanadium. Vanadium is also effective in increasing the hardenability and resistance to loss of strength on tempering in the quenched and tempered steels.

Columbium (niobium) is most often used in steels that receive controlled thermo-mechanical treatment. Small additions in the range from 0.02 to 0.04% provide a significant improvement in yield strength. For a given addition, columbium is approximately two times as effective as vanadium as a strengthener. When the steel is finished below about 1700°F (927°C), columbium improves notch toughness primarily by refining grain size. At higher finishing temperatures, it may be detrimental to toughness.

Copper is added to steel primarily to improve the steel's resistance to corrosion. In the usual amount of from 0.20 to 0.50%, the copper addition does not significantly affect the mechanical properties. Copper oxidizes at the surface of steel products during heating and rolling, the oxide forming at the grain boundaries and causing a hot-shortness which adversely affects surface quality. Copper is also used in some formulations of precipitation strengthened steels in use in shipbuilding and offshore structures. ASTM A-710, *Specification for Low-Carbon Age-Hardening Nickel-Copper-Chromium-Molybdenum-Columbium and Nickel-Copper-Columbium Alloy Steels*, (and the U.S. Navy modification, HSLA 80) has copper and nickel added.² The steel is precipitation strengthened, has high yield strength [80 ksi (55 MPa) min], high toughness, and is more tolerant of unpreheated welding than quenched and tempered steels such as HY-80.

Boron has the unique ability to increase the hardenability of steel when added in amounts as small as 0.0005%. This effect on hardenability is most pronounced at the lower carbon levels, diminishing with increasing carbon content. Because boron is ineffective when it is allowed to combine with oxygen or nitrogen, its use is limited to aluminum-killed steels.

Unlike many other elements, boron does not increase the ferrite strength of steel. Boron additions, therefore, promote improved machinability and formability at a particular level of hardenability. It will also intensify the hardenability effects of other alloys, and in some instances, decrease costs by making possible a reduction of total alloy content.

Aluminum is used principally to control grain size and to achieve deoxidation. The fine-grained steels produced

by aluminum killing show improved notch toughness over coarse-grained steels.

1.1.3 Deoxidation Practices. Entrapped gases are deleterious to mechanical properties of steel. Several techniques exist to remove oxygen from the molten steel.

In most steelmaking processes, a primary reaction involves the combination of carbon and oxygen to form carbon monoxide. Proper control of the amount of gas evolved during solidification determines the type of steel. If no gas is evolved, the steel is termed *killed* because it lies quiet in the mold. Increasing degrees of gas evolution characterize semikilled, capped or rimmed steel.

Rimmed steels are only slightly deoxidized, thereby allowing a brisk evolution of gas to occur as the metal begins to solidify. The gas is produced by a reaction between the carbon and oxygen in the molten steel which occurs at the boundary between the solidified metal and the remaining molten metal. As a result, the outer skin or "rim" of the ingot is practically free of carbon. The rimming action may be stopped mechanically or chemically after a desired period, or it may be allowed to continue until the action subsides and the ingot top freezes over, thereby ending all gas evolution. The center portion of the ingot, which solidifies after the rimming ceases, has a fairly pronounced tendency to segregate.

The low-carbon surface layer of rimmed steel is very ductile. Proper control of the rimming action will result in a very sound surface in subsequent rolling. Consequently, rimmed grades are particularly adaptable to applications involving cold forming, and where surface is of prime importance.

The presence of appreciable percentages of carbon or manganese will serve to decrease the oxygen available for the rimming action. If the carbon is above 0.25% and the manganese over 0.60%, the action is very sluggish or nonexistent. If a rim is formed, it will be quite thin and porous. As a result, the cold-forming properties and surface quality are seriously impaired. It is, therefore, standard practice to specify rimmed steel only for grades with lower percentages of these elements.

Since rimmed steels are only slightly deoxidized and generally furnished in thicknesses up to 1/2 in. (12.5 mm), their use in shipbuilding should be limited to the less important structural members in the ship.

Semikilled steels are intermediate in deoxidation between rimmed and killed grades. Sufficient oxygen is retained so that its evolution counteracts the shrinkage on solidification, but there is no rimming action. Consequently, the composition is more uniform than in rimmed steel, but there is a greater possibility of segregation than in killed steel. Semikilled steels are used where neither the surface and cold-forming characteristics of rimmed steel nor the greater uniformity of killed steels are essential requirements.

2. A list of document numbers and titles is at the back of this guide.

Semikilled steel is superior to rimmed steel because of less segregation. It requires less processing than killed steels and suffers less loss due to "piping." It is commonly used for weldable quality steels. Many common ship steels, both plate and structural, are semikilled.

Killed steels are strongly deoxidized and are characterized by a relatively high degree of uniformity in composition and properties. The metal shrinks during solidification, thereby forming a cavity, or "pipe," in the uppermost portion of the ingot. A refractory hot-top is placed on the mold before pouring and filled with metal after the ingot is poured. The pipe formed will be confined to the hot-top section of the ingot, which is removed by cropping during subsequent rolling. The most severely segregated areas of the ingot will also be eliminated by this cropping.

While killed steels are more uniform in composition and properties than any other type, they are nevertheless susceptible to some degree of segregation. As in the other grades, the top center portion of the ingot will exhibit greater segregation than the balance of the ingot.

The uniformity of killed steel renders it most suitable for applications involving such operations as hot-forging, cold extrusion, carburizing, and thermal treatment.

1.1.4 Heat Treatment of Plate Steels. The versatility of steel is attributable in large measure to its response to a variety of thermal treatments. While a major percentage of steel is used in the as-rolled condition, thermal treatments greatly broaden the spectrum of properties attainable. Heat treatments fall into two general categories: (1) those which decrease hardness and promote uniformity by slow cooling, and (2) those which increase strength, hardness and toughness by virtue of rapid cooling from above the transformation range. Annealing, normalizing, and stress relieving fall in category 1, while quenching and tempering and thermomechanical treatment are typical category 2 treatments.

1.1.4.1 Annealing indicates a single thermal treatment intended to place the steel in a suitable condition for subsequent fabrication. Annealing may be required where machining or severe forming is involved. The steel is heated to a temperature either slightly below or above the transformation temperature followed by a slow cool. The exact temperature and cooling rate or cycle are dependent on the properties desired by the purchaser.

1.1.4.2 Normalizing consists of heating the steel above its critical temperature range [typically 1650 to 1700°F (900 to 927°C) for plate steels] and cooling in air. This heat treatment is commonly specified to obtain uniform grain refinement and results in improved notch toughness compared to as-rolled steels. Normalizing is commonly specified for plates of pressure vessel quality for thickness over 2 in. (50 mm).

1.1.4.3 Stress relieving consists of heating the steel to a suitable temperature after flattening or other cold working, shearing, welding, or cutting to relieve stresses induced by these operations. Stress relieving is primarily a function of temperature, with time at temperature a secondary factor. A typical stress-relieving treatment for plate steel involves heating in the range of 1000 to 1200°F (538 to 649°C) followed by slow cooling. For quenched and tempered steels, the stress relief temperature should be maintained below the original tempering temperature of the plate.

1.1.4.4 Quenching and tempering are used to improve the strength and toughness of steel plate. The treatment consists of heating the steel to the proper austenitizing temperature [for example, 1650°F (899°C) could be used for a 0.20% carbon steel] holding it at temperature to allow complete transformation to austenite to occur and quenching in water. After quenching, the steel is tempered at an appropriate temperature normally in the range of 800 to 1200°F (427 to 649°C). The purpose of tempering is to relieve internal stresses and improve ductility and toughness.

The use of precipitation hardening and quenched and precipitation hardening steels such as ASTM A710 is on the rise. These steels (ASTM A710 and its modifications) are similar to the U.S. Navy steels HSLA 80 and HSLA 100.

1.1.4.5 Thermomechanical Treatments

(1) Control Rolling. As an alternative or substitute for heat treatments that require additional material handling and furnace facilities, improved properties can also be obtained through special processing techniques at the rolling mill. *Control rolling* is widely practiced to increase strength and improve notch toughness of plate steels. Control rolling is a plate-rolling practice that tailors the time-temperature deformation process by controlling the rolling parameters. The parameters of primary importance are (1) the temperature for start of control rolling in the finishing stand where the final rolling of the steel takes place, (2) the percentage reduction from start of control rolling to the final plate thickness, and (3) the plate finishing temperature.

As seen in Figure 1, control rolling involves deformation at much lower temperatures than hot rolling, usually in the range from 1300 to 1500°F (704 to 816°C). In contrast, a normal hot-rolling practice takes advantage of the better hot workability of the material at higher temperatures. Hot-rolled plates are finished as quickly as possible, frequently at temperatures of 1800°F (982°C) and above. For control rolling, a hold or delay is generally taken to allow time for the partially rolled slab to reach the desired intermediate temperature before start of final rolling. Control-rolling practices are designed specifically for use with microalloyed grades which take advantage

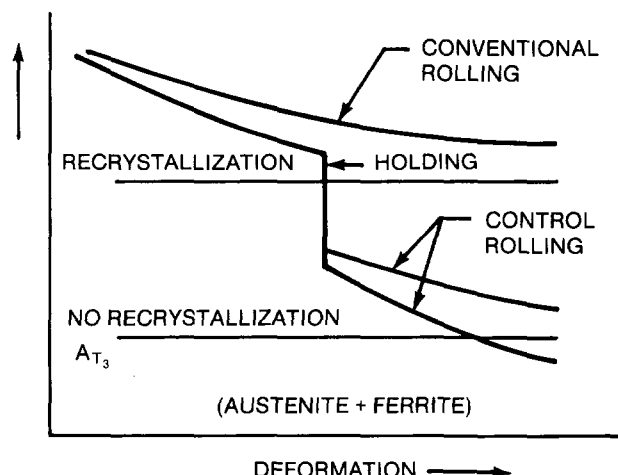


Figure 1—Schematic Temperature Versus Deformation Plot Showing Differences Between Conventional Hot-Rolling and Control-Rolling

of the alloying element's influence on recrystallization and grain growth in combination with the specific reduction schedule. Because of practical considerations, primarily mill load and delay times, control-rolled plates are not normally produced above about 1 in. (25 mm) thickness.

(2) **Control Finishing Temperature Rolling.** The term *control finishing temperature rolling* is used to differentiate from the term *control rolling*. The control finishing temperature rolling is a much less severe practice than control rolling and is primarily aimed at improving notch toughness for thicker plate up to 2-1/2 in. (63.5 mm) thickness. The finishing temperatures in this practice (approximately 1600°F or 871°C) are higher than required for control rolling. However, because heavier plates are involved than in control rolling, mill delays to reach the desired temperatures are still encountered. By controlling the finishing temperature, fine grain size can be obtained with resulting excellent notch toughness.

(3) **Precipitation Strengthened Steels.** Steels using this mechanism of achieving high yield strength and toughness were introduced in shipbuilding in the 1980's. In this method, the steel is heated to drive copper (1.0% to 1.3%) into solid solution in the steel matrix. Carbon is kept relatively low in content (0.07 max. for HSLA-80) which prevents formation of brittle martensite on rapid cooling. A supplementary thermal treatment from 1100 to 1300°F (593 to 704°C) is applied which allows precipitation of copper in the lattices of the matrix steel. The resulting lattice distortion is believed to be the mechanism which inhibits permanent deformation of the steel under stress with resulting increase in yield strength. Steels up to

100 ksi (690 MPa) minimum yield strength are being produced. The reduction in carbon content has allowed welding with little or no preheat and has avoided many of the problems associated with quenched and tempered steels. In addition to use in ship hull plating, HSLA-80 steels have been processed in coils on a strip mill and welded into structural beams using high frequency resistance welding at speeds of over 100 ft/min (30.5 m/min).

1.1.5 Castings and Forgings. The use of large steel castings and forgings is gradually declining in favor of weldments. Some ship parts are still made from forged or cast steel. Large quantities of anchor chain are furnished from both cast and forged steel. Forgings are widely used for such parts as tail shafts, rudder stocks, and anchor sections. The properties of cast and forged steels are determined by the chemical composition, heat treatment, and method of manufacture. Since most forgings and castings may be subject to welding either during initial fabrication or later during repair, the carbon content must be controlled to avoid welding difficulties.

1.2 Higher Strength Steels. To ensure suitable mechanical properties and adequate weldability, care must be exercised in selecting higher strength steels. Higher strength steels for commercial marine applications may be separated into two categories: the higher strength carbon steels having yield strengths of approximately 50 000 psi (345 MPa) and the low alloy steels having yield strengths ranging to approximately 100 000 psi (690 MPa).

Higher strength steels are sometimes used to reduce the steel weight of a ship and to avoid the use of exceptionally thick plates in highly stressed areas. The lighter material often provides the opportunity to increase the length and width of plates that can be ordered from the mill, and this can reduce the number of welding joints required. Alloy steels are necessary for low temperature service, below approximately -70°F (-57°C), and are used in areas where superior notch toughness is required.

When higher strength steels such as ASTM A710 or its modifications are used, those steels which attain their strength from precipitation hardening, sustained minimum preheat, and interpass temperature controls are not required. Moisture drying preheat will be required, and while heat input is not limited, the interpass temperature should not exceed 450°F (232°C) in order to control grain growth and produce adequate notch toughness.

1.3 Notch Toughness Properties of Steel. Notch toughness or impact resistance refers to the ability of a material, under load, to absorb energy by plastic deformation. This property allows the material to resist brittle fracture in the presence of metallurgical or mechanical cracks or notches. When little or no energy is absorbed plastically before fracture, and the break is of the cleavage

type, the behavior of the material is described as brittle. Because this property of steel is strongly dependent upon temperature, transition temperature (the temperature at which the characteristics of the fracture change from ductile to brittle) has become a standard criterion of notch toughness. Depending upon material, the transition can occur over a fairly wide range. For example, the carbon steel transition region exists from -100°F (-73°C) to approximately 50°F (10°C). This is a range of 150°F (83°C).

1.3.1 Transition Temperature. There are a number of methods for specifying material with adequate notch toughness. The most common approaches, including Charpy testing, drop weight testing, and fracture mechanics, are described below.

Charpy V-notch testing is the most widely applied test for determining notch toughness. The Charpy test is shown in Appendix D. This specimen is notched perpendicular to the plate surface. The direction (longitudinal or transverse) of the specimen axis is selected according to the appropriate specifications for steel plate. The specimen is held for ten minutes at test temperature and then broken in the appropriate Charpy-type impact tester by a single blow of a freely swinging pendulum.

On breaking the Charpy specimen, three criterion are commonly measured. The loss of energy in the pendulum swing provides the energy in terms of foot pounds absorbed in breaking the specimen.

The fracture appearance of the broken specimen in terms of ductile and brittle failure can be rated. In addition, the lateral expansion at the base of the fracture opposite the notch can be measured. Any of these criterion can be plotted versus temperature to obtain the typical transition curve. The notch toughness will vary with specimen orientation, and requirements are generally negotiated between the customer and the supplier with a given energy at a specified temperature being the most common criteria.

During World War II, a number of Liberty ships experienced brittle fractures primarily initiating at notches in the deck plate. Service failures were never observed at temperatures at which the Charpy value was 15 ft-lb or greater. As a result, the 15 ft-lb transition temperature requirement was established and has become the most commonly used criterion in specifications. Naturally, this criterion best applies to the plain carbon steels for which it was developed. With the introduction of higher strength steels, the fracture appearance and lateral expansion values provide alternate approaches that can be considered to measure ductile performance.

The Charpy-testing approach suffers from the fact that a small specimen is tested that does not see the same conditions as the material in an actual structure. Therefore, the test results are most useful in rating material on a comparison basis.

A standard Charpy V-notch test specimen is shown in Figure 2A. A typical Charpy V-notch transition temperature curve for one particular grade of mild steel is shown in Figure 2B.

It is important to realize that the thickness and shape or geometry of the specimen or structure has a marked influence on transition temperature. Specimens with sharper notches and greater restraint will have the higher transition temperatures, and larger specimens composed of thicker material will have higher transition temperatures than similar smaller specimens. In addition to the influence of geometry, transition temperature is also influenced by the type of steel used, the general stress level, and the rate of loading. Transition temperatures increase with stress levels and loading rates.

Figure 3 shows Charpy V-notch curves for three grades of ordinary strength steel, one grade of a higher strength quenched and tempered low alloy steel, plus one grade of a quenched and precipitation-hardened steel. It should be remembered, when transition temperatures are compared, that impact energy values required for higher strength steels are usually greater than those specified for ordinary strength steels.

Drop Weight Testing is also used to determine impact toughness of steel plates and the nil-ductility-transition temperature (NDT Temp). This test is carried out in accordance with ASTM E208 as shown in Appendix D. Rectangular pieces are cut from the test plate and a crack-starter bead is deposited across the specimen. A notch is machined across the weld bead. Specimens are tested as a function of temperature. A specimen is set on an anvil, welded surface down and then struck by a guided, free-falling weight. A crack must initiate from the crack starter for the test to be valid. If the crack runs to the edge of the specimen, the specimen is considered a break (failure). The test is strictly a go or no-go result. The NDT temperature is defined as the maximum temperature at which a drop weight specimen breaks in the test. The NDT temperature is very reproducible and can be defined within 10°F (5.6°C) for a given plate.

The physical significance of the NDT value to the designer is that if a material is selected whose NDT is lower than the expected service temperature, brittle failure will not occur at a small crack subjected to yield stress levels under conditions of dynamic loading. Additionally, this (NDT) information can be used to determine tolerable crack size at lesser stress levels. This method is explained by William S. Pellini in "Principles of Fracture-Safe Design" (*Welding Journal*, March 1971).

1.3.2 Effect of Plate Thickness. From a metallurgical standpoint, thicker plates will be more notch sensitive than thinner plates from the same lot or heat of steel. This is due mainly to the difference in mill finishing temperatures. Increasing the plate thickness from 1/2 to 1-1/2 in.

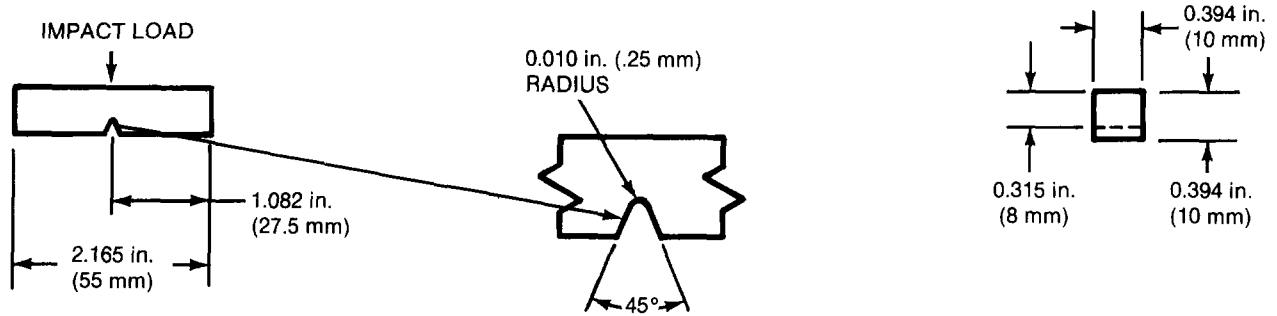
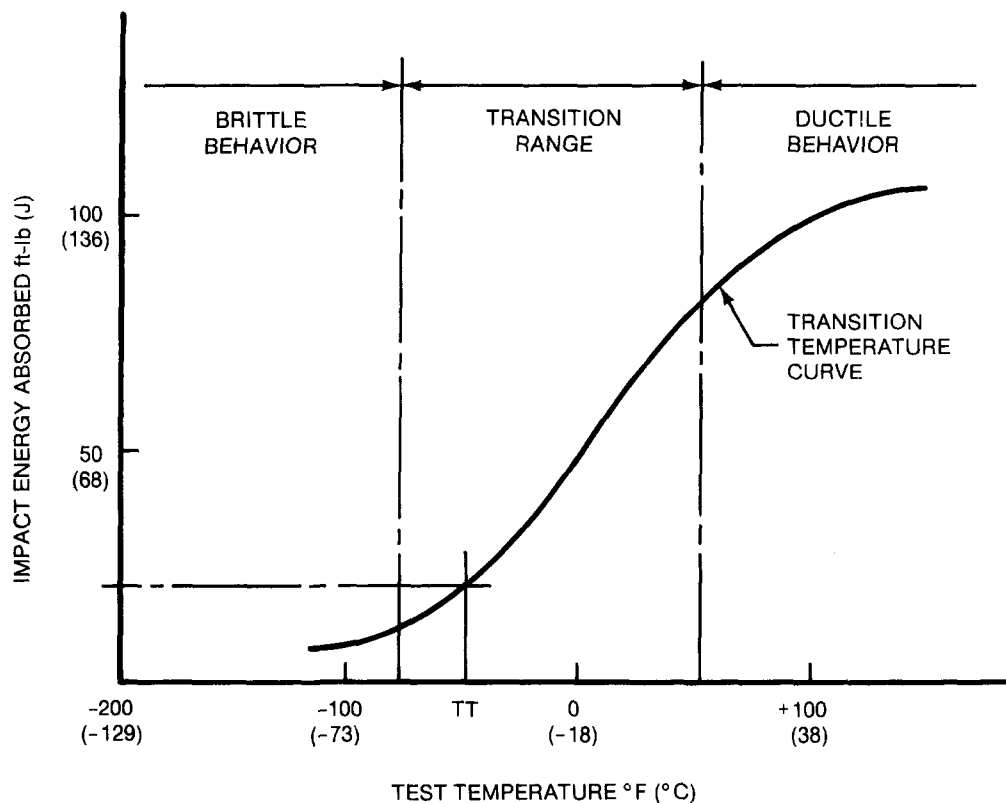


Figure 2A—Standard Charpy V-Notch Test Specimen



NOTE: TRANSITION TEMPERATURE (TT) IS DEFINED AS THE TEMPERATURE AT WHICH THE CURVE CROSSES A SPECIFIED ENERGY VALUE.

Figure 2B—Typical Charpy V-Notch Transition Temperature Curve for ABS Grade D Steel

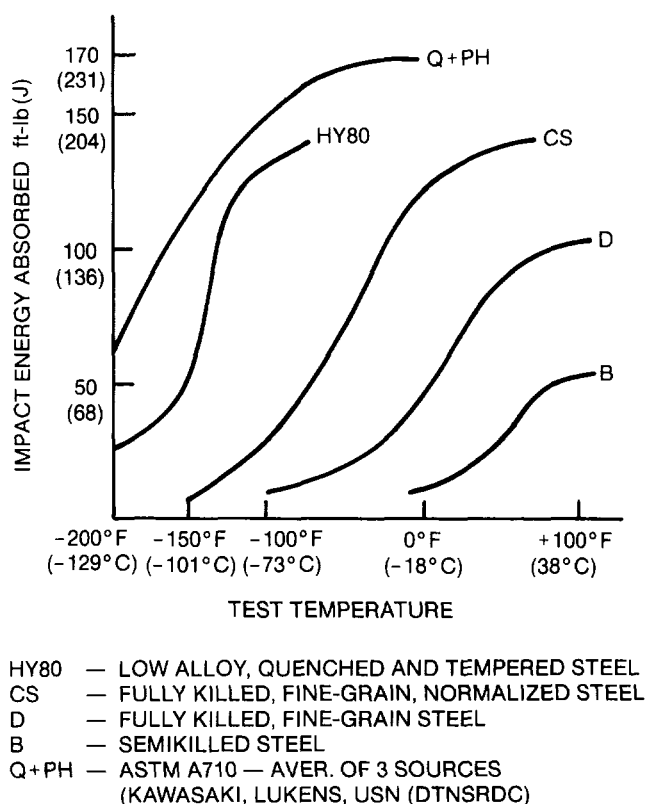


Figure 3—Typical Charpy V-Notch Transition Temperature Curves for Several Grades of Steel

(12 to 38 mm) has been found in some cases to raise the impact transition temperature by 50 to 68°F (28 to 38°C).

As the thickness of a plate increases, its ability to deform in the thickness direction decreases. Hence, from a geometrical standpoint, increased plate thickness in front of a notch adds restraint and increases the chance of brittle failure.

For certain critical locations, this size effect is at least partially offset by the required use of steel having greater notch toughness in the thicker plates. Regardless of location, great care should be exercised in the detailing and fabricating of structures which employ thick plates.

1.3.3 Directional Properties of Rolled Plate. When plates are rolled, the orientation of the constituents is elongated in the direction of rolling. As a result, the Charpy V-notch values of longitudinal specimens are greater than those of transverse specimens. It is, therefore, advisable to orient ship plates fore and aft so that the longitudinal direction of rolling is in the same direction as the primary stress.

The notch toughness of plates is even poorer in the thickness direction, that is, perpendicular to the plate

surfaces. In addition, tensile strength and ductility are also reduced in the thickness direction. Therefore, it is advisable to follow the general practice of not requiring high tensile stresses to be transmitted through the thickness of a plate. Where this is unavoidable, the use of special steels with enhanced through-thickness mechanical properties should be considered.

1.3.4 Effect of Cold Forming. Cold forming may damage the material in several ways. Physical damage, such as surface cracking, may occur as a result of flanging or severe forming. Moderately severe cold working of the steel reduces its notch toughness and ductility. In some steels, there may be a further adverse effect from strain aging, which is usually accelerated by moderate heating.

Reduction in notch toughness due to cold forming becomes significant only when steel is stretched more than 3%. The rolling of bilge plates or rounded gunwales should not present a problem. However, the rolling of thick plates to a small radius would affect the notch toughness and, therefore, may require a stress relief heat treatment. The minimum radius for bending will vary depending upon the specifying agency or recommendations of the manufacturer in the case of proprietary grades of steel. The latest guide for forming, as set forth in *American Bureau of Shipping Rules*, should be consulted.

Strain aging of ship steel is usually of little consequence, but precautions should be taken when using rimmed-type steels for cold-formed members in any kind of structure. These steels, when strain aged, exhibit a significant reduction in ductility.

Removal by grinding of approximately 1/8 in. (3 mm) of the sheared or flame-cut edge and rounding the edge of a plate that is to be formed, particularly a thick plate, reduces the likelihood of a crack starting on the edge.

The quenched and precipitation-hardened steels offer expanded cold-forming capabilities when formed in the quenched-only condition. Since in this condition the plate has only attained 70 to 75% of its final yield strength, improvements in forming limits can be gained. The subsequent precipitation hardening produces the desired yield point as well as good notch-toughness qualities in the steel.

1.4 Notch Toughness of Weld Metal and Heat-Affected Zone. The primary reason for the many different grades of steels, such as those in Tables 1A, 1B, 2A, 2B and 2C, is the requirement for various degrees of notch toughness, depending on the type of structure, the plate thickness, and the service temperature.

Using selected welding conditions and consumables, it is possible to meet the minimum notch toughness properties of the base metal in both the weld and heat-affected zone. However, when high heat input welding processes are used, there is usually a degradation of impact properties. This is a main reason why the use of some welding

Table 1A
American Bureau of Shipping Requirements for Ordinary-Strength Hull Structural Steel
Grades A, B, D, E, DS, CS 51 mm (2 in.) and Under

Grades	A	B	D	E	DS	CS
Deoxidation	Semi-killed or killed steel for (in.)	Semi-killed or killed steel	Fully killed fine-grain practice (1)	Fully killed fine-grain practice	Fully killed fine-grain practice	Fully killed fine-grain practice
Chemical Composition (Ladle Analysis)	For all grades exclusive of Grade A shapes and bars, the sum of carbon content and one-sixth of the manganese content is not to exceed 0.40%. The upper limit of manganese may be exceeded up to a maximum of 1.65% provided this condition is satisfied.					
Carbon %	0.23 max. (2)	0.21 max.	0.21 max.	0.18 max.	0.16 max.	0.16 max.
Manganese %	2.5 x carbon min. for plates over 12.5 mm (0.5 in.)	0.80–1.10 0.60 min. for fully killed or cold flanging	0.71–1.35 0.60 min. for thickness 25 mm (1.0 in.) and under	0.70–1.35	1.00–1.35	1.00–1.35
Phosphorus %	0.04 max.	0.04 max.	0.04 max.	0.04 max.	0.04 max.	0.04 max.
Sulphur %	0.04 max.	0.04 max.	0.04 max.	0.04 max.	0.04 max.	0.04 max.
Silicon %	—	0.35 max.	0.10–0.35	0.10–0.35	0.10–0.35	0.10–0.35
Nickel %	The content of these elements is to be determined and reported, and when the amount present is less than 0.02%, these elements may be reported as < or = 0.02%.					
Chromium %						
Molybdenum %						
Copper %						
Tensile Strength	For all Grades: 41–50 kg/mm ² (58,000–71,000 psi); for Grades A shapes and bars 41–56 kg/mm ² (58,000–80,000 psi). For cold flanging quality: 39–46 kg/mm ² (55,000–65,000 psi)					
Yield point, min.	For all Grades: 24 kg/mm ² (34,000 psi); for Grade A and over 25.0 mm (1.0 in.) in thickness 23 kg/mm ² (32,000 psi). For cold flanging quality: 21 kg/mm ² (30,000 psi)					
Elongation, min.	For all Grades 21% in 200 mm (8 in.) (See 43.3.4d)* or 24% in 50 mm (2 in.) for specimen see Figure 43.2* or 22% in 5.65 A (A equals cross-sectional area of test specimens). For cold flanging quality: 23% in 200 mm (8 in.).					
Impact Test Charpy V-notch Temperature	0°C (32°F) Over 25 mm (1.0 in.)	–10°C (14°F)	–40°C (–40°F)			
Energy Avg. min.						
Longitudinal Specimens	2.8 kg-m (20 ft-lb)	2.8 kg-m (20 ft-lb)	2.8 kg-m (20 ft-lb)			
or						
Transverse Specimens	2.0 kg-m (14 ft-lb)	2.0 kg-m (14 ft-lb)	2.0 kg-m (14 ft-lb)			
Heat Treatment	Normalized over 35 mm (1.375 in.) thick (4)	Normalized (6)	Normalized over 35 mm (1.375 in.)	Normalized		
Marking	AB/A	AB/B	AB/D(5)	AB/EE	AB/DS	AB/CS

*ABS Rules for Building and Classing Steel Vessels, American Bureau of Shipping.

- (1) Grade D may be furnished semi-killed in thickness up to 35 mm (1.375 in.) provided steel above 25.0 mm (1.00 in.) in thickness is normalized. In this case the requirements relative to minimum Si and Al contents and fine grain practice do not apply.
- (2) A maximum carbon content of 0.26% is acceptable for Grade A plates equal to or less than 12.5 mm (0.5 in.) and all thicknesses of Grade A shapes and bars.
- (3) Impact tests are not required for normalized Grade D steel when furnished fully killed fine grain practice.
- (4) Controlled rolling or thermo-mechanical controlled rolling of Grade D steel may be specially considered as a substitute for normalizing.
- (5) Grade D hull steel which is normalized, thermo-mechanical controlled rolled, or controlled rolled in accordance with Note 4 is to be marked AB/DN.
- (6) Controlled rolling or thermo-mechanical controlled rolling of Grade E shapes and thermo-mechanical controlled rolling of Grade E plates may be specially considered as a substitute for normalizing.

Table 1B
American Bureau of Shipping Requirements for
Ordinary-Strength Hull Structural Steel Over 51 mm (2 in.)

Process of Manufacture: Open Hearth, Basic Oxygen, or Electric Furnace

Grades	A	B	D	DS	CS	E
Impact Test Charpy V-notch Temperature	20°C* (68°F)	0°C (32°F)	-10°C (14°F)	-10°C (14°F)	-40°C (-40°F)	-40°C (-40°F)
Energy avg. min Longitudinal Specimens or Transverse Specimens	2.8 kg-m (20 ft-lb) 2.0 kg-m (14 ft-lb)	2.8 kg-m (20 ft-lb) 2.0 kg-m (14 ft-lb)	2.8 kg-m (20 ft-lb) 2.0 kg-m (14 ft-lb)	2.8 kg-m (20 ft-lb) 2.0 kg-m (14 ft-lb)	2.8 kg-m (20 ft-lb) 2.0 kg-m (14 ft-lb)	2.8 kg-m (20 ft-lb) 2.0 kg-m (14 ft-lb)
No. of Specimens	3 from each* 50 tons	3 from each 50 tons	3 from each 50 tons	3 from each 50 tons	3 from each plate	3 from each plate
Heat Treatment	None Required	None Required	Normalized	Normalized	Normalized	Normalized
Deoxidation	Fully killed	Fully killed	Fully killed fine-grain practice	Fully killed fine-grain practice	Fully killed fine-grain practice	Fully killed fine-grain practice

*Impact tests for Grade A are not required when material is produced using a fine grain practice and normalized.

processes should not be permitted for welding joints in highly stressed areas, such as sheer strakes, where special material is required. In this respect, the large casting type of weld structure obtained by such processes as electroslag and electrogas, and some multiple wire submerged arc welding, has reduced toughness as compared to that of multiple-pass welds. Multiple-pass welds may be required in lieu of single-pass welds where superior impact properties are required. This is of particular importance when welding the higher strength steels and steels for low-temperature service.

As the impact requirements become more severe (lower-transition temperature requirements), it becomes more difficult and more costly to produce welds with impact properties to match those of the base metal, particularly for service temperatures below -20°F (-29°C) and for the higher strength steels. With some high-heat-input welding processes, procedures have not yet been developed to make welded joints that meet required impact properties.

1.5 Fatigue. Metal fatigue is the process by which a part, component, or structure degrades or fails when it experiences cyclic loading. Fatigue can account for as much as 90% of all failures. In general, fatigue involves two stages (1) the initiation of a crack, and (2) its subsequent growth

to failure. Failure ultimately occurs when the crack is so large that the uncracked section or ligament is unable to support the applied load. The relative importance of each stage of the cracking process depends upon factors which include the presence of stress raisers (welds, holes, changes in section, etc.), the strength of the material, the applied stress range, and the size of the member. In the case of unnotched specimens, crack initiation can occupy the largest fraction of life, while propagation is the dominant stage when notches are present.

Crack initiation occurs when plastic deformation accumulates in a local region. In absence of a stress raiser, plastic deformation changes an initially flat surface to a notch-peak topography with many small cracks initiating at the base of the surface notches. As cyclic loading progresses, these small cracks join to form a larger one which can grow in response to the applied cyclic loads. In the presence of a notch (hole, weld toe, etc.), this same sequence occurs at an accelerated rate. The number of loading cycles required for crack initiation depends on the material, cyclic load range, and stress concentration factor of the notch.

Crack propagation is similar to crack initiation in that its driving force is the localized plasticity that occurs at the crack tip in response to the applied loads. As the tensile

Table 2A
American Bureau of Shipping Requirements for Higher Strength Hull Structural Steel
Grades AH32, DH32, EH32, AH36, DH36, and EH36 51 mm (2 in.) and Under

Process of Manufacture: Open Hearth, Basic Oxygen, or Electric Furnace

Grades (1)	AH32	DH32	EH32	AH36	DH36	EH36
Deoxidation	Semi-killed or Killed ⁴	Killed, Fine Grain Practice ⁴	Killed, Fine Grain Practice ⁴	Semi-killed or Killed ³	Killed, Fine Grain Practice ⁴	Killed, Fine Grain Practice ⁴
Chemical Composition for All Grades (Ladle Analysis)	Carbon, %	0.18 max.				
	Manganese, % ²	0.90–1.60				
	Phosphorus, %	0.04 max.				
	Sulfur, %	0.04 max.				
	Silicon, %	0.10–0.50				
	*Nickel, %	0.40 max.	These elements need not be reported on the mill sheet unless intentionally added.			
	*Chromium, %	0.25 max.				
	*Molybdenum, %	0.08 max.				
	*Copper, %	0.35 max.				
	Columbium, % (Niobium)	0.05 max.				
Vanadium, %	0.10 max.					
The content for any other element intentionally added is to be determined and reported.						
Tensile Strength	48–60 kg/mm ² ; 68,000–85,000 psi 32 kg/mm ² ; 45,000			psi 50–63 kg/mm ² ; 71,000–90,000 psi psi 36 6 kg/mm ² ; 51,000 psi		
Elongation, min.	For all Grades: 19% in 200 mm (8 in.) (see 43.3.4d)** or 22% in 50 mm (2 in.) (for specimen in Figure 43.2)** or 20% in 5.65 A (A equals cross-sectional area of test specimen).					
Heat Treatment	See Table 2C					
Impact Test Charpy V-notch Temperature	0° (32°F)	–20°C (–4°F)	–40°C (–40°F)	0°C (32°F)	–20°C (–4°F)	–40°C (–40°F)
Energy, avg. min.						
Longitudinal Specimens or Transverse Specimen	3.5 kg-m (25 ft-lb) ⁵ (17 ft-lb) ⁵	3.5 kg-m (25 ft-lb) ⁵ (17 ft-lb) ⁵	3.5 kg-m (25 ft-lb) (17 ft-lb)	3.5 kg-m (25 ft-lb) ⁵ (17 ft-lb) ⁵	3.5 kg-m (25 ft-lb) ⁵ (17 ft-lb) ⁵	3.5 kg-m (25 ft-lb) (17 ft-lb)
Marking	AB/AH32	AB/DH32	AB/EH32	AB/AH36	AB/DH36	AB/EH36

Notes:

- The numbers following the Grade designation indicate the yield point or yield strength to which the steel is ordered and produced in kg/mm².
- Grade AH 12.5 mm (0.50 in.) and under in thickness may have a minimum manganese content of 0.70%.
- Grade AH plates to 12.5 mm (0.50 in.) inclusive and all thickness of AH shapes may be semi-killed in which case the 0.10% minimum silicon does not apply. Unless otherwise specially approved, Grade AH plates over 12.5 mm (0.50 in.) are to be killed with 0.10 to 0.50% silicon.
- Grades and EH are to contain at least one of the grain refining elements in sufficient amount to meet the fine grain practice requirement.
- Impact tests are not required for All, 12.5 mm (0.5 in.) and less in thickness, and aluminum treated Grade AH, 35 mm (1.375 in.) and less in thickness. Impact tests are not required for any fully killed, fine grain normalized Grade AH, or DH, 51 mm (2 in.) and less in thickness.
- The marking AB/DHN is to be used to denote Grade DII plates which have either been normalized, thermo-mechanical controlled rolled or control rolled in accordance with an approved procedure.
- ABS 1991 Rules include changes reflecting IACS's unified requirements for the addition of AH, DH, & EH40 to replace AH, DH, and EH36.

*These elements may be reported as < or = 0.02% when the amount present is less than 0.02%.

**ABS Rules for Building and Classing Steel Vessels, American Bureau of Shipping.

Table 2B
American Bureau of Shipping Requirements for
Higher Strength Hull Structural Steel Over 51 mm (2 in.)

Process of Manufacture, Open Hearth, Basic Oxygen, or Electric Furnace			
Grades	AH 32 and 36	DH 32 and 36	EH 32 and 36
Impact Test Charpy V-notch Temperature	0°C (32°F)	-20°C (-4°F)	-40°C (-40°F)
Energy avg. min Longitudinal Specimens	3.5 kg-m (25 ft-lb)	3.5 kg-m (25 ft-lb)	3.5 kg-m (25 ft-lb)
or Transverse Specimens	2.4 kg-m (17 ft-lb)	2.4 kg-m (17 ft-lb)	2.4 kg-m (17 ft-lb)
No. of Specimens	3 from each 50 tons	3 from each 50 tons	3 from each plate
Heat Treatment	Normalized	Normalized	Normalized

Table 2C
American Bureau of Shipping Normalizing Heat Treatment Requirements
for Higher Strength Hull Structural Steels

Grade	AH	DH ¹	EH ³
Aluminum Treated Steels	Over 51 mm (2 in.) Thick	Over 25.5 mm (1 in.) Thick	All Thicknesses
Columbium ² or Vanadium	Over 51 mm (2 in.) Thick	Over 12.5 mm (0.5 in.) Thick	All Thicknesses

Notes:

1. Controlled rolling or thermo-mechanical controlled rolling of Grade DH may be specially considered as a substitute for normalizing.
2. When columbium (niobium) or vanadium is used in combination with each other or with aluminum, the heat treatment requirements for columbium (niobium) or vanadium apply.
3. Controlled rolling or thermo-mechanical controlled rolling of Grade EH shapes and thermo-mechanical controlled rolling of Grade EH plates may be specially considered as a substitute for normalizing.

stress is increased, the crack grows and ultimately the crack-tip is enlarged or blunted. On unloading, the crack-tip radius is resharpened for the next loading cycle. The rate at which a crack grows during one loading cycle is usually expressed in terms of the range in stress intensity factor (a function of the load range, crack length, and the specimen geometry), and is typically insensitive to the strength of the material. There are numerous references dealing with the kinetics of crack propagation, i.e., plots of crack growth rate versus the range in stress intensity factor.

Variables Affecting Fatigue

Some of the most important variables affecting fatigue are the following:

(1) Stress range — life decreases as stress range increases

(2) Residual stresses — life decreases for tensile residual stress and increases for compressive residual stress

(3) Notches or welds — reduce fatigue life

(4) Material properties — long-life fatigue strength (10^6 – 10^7 cycles) increases with increasing tensile strength in absence of a notch

(5) Corrosive environment — typically degrades fatigue performance

In addition, other variables such as stress state, stress ratio, surface condition, microstructure, inclusions, grain size, heat treatment, and deoxidation practice, can play a role in the fatigue process. However, the influence of these

variables is generally of secondary importance relative to those listed above.

Material effects in fatigue are primarily controlled by the tensile strength with higher strength materials having proportionally higher long-life (10^6 to 10^7 cycle) fatigue resistance. In the presence of a sharp notch, fatigue life is insensitive to differences in strength level because crack propagation, the dominant phase of life in this case, is insensitive to differences in strength level. In practice, manufactured products frequently have notches or details which act like notches. Thus, it is seldom possible to achieve greater fatigue life through material selection alone.

Changing materials to increase the fracture toughness increases the critical crack length for failure under a given loading condition, and increases the margin of safety against overloads causing failure when cracks are small. However, increasing fracture toughness will not markedly lengthen fatigue life because the bulk of life is spent in crack growth when the crack is much smaller than the critical crack size.

Fracture and fatigue are best controlled by proper methods of design, fabrication, and inspection. Improved material properties and quality will not compensate for poor performance in any of the following:

(1) Every effort should be made to minimize the severity of notches, or at the least, to reduce the stress in the vicinity of the notch.

(2) In the presence of a sharp notch such as the toe of weldment, most of the fatigue life will be spent in crack propagation.

Several ways to improve the fatigue life of welded joints include the following:

(a) grinding off the groove weld reinforcement
(b) dressing fillet welds and avoiding undercut or overlap

(c) locating the weld in a low stress region
(d) avoiding joints with large variation in stiffness
(e) avoiding use of intermittent welds

(3) Initial and periodic inspections are necessary to the development of a rational plan for controlling fatigue and fracture.

(4) A thorough fatigue design will consider the possible influences of temperature and environment.

1.6 Specifications for Steel

1.6.1 Ordinary and Higher Strength Steels. The American Bureau of Shipping (ABS) and the American Society for Testing and Materials (ASTM) have issued similar requirements covering hull steels. Tables 1A, 1B, 2A, and 2B give the principal ABS requirements for ordinary strength and higher strength hull structural steels.

Unless otherwise specified, shapes and bars may be made of steel meeting the requirements of Grade A or AH

quality. Other grades of steel like A36 may be used as long as the chemistry, strength, toughness, and weldability are adequate for their intended application.

Popular commercial grades of high-strength steel that have a 45 000 to 60 000 psi (315 to 420 MPa) yield strength have been used in ships for special applications involving high stress or low temperature service, i.e., such steels as ASTM A537 Class 1 and Class 2. In some instances, steels developed by the U.S. Navy, HY 80, HY 100, HSLA 80, and HSLA 100 are used. HSLA 80 is actually a modified ASTM A710, Gr A, Class 3 for structures and ASTM A736, Gr A, Class 3 for pressure vessels.

1.6.2 Plate Thickness Limitations. The various grades of steel plate have thickness limitations depending on the location of the plate in the structure, as given in Table 3. Note especially the thickness of plate for special applications.

1.6.3 U.S. Navy. The U.S. Navy has specifications for mild steel, high tensile, and low alloy high-strength steels. Specification MIL-S-22698, covering structural carbon steel for ships, is in substantial agreement with the ABS specification for ordinary strength hull steel. For thicker plates, both specifications contain specific requirements for normalizing to enhance the notch toughness.

Several strength levels of quenched and tempered steels from 50 000 to 100 000 lb/in (345 to 690 MPa) yield strength are covered by Naval Material Procurement Specifications. Development work shows promise for 130 000 to 150 000 lb/in (860 to 1035 MPa) yield-strength material for weldments of high toughness. The low alloy quenched and tempered HY80 and HY100 steels are covered in MIL-S-16216.

HSLA-80 is specified in MIL-S-24645, which also includes HSLA-100. The primary differences in chemistry between HSLA-80 and ASTM A710 are for HSLA-80 allowable sulfur has been reduced to 0.010%, and 0.06% maximum columbium is permitted. Calcium treatment of the melt is also required for sulfide inclusion shape control. Mechanical property requirements include 80 to 99.5 ksi (55 to 69 MPa) yield strength and transverse Charpy-V-notch requirements of 35 ft/lb at -120°F (-85°C) and 60 ft/lb at 0°F (18°C).

The welding standard applicable to most current U.S. Navy surface combatant fabrication is MIL-STD-1689, *Fabrication, Welding and Inspection of Ships Structures*. This is a later document than NAVSHIPS 0900-000-1001 which may still apply under some contracted work. Both documents have extensive lists of references to applicable material specifications, Military Standards, and other relevant publications.

When requesting specifications, it is important that the proper contractual issue is obtained.

Table 3
Thickness Limitations for ABS Steel Grades

Type	Grade	Ordinary I, II, III ^a Applications		Special IV, V ^a L > 820 ft (250 m) Applications ^b	
		in.	mm	in.	mm
Ordinary Strength	A	0.79	20	0.060	15 ^c
	B	0.98	25	0.79	20
	D	1.38	35	0.98	25
	D	1.57	40 when normalized	1.18	30 when normalized
	DS	1.38	35	0.98	25
	CS	2.00	51	2.00	51
	E	2.00	51	2.00	51
Higher Strength	AH	0.98	25	0.79	20
	DH	1.57	40	1.18	30
	EH	2.00	51	2.00	51

Notes:

a. Roman numerals I, II, III, IV, and V are ABS material classes.

b. When special material is required in the rules because of applications in bilge strake, sheerstrake, strength-deck hatch-side strake, or stringer plate.

c. Acceptable to 0.79 in. (20 mm) maximum for bilge strake with a double bottom over the full breadth and with a length less than 492 ft. (150 m).

1.6.4 Castings and Forgings. Castings normally conform to ASTM A27 (Grade 60-30), and forgings to ASTM A668, latest editions. See MIL-STD-1689, *Fabrication, Welding, and Inspection of Ships Structure*, for Federal and Military Specifications pertaining to castings and forgings.

1.6.5 Requirements for Low Temperature Services. Chapter VI of the IMO *International Code for the Construction and Equipment of Ships Carrying Liquefied Gas in Bulk* (International Gas Carrier Code) is the governing document for material selection for low-temperature service. There are four general temperature ranges covering material requirements for primary cargo tanks as follows:

1.6.5.1 Service Temperature 32°F (0°C) or Above. See International Gas Carrier Code, Table 6.1. Steels intended for this temperature range are normally carbon manganese, fully killed steels with fine grain practice in thickness over 0.79 in. (20 mm). ABS Grades D up to 0.79 in. (20 mm) thick and E may be used subject to special agreement and additional Charpy V-notch testing. Steels should be normalized or quenched and tempered. An improved controlled rolling procedure may be substituted for normalizing.

1.6.5.2 Service Temperatures at or above -67°F (-55°C) up to 32°F (0°C). See International Gas Carrier Code, Table 6.2. Steels intended for this temperature range are normally carbon manganese steels furnished fully killed, fine grain, normalized.

1.6.5.3 Service Temperatures at or Above -320°F (-196°C) up to -67°F (-55°C). See International Gas Carrier Code, Tables 6.3 and 6.4. Steels intended for this temperature range are normally of the ferritic nickel alloy type made with fine grain practice. Austenitic steels or aluminum alloys may be used as well. In general, the following ASTM grades may be used for the temperatures listed:

A203, 2-1/4% Ni	-80°F (-62°C)	for Grade A
	-75°F (-59°C)	for Grade B
A203, 3-1/2% Ni	-130°F (-90°C)	for Grade D
	-110°F (-79°C)	for Grade E
A645, 5% Ni	-155°F (-105°C) ¹	
A353, 9% Ni	-320°F (-196°C)	
A553, 9% Ni	-320°F (-196°C)	
Austenitic Stainless Steel	-320°F (-196°C)	
A658, 36% Ni	-320°F (-196°C) ²	
B209, Type 5083, Aluminum Alloy	-320°F (-196°C)	

Notes:

1. 5% nickel steel may be used down to -265°F (-165°C) upon special consideration provided that impact tests are conducted at -320°F (-196°C).

2. Chemistry will be specially considered for lowering the coefficient of expansion.

For all of the specifications above, chemical composition, heat treatment, tensile, and impact properties are to conform to the requirements of the approved specification.

1.6.5.4 Service Temperatures Below -320°F (-196°C). Austenitic low carbon (less than 0.10%) stainless steels and aluminum alloys are to be used for these temperatures. Stainless steel types 304, 304L, and 347 and type 5083 aluminum alloy do not require toughness testing for service temperatures above -425°F (-254°C). Toughness tests for -425°F (-254°C) service temperature and below will be subject to special considerations.

For service temperatures below 0°F (-18°C), procedure qualification tests and testing of production welds should be in accordance with the International Gas Carrier Code and the appropriate regulatory body and classification society rules and regulations.

If a secondary barrier is needed, the material type will be equal to that of the primary tank plating. This affords temporary containment of any cargo leakage and prevents lowering the temperature of the surrounding ship structure to an unsafe level.

A few low-temperature products and their service temperatures are listed below for reference:

Approximate Service Temperature	$^{\circ}\text{F}$	$(^{\circ}\text{C})$
Vinyl Chloride	+7	(-14)
Ammonia	-28	(-33)
Liquefied petroleum gas (LPG)	-50	(-46)
Liquefied natural gas (LNG)	-260	(-162)

1.7 Specifications for Welding Consumables. The many different types of electrodes, filler metals, and fluxes available are designed to produce welds with superior strength, toughness, or corrosion resistance, as the application demands. Care should be exercised in the choice of consumables to ensure that those used will be suitable for the application.

All filler metals for ship construction must be approved by regulatory agencies. For approval, ABS requires witnessed tests by the manufacturer to demonstrate that the electrodes, wire, and flux meet specified requirements. The U.S. Coast Guard accepts ABS-approved consumables and allows fabricators to obtain approval for other filler metals by passing a Weld Procedure Qualification test. The U.S. Navy has its own test and approval procedures.

Filler metals used in shipbuilding are described in a variety of specifications issued by the American Bureau of Shipping, the U.S. Navy, and the American Welding Society. The specifications most commonly used for steel hull construction are given in Table 4.

Certain electrodes and fluxes adopted for high speed, single pass welding have relatively low ductility. All filler metals and flux combinations used for welding joints in main strength members with joints made by high speed, single pass procedures should be shown by appropriate tests to demonstrate adequate mechanical properties.

1.8 Selection of Materials. When selecting and using a steel for a particular application, the suitability of the material will depend partly on its weldability. There are two aspects of weldability that are of concern. The first concern is the ease of joining in the shop or field while maintaining a sound joint. This aspect of weldability can be strongly influenced by the chemistry of the base metal as well as by the welding procedure and welding materials. In general, as the carbon or alloy content increases, the hardenability will also increase, and the weldability will be reduced (i.e., the weldment's resistance to cracking will decrease). The second consideration is the ability of the steel to meet the service performance requirements, such as mechanical properties, for the intended application.

Much research and development have gone into the design of modern alloy steels and into welding technology to ensure that steels can be successfully welded. As the technology of making, shaping, and treating of steels has advanced, designers and specifying agents have taken advantage of the opportunity to be more selective in their specification requirements. Although the selection of material is governed largely by requirements of regulatory agencies or classification societies, many different grades of structural steel are available for structural work. Some grades can be improved by appropriate steel making practices such as controlled rolling practices, grain refining, additions of alloying elements, and various heat treatments.

ABS ordinary and higher strength steels listed in Tables 1A, 1B, 2A, 2B and 2C are the most commonly used shipbuilding steels. Investigation of notch toughness and fatigue, in addition to tensile properties, should be made before selecting a steel for a particular application. Sometimes analysis or experimental evidence demonstrating the adequacy of the design or the material, including weld metal, is required by regulatory agencies before final approval is granted.

The selection of a material may be influenced by the possible future necessity to make repairs in remote locations of the world. Shipboard plans should show where hull steels with unusual properties have been used. Recommended repair procedures and appropriate welding procedures should be included with the plans and drawings delivered with the ship.

1.9 Weld Cracking. Cracks can occur in many places in a weldment, can take on various forms and sizes, can be influenced by many factors, and can form at low and high temperatures. For example, cracks can occur at elevated temperatures in the weld metal or heat-affected zone (HAZ) several hours after welding. They can be a result of an incompatibility between the steel grade and the welding procedure or due to lack of control over an otherwise acceptable welding technique.

Table 4
Specifications for Filler Metals

American Welding Society	
A5.1	— Covered Carbon Steel Arc Welding Electrodes
A5.3	— Aluminum and Aluminum Alloy Electrodes for Shielded Metal Arc Welding
A5.4	— Covered Corrosion-Resisting Chromium and Chromium-Nickel Steel Welding Electrodes
A5.5	— Low-Alloy Steel Covered Arc Welding Electrodes
A5.9	— Corrosion-Resisting Chromium and Chromium-Nickel Steel Bare and Composite Metal Cored and Stranded Welding Electrodes and Welding Rods
A5.10	— Bare Aluminum and Aluminum Alloy Welding Electrodes and Rods
A5.17	— Carbon Steel Electrodes and Fluxes for Submerged Arc Welding
A5.18	— Carbon Steel Filler Metals for Gas Shielded Arc Welding
A5.20	— Carbon Steel Electrodes for Flux Cored Arc Welding
A5.22	— Flux-Cored Corrosion Resisting Chromium and Chromium-Nickel Steel Electrodes
A5.23	— Low Alloy Steel Electrodes and Fluxes for Submerged Arc Welding
A5.25	— Consumables Used for Electroslag Welding of Carbon and High Strength Low Alloy Steels
A5.26	— Consumables Used for Electrode Gas Welding of Carbon and High Strength Low Alloy Steels
A5.28	— Low Alloy Steel Filler Metals for Gas Shielded Arc Welding
A5.29	— Low Alloy Steel Electrodes for Flux Cored Arc Welding

American Bureau of Shipping

“Approved Welding Electrodes, Wire Flux and Wire and Wire Gas Combinations”

Appendix A	— Requirements for the Approval of Filler Metals Sections
1	— General Requirements
2	— Electrodes for Manual Arc Welding
3	— Wire Flux Combinations for Submerged Arc Welding
4	— Wire and Wire Gas Combinations for Gas Metal Arc Welding

For a few steel grades, cracks can also occur during subsequent stress-relief of the weldment. However, the predominant type of cracking is called *hydrogen-assisted cracking*. This type of cracking is also known by various other names, such as *underbead*, *cold*, or *delayed cracking*. Such cracks most frequently occur in the HAZ, but may also occur in the weld metal. HAZ cracks are usually longitudinal underbead cracks, and may be initiated by stress raisers at the toe or root of the weld. Hydrogen-assisted cracks in the weld metal may occur in either a transverse or longitudinal orientation to the weld axis. These weld metal cracks may manifest themselves not only as gross cracks that are revealed at the weld joint surface, but also as fine microcracks contained entirely within the interior of the weld metal. These fine cracks are most likely when the hydrogen content is not controlled to very low levels. The probability of hydrogen-assisted cracks can be reduced with higher preheat temperatures.

Hydrogen-assisted cracking is generally the result of hydrogen embrittlement combined with stresses or strains. The major factors responsible for hydrogen-assisted cracking are the presence of hydrogen, a susceptible microstructure, and tensile stresses acting on the weld. The prevention of hydrogen-assisted cracking in practice depends on the control of one or more of these factors.

During welding, hydrogen is always present. The source may be moisture in welding flux, shielding gas, electrode covering or base plate. It is absorbed by the welding pool and can diffuse into the HAZ. This movement of hydrogen can occur at either elevated temperatures immediately following welding or at lower temperatures as the part is cooling. Diffusion becomes more difficult at temperatures below 392°F (200°C), and the hydrogen will become entrapped in the HAZ and weld nugget. Potential cracking due to the residual hydrogen may not become apparent until several hours after the weld is completed.

The susceptibility of cracking, in general, increases with harder microstructures. Softer microstructures can tolerate more hydrogen and higher stresses without cracking. Cracking is most likely to occur when the microstructure contains some martensite.

One factor contributing to the cracking susceptibility of martensite is the high level of local transformation stresses present in the phase. The microstructure produced in a weldment depends on the weld cooling rate through the transformation range and the chemical composition and hardenability of the material. Stresses developed in the weldment other than those from the martensitic transformation are caused by thermal contraction of the weldment and restraint of the weld joint. These factors are in turn

influenced by the strength of the base plate and weld metal, weld size, joint design, and external restraint.

The contribution of chemical composition to hardenability and microstructure can be described generally by empirical formulae called *carbon equivalents*. One such formula which predicts the total contribution of alloyed elements for steel with approximately 0.20% carbon and higher is the following:

$$C. E. = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} \quad (\text{Eq. 1})$$

For steels with lower carbon contents, below about 0.17%C, the P_{cm} equation has been found to be a better representation of the contribution of chemical composition:

$$P_{cm} = C + \frac{Mn}{20} + \frac{Si}{30} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B \quad (\text{Eq. 2})$$

Calculations of C.E. or P_{cm} values provide means for comparing the weldability of various steels.

Primary measures taken to avoid cracking are controlling the material's microstructure and the hydrogen content in the HAZ and weld metal. There are several common methods of preventing hydrogen-assisted cracking, such as the use of low-hydrogen welding techniques, higher heat inputs to produce softer microstructures, and preheating.

Preheating is an effective method of preventing possible cracking and has three principal effects:

- (1) A less susceptible microstructure results from a slower cooling rate through the transformation temperature range, 1472–932°F (800–500°C).
- (2) It provides a longer time at elevated temperatures so hydrogen has additional time to diffuse out of the weld metal and HAZ.
- (3) Reduced shrinkage stresses in the weldment results, which is of particular importance in highly restrained joints.

One additional type of cracking, namely *lamellar tearing*, deserves mention. Lamellar tearing can result when welds are made in joints that produce high stresses in the through-thickness direction from contraction occurring during solidification and subsequent cooling of the weld, such as in corner or T-joints. Lamellar tearing occurs in the HAZ or in the base plate adjacent to the HAZ in highly restrained joints when the ductility in the through-thickness direction is insufficient to accommodate the developed strains. The tearing generally initiates at nonmetallic inclusions and propagates by linking small ductile shear frac-

tures between inclusion particles into an expanded crack, taking on a characteristic step-like appearance.

There are several fabrication techniques to minimize lamellar tearing: for example, a change in joint design to reduce the through-thickness strains, "buttering" the joint surfaces prior to welding, use of lower strength electrodes, control of hydrogen content in the weld, or use of preheating and postheating. In addition, a very effective and reliable method for minimizing lamellar tearing is the use of special steels designed to minimize the harmful effect of inclusions.

Sulfide inclusions are generally the most detrimental type inclusions, but silicate and alumina inclusions can also influence susceptibility to lamellar tearing. Special steels generally possess good ductility (> 20% reduction of area) in the through-thickness direction and can accommodate the through-thickness strains required to prevent lamellar tearing. In recent years, the steel making practice of reducing sulfur content and performing steps to inhibit aggregation of remaining sulfides has greatly reduced susceptibility of welded steel plate to lamellar tearing. These requirements can often be added to steel plate orders as an option with only nominal increases in cost.

1.10 Service Performance of Welds. Welded steel structures perform reliably when proper fabrication techniques are employed. Most conventional construction grades are readily weldable and possess satisfactory mechanical properties for service when care is taken in selection of welding materials and procedures. Welded joints should have sufficient strength, ductility, and notch toughness for the intended application. However, it should be kept in mind that, as the strength level of steel is increased and service requirements become more severe, greater care must be taken in choosing the welding materials and procedures.

Since the weld metal and HAZ properties are microstructure-sensitive, the properties can change with welding procedure. Generally, although not always, strength and notch toughness are adversely affected by increasing welding heat (heat input and preheat). The effect of the welding heat becomes significant as the strength of the steel increases. Fortunately, for most normalized and as-rolled steels, welding consumables are available to provide published minimum properties over a common range of welding heat inputs. However, where specific mechanical properties are required, procedure plates should be welded and tested to ensure that suitable weld metal and HAZ properties will meet with the chosen welding materials and procedure. This is particularly important when low-temperature notch toughness requirements are specified. As the heat input is increased, the grain size becomes coarser, and the microstructure continuously changes across the weld, resulting in reduced notch toughness in the weld joint.

3. P_{cm} is the composition parameter. See ANSI/AWS D1.1-90, *Structural Welding Code-Steel*, Appendix XI.

The effect of welding heat on properties is particularly important in quenched-and-tempered steels. The higher the welding heat (heat input or preheat), the slower the weld cooling rate, and in turn, the lower the strength of the HAZ and weld metal. For a given joint thickness and preheat temperature, the welding heat input must not exceed a specific level to maintain a microstructure with suitable mechanical properties. If the preheat temperature is increased or the joint thickness decreased, then the heat input must be decreased to maintain the required microstructure. The maximum heat input for thicker plate is higher than for thinner plate, since the welding heat is dissipated faster for the thicker plate.

However, at the other end of the heat input spectrum (i.e., low heat input), typical of small, high-speed welds on relatively cool, thick plate, and typical of small tack welds or arc strikes, creates localized embrittlement of the heat-affected zones and the welds which can lead to cracking.

As the number of modern constructional-steel grades increases and as the mechanical property requirements for new steels become more severe, the success in fabricating welded structures depends more and more on design and effective use of expanding welding technology. Some practical welding suggestions are presented below for consideration, particularly when welded joints are subject to severe conditions:

(1) Avoid arc striking on the surface of the base plate. Always strike the arc in the groove or on the area to be welded.

(2) Tack welds are particularly prone to weld cracking. Preheating prior to tack welding is sometimes required, and the preheat temperature necessary to prevent cracking can be higher than for the normal weld. The tack welds should be a minimum of about 4 in. (100 mm) in length when possible, and care should be exercised to fill craters. The use of low-hydrogen electrodes is desirable.

The single most important precaution in preventing cracks in tack welds may be the utilization of low-strength electrodes to provide good weld metal ductility and low residual stresses in the weld joint. The use of low-strength electrodes should be restricted when the tack welds cannot be fully penetrated by the subsequent welding or removed by back gouging.

(3) Particular attention should be given to welding sequence to control unnecessary welding stress. For example, back-stepping techniques can be used sometimes to lower the risk of cracking. Also, by controlling the sequence of welding, excessive rotation of one workpiece relative to the other workpiece can be minimized, further reducing the tendency toward cracking.

(4) It is good practice to clean carbon-arc gouged grooves with a grinder prior to welding to remove high-carbon-content material.

(5) Hot bending or straightening of welded plate in quenched and tempered and control-rolled steels should be avoided, since the microstructure and the resulting plate strength may be altered.

(6) Stress raisers at the toe of fillet welds must be avoided by maintaining a smooth contour from the toe of the fillet weld to the base material. In groove welds, excessive weld reinforcement must be avoided.

(7) Notch extension cracking is defined as transverse weld metal cracking which may occur as a result of welding over back-up strip discontinuities or other notches. High-strength steels are particularly prone to this type of cracking. The cracking initiates at the notch or discontinuity and propagates up through the weld under the action of high welding stresses. Cracking will be most extensive at low-heat input. It should be emphasized that welding over discontinuities such as cracks is an undesirable practice that must be avoided, particularly when welding higher strength steels. Where backing bars are required, they should be made continuous.

(8) For higher strength steels and particularly quenched and tempered steels, excessive heat inputs should be avoided. For example, a stringer bead welding technique is preferable over a wide bead weaving technique.

(9) At the other extreme, care should be taken, particularly with higher strength steels, to prevent heat inputs from being so low that the weld metal ductility is reduced to where bend test requirements could not be met or cracking could occur.

In the traditional sense, fast cooling rates can lead to high-hardness microstructures that are susceptible to hydrogen-assisted cracking. Recent research from the Ukraine indicates that fast cooling rates can lead to microcracking which can serve as sites for initiation of hydrogen-assisted cracking. An article in *Automatic Welding*, No. 3, 1988, Paton Welding Institute, puts forth the following:

Increased cooling rates during the thermo-deformation welding cycle result in the intensification of plastic deformation during the phase transformation and pushes this process into a range of lower temperature (for some steel the reduction may be more than 100°C). The high speed of deformation at lower temperatures makes it difficult to accommodate microdeformation inside the grains. All relaxation takes place at austenite grain boundaries, and some boundaries collapse, becoming a spot from which cold cracks can start or are susceptible to starting.

(10) To prevent hydrogen-assisted cracking difficulties, the hydrogen content of the weld should be kept to a minimum. The following are common sources of hydrogen:

(a) Manual shielded metal-arc electrode coatings. Low and extra-low-hydrogen electrodes, as well as moisture-resistant electrodes, are available for manual welding of high-strength steels. These electrodes should always be

properly stored and dried prior to welding. Low-hydrogen electrodes should not be exposed to the atmosphere for lengths of time longer than that suggested by the manufacturer.

- (b) Moisture, oil, paint, or rust on the plate.
- (c) Submerged-arc welding flux that has been improperly stored or dried.
- (d) Certain flux-cored wire. Actual hydrogen content of the wire is strongly dependent on the manufacturing techniques.
- (e) Moisture contamination in shielding gas.

1.11 Welding of Higher Strength and Low-Temperature Service Steels. Compared to welding ordinary strength steels, special precautions regarding electrodes, preheat, and interpass temperatures are necessary in welding higher strength steels. Low-hydrogen electrodes of matching strength should be used for all important members, and preheat should generally be used. Interpass temperature and heat input control may be required, depending on the type of steel.

When ordinary strength steels are welded to higher strength steels, it is advisable to use low-hydrogen electrodes, but it is not necessary to match the strength of the higher strength material. Under conditions of high restraint, it is preferable to use electrodes giving lower strength weld deposits. However, electrode moisture content restrictions suitable for the higher strength steel should be applied.

1.11.1 Low-Temperature Service. Ordinary or higher strength steels, intended for low-temperature service below 0°F (−18°C), are required to meet certain notch toughness requirements at 10°F (5.5°C) below the minimum expected service temperature. The weld metal and

HAZ must meet the same notch toughness requirements. To meet these requirements, welding procedures using controlled rates of heat input are usually necessary. Consequently, a greater number of weld passes may be needed than for ordinary steel applications, and interpass temperature control may become important.

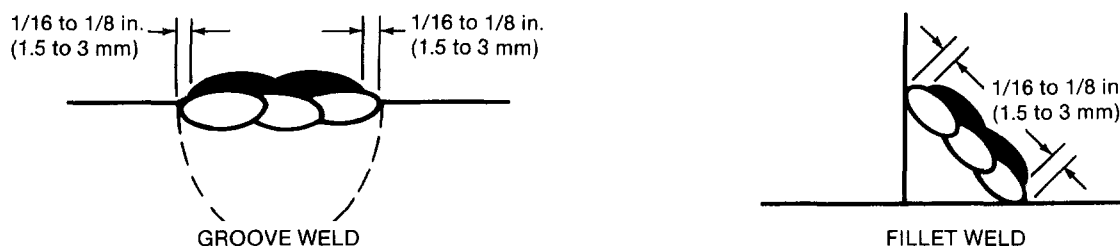
1.11.2 Quenched and Tempered Low Alloy Steels.

The welding of quenched and tempered steels requires special welding procedures. Low-hydrogen electrodes are necessary. The base material heat-affected zone may experience some degradation, due to high welding heat inputs, and therefore, may exhibit both reduced notch toughness values and loss of strength. Submerged arc welding may be used on quenched and tempered steels, but only with carefully controlled heat input and after special procedure qualifications are met. It is most important to follow welding specifications and the steel manufacturer's recommendations as previously stated.

It is suggested that tempering passes be used in critical areas. The tempering passes are considered effective in reducing the tendency for cracking at the toe of finish passes (see Figure 4). Tempering passes are no longer required by the Navy for surface ships.

When joints are prepared by air carbon arc gouging, a dark discoloration may form on the joint surfaces if the process is improperly applied. This discoloration is a carbon deposit that should be removed by grinding the surfaces to bright metal.

1.12 Welding of Clad Steel. Structural tanks that carry certain chemicals are often made of clad steel to provide the required corrosion resistance. The cladding, such as stainless steel or nickel alloys, is very thin and is normally 1/16 to 1/8 in. (1.6 to 3 mm) thick. When clad steel is welded, great care must be taken to prevent contamina-



NOTE: TEMPERING BASES, SHOWN IN BLACK, SHOULD BE DEPOSITED APPROXIMATELY 1/16 to 1/8 in. (1.6 to 3 mm) FROM THE BASE MATERIAL

Figure 4—Tempering Passes

tion of the clad surface welds by iron pickup from the structural carbon steel backing.

Ordinary carbon-steel electrodes must never be used to weld to the cladding or to the clad weld metal. The steel backing is welded first with ordinary steel electrodes, and then the clad side is welded with the appropriate electrode for the cladding. A typical detail is shown in Figure 5. Generally, gas metal arc and submerged arc welding can be applied successfully for welding the clad side.

An alternate approach would be to weld the entire joint by using filler metal appropriate for the cladding. Undercutting should be avoided because it could destroy the effectiveness of the thin cladding.

It is often necessary to take samples of surface weld metal to ensure that the iron pickup is not above the maximum allowed. If there is excessive iron pickup, the surface welding must be removed, usually by grinding, and a new layer of clad weld metal deposited. Often multiple layers of weld are required to minimize dilution.

Extreme care in material handling, cutting, welding, and maintaining cleanliness is required in the fabrication of clad steel plates, but it is possible here only to mention that this fabrication calls for special overall planning.

1.13 Explosion Bonded Transition Joints. The problem of welded transition joints between aluminum and steel has been approached by the use of an explosion bonded aluminum to steel coupling. These transition joints are used extensively in joining aluminum deck houses to steel decks. Recently, improvement in the strength of the transition have been produced by inserting a strip of titanium between the aluminum and steel prior to explosion bonding.

2. Welding Processes

2.1 Introduction. Manual shielded metal arc, semiautomatic flux cored arc, and mechanized submerged arc

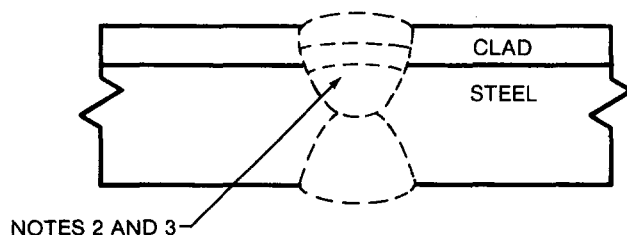
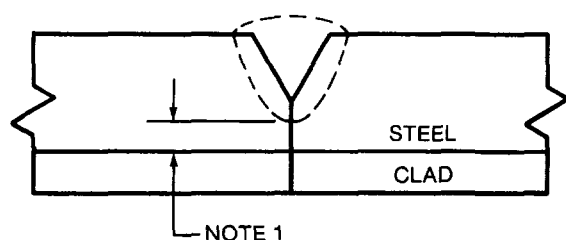
welding are the major welding processes used in ship construction. However, other automatic and semiautomatic processes are being used successfully in specialized operations. Such processes include submerged arc, gas metal arc, flux cored arc, electroslog, and electrogas. Processes such as electroslog and electrogas enable heavy-section welds to be made in one pass. Special submerged arc welding techniques have been successfully applied in making one-side butt welds in long lengths. In the future, new processes such as electron beam welding and laser beam welding may find application in shipbuilding. Significant features of the processes currently employed in shipbuilding are outlined in this section.

Selection of the process and filler metal to be used depends on many factors: material to be welded, welding position limitations, joint accessibility, joint design, accuracy of edge preparation, prescribed procedures and sequencing of the work; suitability of welding equipment, and welder skill. To ensure welder skill, thorough training regarding the characteristics of the various types of electrodes, and the preferable welding techniques for each is essential. A process and filler metal should be selected so that the weld deposit will be compatible with the base metal and will have mechanical properties similar to those of the base metal. Generally, there are no prequalified procedures, and procedures usually may not be transferred from one shipyard to another.

Regulatory agency codes require Welding Procedure Qualification and Welding Performance Qualification prior to performing any production welding. These qualifications are normally required for each shipyard.

Table 5 indicates applicable ABS/AWS filler metal designations for different welding processes for the various ABS ordinary and higher strength hull structural steel base metal.

2.2 Shielded Metal Arc Welding (SMAW). Several grades of electrodes exhibit low ductility compared with other electrodes of the same strength level. These low



NOTES:

1. WELD BACKING STEEL WITHOUT PENETRATING THE CLADDING.
2. BACK GOUGE TO SOUND METAL.
3. WELD THE CLAD SIDE WITH MATCHING FILLER METAL USING MULTIPLE PASSES TO CONTROL DILUTION FROM THE STEEL.

Figure 5—Typical Detail for Groove Welding Clad Plating

Table 5
Applicable Filler Metal (ABS Grade and AWS Classification) — Base Plate Combinations

Filler Metal Properties		Ordinary Strength			Higher Strength		
Tensile strength (psi) (a)		58,300–95,000 (402–655 MPa)			71,000–95,000 (490–655 MPa)		
Yield point, min (psi)		44,100 (304 MPa)			54,000 (372 MPa)		
Elongation in (2 in.), min %		22			20		
ABS filler metal grade		1 (b)	2 (b)	3 (b)	1Y (b)	2Y (b)	3Y (b)
Charpy V-impacts ft-lb @ °C							
Manual and semiautomatic		35 @ 20	35 @ 0	35 @ -20	20 @ 0	20 @ -20	20 @ -40
Automatic		25 @ 20	25 @ 0	25 @ -20	20 @ 10	20 @ -10	20 @ -30
Equivalent AWS classification							
Covered electrodes (SMAW)		E6010, E6011, E6027, E7015, E7016, E7018, E7027, E7048 E7028			E7015, E7016, E7028, E7018, E7048, E8016-C3, E8018-C3, E7016-1, E7018-1		
Wire-flux (SAW) (c)		F6A2X, F7A2X, F6A0X	F6A4X, F7A4X, F7A0X	F6A6X, F7A6X	F7A2X, F8A2X, F7A0X	F7A4X, F8A4X, F8A0	F7A6X, F7A4X, F7A2X, F8A2X, F8A4X
Wire-gas (GMAW)		ER70S-2, ER70S-6, ER70S-7, ER70S-3			ER70S-2, ER70S-3, ER70S-6, ER70S-7, ER80S-Ni1		
Flux-cored (FCAW)		E6XT-5, E6XT-6, E6XT-8, E7XT-6, E7XT-8, E7XT-5, E6XT-1, E7XT-1			E7XT-1, E7XT-5, E7XT-6, E7XT-8		
Applicable ABS		A to 1/2 in. (12.5 mm) inclusive			AH to 1/2 in. (12.5 mm) inclusive		
Base plate		A over 1/2 in. (2.5 mm) B, D, DS			AH over 1/2 in. (12.5 mm), DH		
Material grades		CS, E			EH		

██████████ Suitable for grades 1, 2, or 1Y, 2Y as indicated.

Remainder Suitable for grades 1, 2, 3, or 1Y, 2Y, 3Y as indicated.

(a) $(\text{psi} \times 6.895) \div 1000 = \text{MPa}$

$(\text{MPa} \times 1000) \div 6.895 = \text{psi}$

(b) Ref: ABS publication: "Rules for Welding Electrodes, Wire Flux and Wire Gas Combinations."

(c) X represents electrode chemistry designation such as EL8, EM15K, etc.

ductility electrodes (E6012, E6013, E7014, E7024) are not approved for joints in main strength members such as strength decks, shell, and tank tops.

In gravity feed welding, electrodes having specially formulated high iron oxide and iron powder coatings are used to make fillet welds without manipulating the electrodes. The electrodes are approximately 25 to 30 in. (635 to 760 mm) long, and one welding operator can handle four to six electrodes simultaneously by using special electrode holders (see Figure 6). Because of space requirements for setting up the tripod holder, gravity welding in many closely confined areas may be accomplished with specially designed holders. These holders and electrodes generally must be imported into the United States.

To avoid contamination, damage, or undue moisture pick-up, electrodes must be stored in a clean, dry place. The various types of electrodes require different moisture content control. The E6010 and E6011 types require some moisture in the coatings for satisfactory operation and generally should not be redried after manufacture unless wet or exposed to extreme humidity for a considerable time. The redrying temperature should not exceed 150°F (66°C).

Low-hydrogen electrodes, however, must be dry. Most are supplied prebaked in hermetically sealed containers in which they should be stored until shortly before use. Those not supplied in hermetically sealed containers, or not prebaked, should be baked before use in accordance with

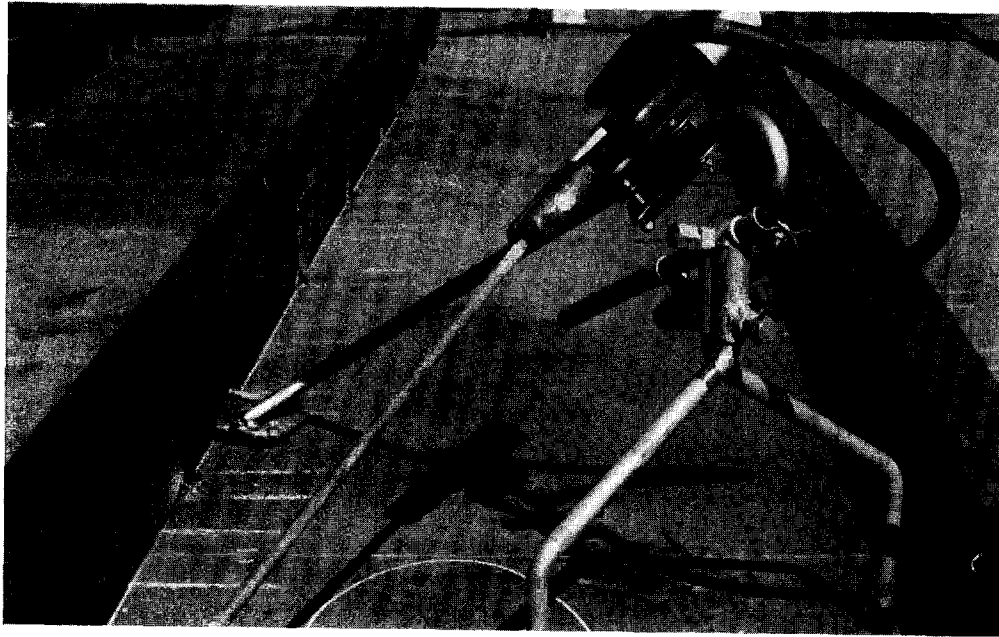


Figure 6—One Type of Gravity Feed Welding

the manufacturer's recommendations and the welding specifications covering the work. Once baked or removed from hermetically sealed containers, they should be placed in holding ovens at 150 to 300°F (65 to 150°C). Prolonged exposure to the atmosphere after removal from the welding ovens requires rebaking at 700 to 800°F (371 to 427°C). When higher strength steels and highly restrained ordinary strength steels are welded, it may be advantageous to rebake the electrodes to ensure that a low level of hydrogen is obtained. The electrode specifications and electrode manufacturers define the baking requirements with regard to time and temperature.

At ambient temperatures, the coatings of low-hydrogen electrodes pick up moisture from the air. Exposure time is usually limited to between 4 and 9 hours, depending on temperature and humidity conditions, type of electrode, and application. For more critical applications or for welding some of the higher strength steels, the maximum time could be much less than 4 hours, especially in humid weather. Portable ovens operating at approximately 250°F (120°C) should be used for such applications during inclement (higher humidity) weather conditions. Rebaking at temperatures as high as 800°F (427°C) is normally required when electrodes have been exposed to moist conditions beyond 9 hours. The exact procedure should be in accordance with the fabrication/welding specifications and manufacturer's instructions. Some manufacturers, however, offer low-hydrogen electrodes which are highly resistant to moisture, and some are offered at extremely

low-moisture content. When these are used, special handling procedures should be developed by the user.

2.3 Submerged Arc Welding (SAW). The submerged arc welding process is widely used for welding butts and seams in flat plate assemblies (decks, bulkheads and flat sections of bottom and side shells) and for fillet welding in the flat or horizontal position. Horizontal groove welds can be accomplished with special equipment.

In shipboard welding, when the machine travel is in a downhill direction, the angle of decline should not exceed one degree in single-pass welding of a butt joint in plates 3/4 in. (19 mm) thick or greater and should not exceed three degrees in multiple-pass welding of groove or fillet welds. Many welds, however, are made in the uphill direction.

It is advisable that each yard adopt standard welding procedures and joint details for various plate thicknesses. Factors to be controlled are type and size of the electrode, moisture content of the flux, grade, and mesh of the flux, current, voltage, and travel speed. Welding personnel should know what deviation from the standard control data may be made to meet variations in root opening and other unusual conditions. Plate edge preparation and fit-up require more attention than in manual welding.

Tack welds should be only large enough to preclude their cracking. They should be short and closely spaced to hold the plates securely together. Cracked tack welds should be removed if they cannot be remelted and incor-

porated in the finished weld. Flux must be removed from the tack welds prior to submerged arc welding.

Temporary steel run-off tabs should be provided at both ends of the joint to be welded. The tabs should be securely welded to the plating to prevent them from spreading apart under the heat of welding. Grooves should be made in the run-off tabs to conform to the groove contour of the joint. Each pass should be started as near the outer edge of the run-off tab as possible so that welding conditions will be stabilized when the weld head reaches the weld joint. In some cases, the weld pass is stopped before the opposite end of the joint is reached. The machine is then moved out to start on the opposite run-off tab and run back along the weld joint to the point of previous stopping. In other cases, the welding is continued, without stopping, until it is run well out onto the run-off tab at the end of the joint.

A backstep type of sequence for welding together two plates minimizes distortion and chances of hot cracking at the finish end of the weld. The first 6 to 8 ft (2 to 2-1/2 m) of the seam is back stepped with the submerged arc machine. Then the weld is completed by welding from the opposite end onto the original start.

The most commonly employed equipment is mounted on a carriage which travels along a track positioned parallel to the weld joint. Although single-arc systems are most common, multiple-arc systems employing two or three electrodes are often used to increase deposition rates. In addition to multiple-arc systems, special methods such as hot wire and powdered metal additions (which require special procedure qualification by most code issuing bodies) have been employed to further increase the deposition rate.

When steels, particularly higher strength steels, are welded for low-temperature service, it is often necessary to employ a greater number of passes than normal to keep heat inputs low. This will help retain the weld metal and base-metal toughness.

One-side automatic submerged arc welding has been developed so that reliable welds can be made with minimal repair on the opposite side. One of many methods used for backing is illustrated in Figure 7. It must be capable of withstanding high-heat inputs and must contain the molten weld metal so that an acceptable bottom weld contour will be formed.

The copper bar holding the flux is usually grooved from 19/32 to 25/32 in. (15 to 20 mm) wide and 1/16 in. (1.6 mm) deep, and is held against the flux with air pressure or other means. The steel plates to be welded are held in place by mechanical means or by magnets.

Fillet welds can be made automatically where the members being joined are held rigidly in place, (see Figure 8).

The flux, if not stored in a hermetically sealed container, should be stored in a dry place to prevent moisture pickup. The flux, which provides a low-hydrogen-type

shield during welding, may need to be baked and stored in a heated container before it is used if its moisture content becomes too high.

2.4 Gas Metal Arc Welding (GMAW). In the gas metal arc welding process, a continuous solid electrode is fed to the arc region with the arc shielded by gas. The operation may be automatic or semiautomatic. In the semiautomatic method, the wire and gas are fed to a hand-held arc welding gun through a flexible conduit and hose. Various gases are used for shielding, including argon, carbon dioxide, or mixtures of argon and carbon dioxide, oxygen, and helium.

The coiled wire should be stored in a dry place so that a clean, bright surface will be maintained on the wire.

Some of the advantages of gas metal arc welding, compared to the SMAW welding processes, are as follows:

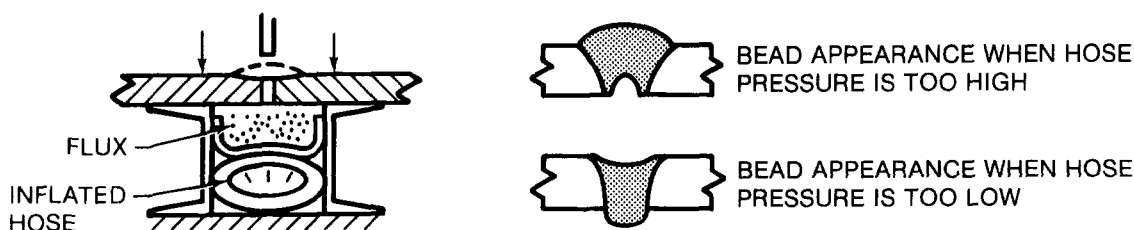
- (1) Concentration of arc heat limits distortion
- (2) Deep penetration can be obtained
- (3) Deposition rates and welding speed (for a given weld size) are higher
- (4) Less skill is required for welders

Because of these features, the GMAW process is used for subassembly welding and for hull construction in unlimited thicknesses.

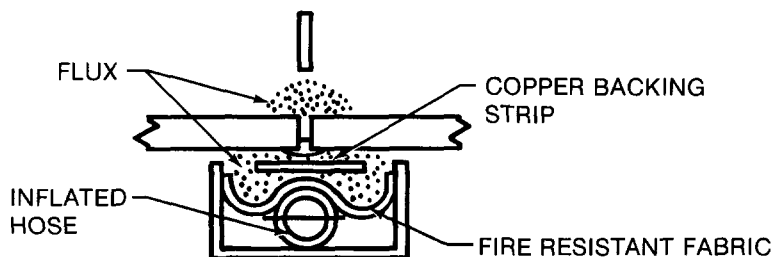
This arc welding process is used for welding aluminum, titanium, and other nonferrous metals as well as steel. It is also useful for welding low alloy steels with a yield point of 80 000 psi (550 MPa) or higher because of the very low level of hydrogen in the arc region and the excellent notch toughness of the finished welds.

The type of metal transfer across the welding arc depends on a combination of process parameters such as current, shielding atmosphere, voltage, and electrode extension. Variations of the gas metal arc welding (GMAW) process include pulsed gas metal arc welding (GMAW-P), short circuit gas metal arc welding (GMAW-S), arc spot welding, and electrogas welding (EGW). These variations and the basic process also encompass several modes of weld metal transfer, including axial spray transfer, globular transfer, and short circuiting transfer.

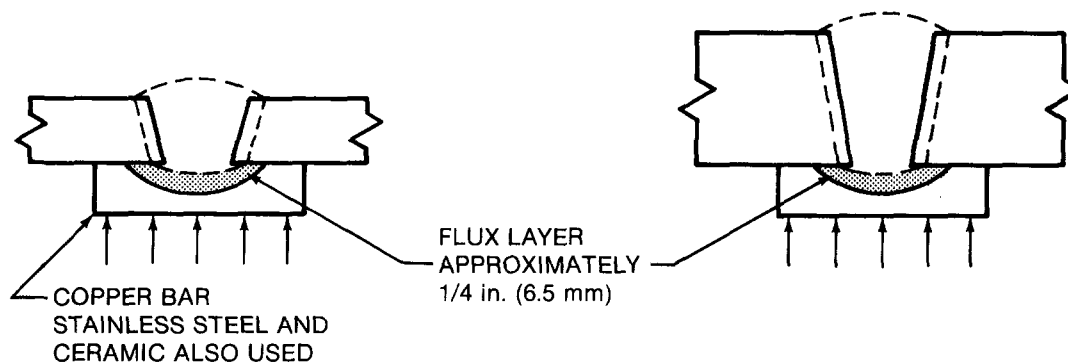
In short circuiting transfer, the electrode makes physical contact with the workpiece, creating an electrical short circuit. The molten end of the electrode is drawn into the workpiece by surface tension, without requiring high amperage and voltage. Variations in welding parameters can create excessive spatter and fusion defects. The reduced heat input enables the process to be used in welding thin metal and in welding positions other than flat and horizontal. Due to its relatively low penetration characteristics, this technique is generally not applicable to structural welding of thicknesses over 1/4 in. (6.3 mm). It should be noted that some codes do not permit the use of GMAW short arc welding. The low-heat input may lead



(A) TYPICAL SCHEME FOR ONE SIDE SINGLE PASS WELDING OF PLATES UP TO 5/16 in. (8 mm) IN THICKNESS



(B) TYPICAL SCHEME FOR ONE SIDE WELDING OF PLATE THICKNESSES RANGE OF 5/16 to 5/8 in. (8-16 mm)



(C) TYPICAL JOINT DETAILS FOR ONE SIDE SUBMERGED ARC WELDING

Figure 7—Typical Joint Details and Backing Material Positioning for One-Side Submerged Arc Welding

to lack of fusion type defects; therefore, it must be carefully controlled.

The spray transfer variation, usually shielded with a minimum of 80% argon, transfers metal across the arc in the form of axially directed small droplets. The spray variation offers the greatest operator appeal, weld quality, and metal deposition efficiency. Penetration is deeper than that obtained with the SMAW process, but less than can be obtained with the globular transfer mode of GMAW, with carbon dioxide shielding. The spray mode is characterized by high-current density which makes spray transfer possible.

In the pulsed arc variation, the power source provides two current levels: a steady background level, too low to produce any metal transfer, and a pulsed peak current metal transfer that can be regulated independently of heat

input by pulse parameter adjustment (level, shape, and frequency). This variation of GMAW may be used for applications where higher heat inputs cannot be tolerated. Strict adherence to appropriate established welding parameters is very important in order to prevent incomplete fusion defects in the heavier thicknesses, but it is not as critical as with short circuiting arc GMAW. Pulsed arc can be used for all position welding, and its use is particularly advantageous when joining thin plates of steel, aluminum, and copper alloys. Since its heat input is similar to that of short-arc but with less tendency towards defects, and since there is very little spatter, pulsed gas metal arc welding (GMAW-P) is quickly gaining favor.

In globular metal transfer, usually shielded with carbon dioxide, the molten metal at the end of the electrode, when transferred across the arc to the molten weld pool, forms

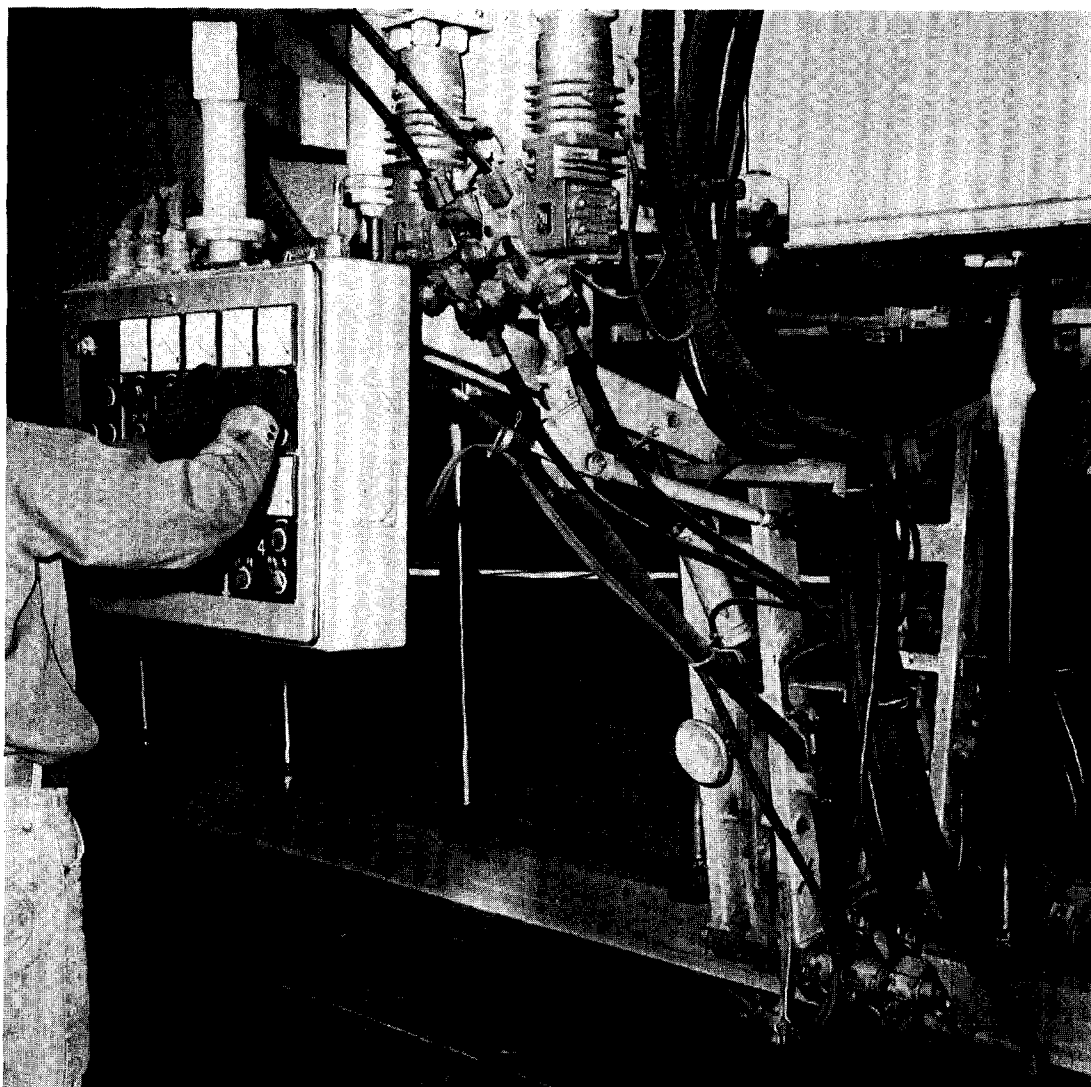


**Figure 8—Automatic Fillet Welding of Stiffeners to Plate Panel—
Welds are Being Made Simultaneously on Both Sides of Stiffener**

comparatively large irregular globules, resulting in a rough bead appearance (ripple effect) and spatter. The weld bead profile exhibits extremely deep penetration.

AWS classifications of GMAW carbon and low alloy electrodes are listed in Table 6. The information shown in Table 6 is extracted from AWS A5.28-79, *Specification for Low Alloy Steel Filler Metals for Gas Shielded Arc Welding* and AWS A5.18-79, *Specification for Carbon Steel Filler Metals for Gas Shielded Arc Welding*.

Some shipyards are making use of tractor systems for mechanization of GMAW-P and FCAW in all positions. Hull and deck plating is particularly suited to this.

2.5 Flux Cored Arc Welding (FCAW). The flux cored arc welding process is similar to the gas metal arc process except that the wire has a core containing flux or alloying

additions, or both. Shielding gas is required for some electrodes to operate correctly. However, the flux does change both the arc action and metallurgical reactions in the weld pool, making them similar to the action and reactions of conventional covered electrodes. These changes make this process more tolerant to surface contaminants and weather than the gas metal arc process, and thus more adaptable to outdoor shipyard welding. Vertical and overhead welds can be made with certain gases and types of wire.

The fluxes vary and are selected to suit metallurgical requirements and operations with or without gas shielding. Generally, gas shielding is beneficial from the point of view of notch toughness and minimizing defects. Powdered metal alloys may also be added to produce deposits with increased strength, toughness, or hardness.

Table 6
Carbon and Low Alloy Steel Solid or Composite Electrodes and Rods

AWS Classification	Weld Metal Composition ^{a, b}										Minimum Charpy V-notch Impact Properties ^c						
	C	Mn	Si	P	S	Ni	Cr	Mo	V	Cu	Ti	Zr	Al	ft-lb	°F	J	°C
ER70S-2	0.07	0.90-1.40	0.40-0.70	0.025	0.035	—	—	—	—	0.50	0.05-0.15	0.02-0.12	0.05-0.15	20	-20	27	-29
ER70S-3	0.06-0.15	0.90-1.40	0.45-0.70	0.025	0.035	—	—	—	—	0.50	—	—	—	20	-0	27	-18
ER70S-6	0.07-0.15	1.40-1.85	0.80-1.15	0.025	0.035	—	—	—	—	0.50	—	—	—	20	-20	27	-29
ER70S-7	0.07-0.15	1.50-2.00	0.50-0.80	0.025	0.035	—	—	—	—	0.50	—	—	—	20	-20	27	-29
ER80S-Ni1	0.12	1.25	0.40-0.80	0.025	0.025	0.80-0.10	0.15	0.35	0.05	0.35	—	—	—	20	-50	27	-46
ER80S-Ni2 ^a	0.12	1.25	0.40-0.80	0.025	0.025	2.00-2.75	—	—	—	0.35	—	—	—	20	-80	27	-62
ER80S-Ni3 ^a	0.12	1.25	0.40-0.80	0.025	0.025	3.00-3.75	—	—	—	0.35	—	—	—	20	-100	27	-73
E80C-Ni1	0.12	1.25	0.60	0.025	0.035	0.80-1.10	—	0.65	0.05	0.35	—	—	—	20	-50	27	-46
E80C-Ni2 ^a	0.12	1.25	0.60	0.025	0.030	2.00-2.75	—	—	—	0.35	—	—	—	20	-80	27	-62
E80C-Ni3 ^a	0.12	1.25	0.60	0.025	0.030	3.00-3.75	—	—	—	0.35	—	—	—	20	-100	27	-73
ER80S-D2	0.07-0.12	1.60-2.10	0.50-0.80	0.025	0.025	0.15	—	0.40-0.60	—	0.50	—	—	—	20	-20	27	-29
ER100S-1	0.08	1.25-1.80	0.20-0.60	0.010	0.010	1.40-2.10	0.30	0.25-0.55	0.05	0.25	0.10	0.10	0.10	50	-60	68	-51
ER100S-2	0.12	1.25-1.80	0.20-0.60	0.010	0.010	0.80-1.25	0.30	0.20-0.55	0.05	0.35-0.65	0.10	0.10	0.10	50	-60	68	-51
ER110S-1	0.09	1.40-1.80	0.20-0.55	0.010	0.010	1.90-2.60	0.50	0.25-0.55	0.04	0.25	0.10	0.10	0.10	50	-60	68	-51
ER120S-1	0.10	1.40-1.80	0.25-0.60	0.010	0.010	2.00-2.80	0.60	0.30-0.65	0.03	0.25	0.10	0.10	0.10	50	-60	68	-51

Notes:

a. Chemical composition of solid electrodes is based on as-manufactured composition. Chemical requirements for composite electrodes are based on undiluted weld metal in the as-welded condition deposited using shielding gases specified in Table 4 of A5.28.

b. Single values are maximum.

c. As-welded condition.

d. Postweld heat treated in accordance with Table 12 of A5.28.

(Refer to AWS A5.18, Specification for Carbon Steel Filler Metals for Gas Shielded Arc Welding, and AWS A5.28, Specification for Low Alloy Steel Filler Metals for Gas Shielded Arc Welding.)

