Module 7

Steels and Non-Ferrous Alloys in Marine Applications: Composition and Properties

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Module 7: Steels and Non-Ferrous Alloys

Contents

1 Introduction

Many metallic material types are used in a wide range of applications in marine environments. The materials' strength, toughness and resistance to corrosion is vital in applications such as sea going craft and on/offshore structures if structural integrity is to be retained over the design life. In the 1970s, 1980s and 1990s, much valuable knowledge was gained about how to avoid structural and corrosion short comings in marine and seawater service, however, this information was published in journals and conferences of the time and are not readily found electronically. This knowledge helped minimise the risk of unsatisfactory performance, though in recent years, arguably problems are appearing again and today's engineers are not always aware of the large body of past work that helped mitigate these risks.

This module is designed to acquaint the reader with the common material types used in the marine environment, their designations, compositions and properties with the expectation that the information will assist in material identification in the field. It is closely associated with module 8, 'Corrosion mechanisms that degrade metals in the marine environment', which considers the specific ways these material types degrade via corrosion in the zones of the marine environment and, in that way, may further assist in the diagnosis of problems concerned with material degradation and premature component failure.

The sections first covers ferrous materials and then non ferrous materials beginning with the most prevalent material used in shipbuilding and marine structures – low carbon and low alloy steels.

2 Steel Categories and Designations

Steels form one of the most complex group of alloys in common use, and there are many ways to classify steel. Classification of steels based on chemical composition is a widely used method. There are three very broad-based categories of steel based on composition: plain carbon steels, low-alloy steels, and high-alloy steels (which include stainless steels), see Figure 1. Plain carbon and low-alloy steels are briefly introduced here.

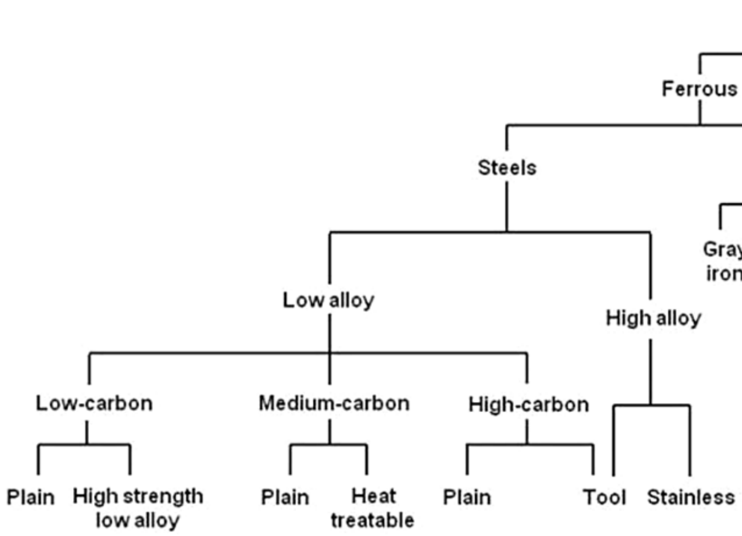


Figure 1. Basic Classification of Ferrous Alloys

Steels are classified in many other ways, too. For example, classification may be based on:

i) The steelmaking method, such as open hearth, basic oxygen process, or electric furnace methods

ii) The deoxidation practice during steel making, such as killed, semi-killed, capped, or rimmed steel

iii) The solidification method, such ingot casting, continuous casting, or component (shape) casting

iv) The mill product form, such as bar, plate, sheet, strip, tubing, or structural shape

v) The finishing method, such as hot rolling or cold rolling

vi) The microstructure, such as ferritic, pearlitic, and martensitic

vii) The required strength level, as specified in standards

viii) The heat treatment, such as annealing, quenching and tempering, and thermomechanical processing

ix) Quality descriptors, such as forging quality and commercial quality

Steelmaking can be broadly classified into important steelmaking processes are the electric arc furnace (EAF) process and the basic oxygen furnace (BOF) or LD (Linz-Donawitz) process. The EAF process accounts for 35 to 40% of the world steel production and BOF process produces 55-65%.

2.1 Deoxidation Practice

Oxygen is generally considered an undesirable element in steel because it combines with other elements (e.g., manganese, silicon, aluminum, and titanium) to form oxide inclusions that can degrade toughness and fatigue resistance. Deoxidation during steel melting typically involves the use of certain deoxidizing elements such as silicon and aluminum (although vanadium, titanium, and zirconium are sometimes used). Vacuum degassing is another method.

Steels cast into ingots can be classified based on the deoxidation practice employed or, alternatively, by the amount of gas evolved during solidification. The term killed steel refers to steels that have been deoxidized, usually with aluminum and/or silicon in the melt. There is only a slight evolution of gases during solidification of the metal after pouring of killed steels.

Killed steels, which have less porosity than semi-killed or rimmed ingots, see Figure 2, are produced with a more uniform chemical composition in the ingot. Almost all steels are killed, especially alloy steels, forging steels, and steels for carburizing. Killed steels are also preferred for sheet steel, because they have better formability and are not subject to aging or strain aging (i.e., mechanical properties do not change with time).

“rimmed steel.” Rimmed steels are characterized by marked differences in chemical composition across the section and from the top to the bottom of the ingot. They have an outer rim that is lower in carbon, phosphorus, and sulphur than the gas entrapped during solidification is in excess of that needed to counteract normal shrinkage. The result is a tendency for the steel to rise in the ingot mold.

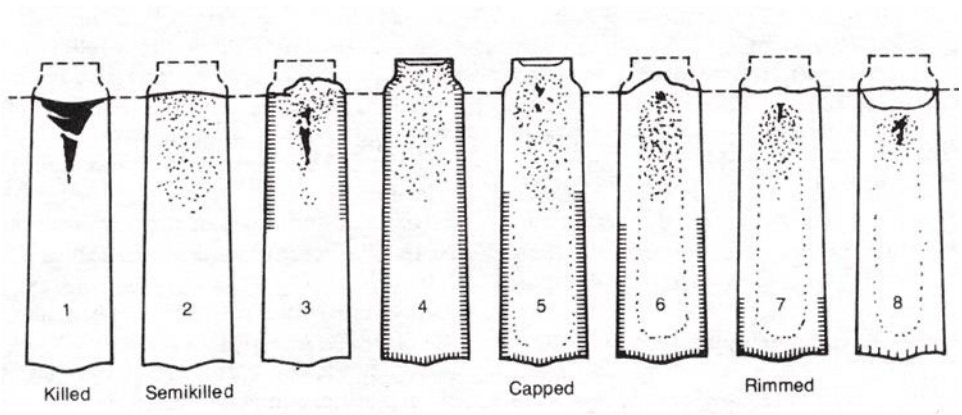


Figure 2. Difference between Killed, Semi-Killed, Capped and Rimmed Steel (Upper horizontal dashed line indicates level to which steel was poured

When no deoxidizing agents are added in the furnace, the resulting steel is referred to as

In the past, rimmed (or capped) ingot cast steel has been used because of its lower price. More recently, however, rimmed steels have been largely replaced by killed steels produced by the continuous casting process. Continuous casting is inherently suited to the production of killed steels, but killed steels are also produced by ingot metallurgy.

2.2 Product Forms

Various steel product forms termed 'mill products', are produced in steel mills either by continuous casting methods or by the breakdown of ingots into various wrought forms rolling, drawing, or extrusion operations. The various types of mill steel products include:

i) Sheets and coils of low-carbon steel for applications ranging from transport (ships, trains, cars etc.) to appliances

ii) Wire, used in such products as wire rope, wire fabric and nails

iii) Structural shapes used in ships, offshore structures, bridges and buildings

iv) Bars for forgings and machined parts, such as gears and bearings

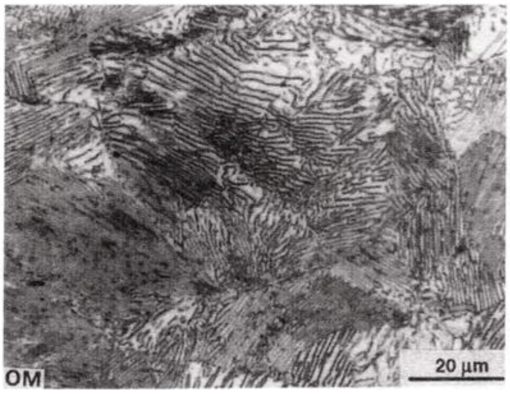
Steel grade powders are also produced for various applications, including production of parts by powder metallurgy processes. Powder metallurgy involves mechanical consolidation of powders into compacts that are then sintered for densification.

2.2.1 Finishing Methods

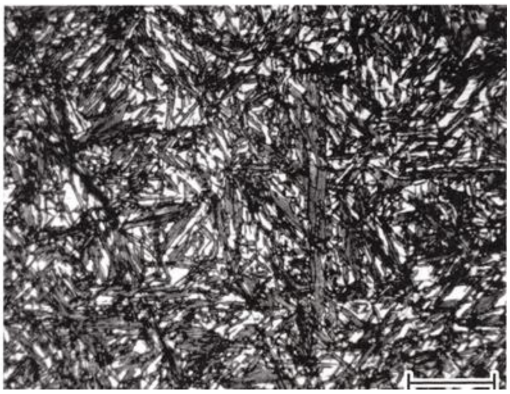
The surface of steel products is influenced by its finishing method. In rolled mill products, finishing is by either hot rolling or cold rolling. Hot rolled unpickled steel seldom offers any problem in maintaining face finish. Rolling removes much of the scale and usually improves the finish. The cold rolling process allows thinner gauges to be produced than can be obtained by hot rolling. Other advantages of cold rolled steel are its better surface finish and dimensional control.

2.2.2 Microstructure

Steels can be classified according to the microstructure at room temperature, see Figure 3. Heat treatments are used to produce microstructures that can consist of either pearlite, martensite, or bainite, or some combition thereof. Proper alloying also can induce a stable austenitic phase all the way down to room temperature. Most steels primarily have a body-centered cubic crystal (ferritic) structure at room temperature, but alloying with some metals (such as nickel and manganese, in particular) can give some steels a face-centered cubic (austenitic) crystal structure at room temperature. Various types of stainless steel alloys have austenitic or duplex (ferrite-austenite) structures. Another example is austenitic manganese steel, containing approximately 1.2 wt.% C and 12% Mn, invented by Sir Robert Hadfield in 1882. Hadfield's manganese steel was unique in that it combined high toughness and ductility with high work-hardening capacity and, usually, good resistance to wear. It rapidly gained acceptance and is still a very useful engineering material.



(a) Pearlite; consisting of ferrite and cementite (Fe_3C) lamellae



(b) Plate Martensite in water-quenched eutectoid (~0.8wt. % C) AISI 1080

Figure 3. Appearance of (a) Pearlite (ferrite and cementite (Fe3C) lamellae) and (b) Plate Martensite in AISI 1080 Steel

2.2.3 Required Strength Level

Purchasing standards of steels and many other materials often specify a minimum required level of strength, and some categories of steels are defined by their mechanical properties. For example, high-strength low-alloy (HSLA) steels are designed to meet specific mechanical properties rather than a chemical composition. The production of HSLA steels involves various mill and forged products, and HSLA steels have yield strengths greater than 275 MPa (40 ksi). The chemical composition of an HSLA grade may vary for different product thicknesses to meet mechanical property requirements.

Another category of steel based on strength is a group called ultrahigh-strength steels. These are commercial structural steels capable of a minimum yield strength of 1380 MPa (200 ksi). Three types of ultrahigh-strength steels are:

- Medium-carbon, low-alloy steels
- Medium-alloy, air-hardening steels
- High-alloy, hardenable steels

The high-alloy types of ultrahigh-strength steels include several of stainless steels see Section 3. Other high-alloy types include high-fracture- toughness 9Ni-4Co steels and 18 Ni maraging steels.

2.2.4 Heat Treatment

One of the primary advantages of steels is their ability to attain high strengths through heat treatment while still retaining some degree of ductility. Heat treatments can be used to not only harden steels but also to provide other useful combinations of properties, such as ductility, formability, and machinability. The various heat treatment processes include annealing, stress relieving, normalizing, spheroidizing, and hardening by quenching and tempering.

2.2.5 Quality Descriptors.

Steels are described by a host of quality descriptors, depending on the product and types of application. Some of the quality descriptors listed in Tables 1 and 2, such as forging quality or cold extrusion quality, are self-explanatory. The meaning of others is less obvious: for example, merchant quality hot-rolled carbon steel bars are made for noncritical applications requiring modest strength and mild bending or forming, but not requiring forging or heat treating. The descriptor for one particular steel commodity is not necessarily carried over to subsequent products made from that commodity - for example, standard quality cold-finished bars are made from special quality hot-rolled bars.

The various mechanical and physical characteristics implied by a quality descriptor arise from the combination of several factors, including:

- The degree of internal soundness
- The relative uniformity of chemical composition imperfections
- The size of the discard cropped from the in-got
- Extensive testing during manufacture
- The number, size, and distribution of non-metallic inclusions
- Hardenability requirements

Control of these factors during manufacture is necessary to achieve mill products having the desired characteristics. The extent of the control over these and other related factors is another piece of information conveyed by the quality descriptor. Understanding the various quality descriptors is complicated by the fact that most of the requirements that qualify a steel for a particular descriptor are subjective. Only nonmetallic inclusion count, restrictions on chemical composition ranges and incidental alloying elements, austenitic grain size, and special hardenbility are quantified.

2.2.6 Carbon Steels

All steels are iron-carbon alloys with carbon contents from 0.02% to less than 2%. The so-called plain carbon steels contain small amounts of manganese and silicon. Carbon steels (Table .3) can be classified further on the basis of carbon content:

- Steel containing less than 0.30% C is called low carbon steel or mild steel
- Steel containing between 0.20 and 0.60% C is called medium-carbon steel
- Steel containing more than 0.60% C is called high-carbon steel
- Free machining grades

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Spark patterns can be used to identify low, medium-, and high-carbon steels, Figure 2.

Table 1. Quality Descriptions of Carbon Steels

Semifinished for Forging	**Hot-rolled Sheets**	**Cold Rolled Strip**
Forging quality	Commercial quality	**Tin mill products**
Special hardenability	Drawing quality	**Carbon steel wire**
Special internal soundness	Drawing quality special killed	Industrial quality wire
Nonmetallic inclusion requirement	Structural quality	Cold extrusion wires
Special surface	**Cold-rolled sheets**	Heading, forging, and roll-threading wires
Carbon steel structural	Commercial quality	Mechanical spring wires
Structural quality	Drawing quality	Upholstery spring wires
Carbon steel plates	Drawing quality special killed	Welding wire
Regular quality	Structural quality	**Carbon steel flat wire**
Structural quality	**Porcelain enameling**	Stitching wire
Cold-drawing quality	Commercial quality	Stapling wire
Cold-pressing quality	Drawing quality	**Carbon steel pipe**
Cold-flanging quality	Drawing quality special killed	**Structural tubing**
Forging quality	**Long terne sheets**	**Line pipe**
Pressure vessel quality	Commercial quality	**Oil country tubular goods**
Hot-rolled carbon steel bars	Drawing quality	**Steel specialty tubular products**
Merchant quality	Drawing quality special killed	Pressure tubing
Special hardenability	Structural quality	Mechanical tubing
Special internal soundness	**Galvanized sheets**	Aircraft tubing
Nonmetallic inclusion requirement	Commercial quality	**Hot-rolled wire rods**
Special surface	Drawing quality	Industrial quality
Scrapless nut quality	Drawing quality special killed	Rods for electric welded chain
Axle shaft quality	Lock-forming quality	Rods for heading, forging, and roll-threading
Cold extrusion quality	**Electrolytic zinc coated**	Rods for lock washer wire
Cold-heading/forging quality	Commercial quality	Rods for scrapless nut wire
Cold-finished carbon steel bars	Drawing quality	Rods for upholstery spring wire
Standard quality	Drawing quality special killed	Rods for welding wire
Special hardenability	Structural quality	
Special internal soundness	**Hot-rolled strip**	
Nonmetallic inclusion requirement	Commercial quality	
Special surface	Drawing quality	
Cold-heading and cold-forging	Drawing quality special killed	
Cold extrusion quality	Structural quality	

Table 2. Quality Descriptions of Alloy Steels

Alloy Steel Plates	Alloy Steel Wire	Steel Tubular Products
Drawing quality Pressure vessel quality Structural quality Aircraft quality	Aircraft quality Bearing quality Special surface quality	Pressure tubing Mechanical tubing Stainless and heat resistant pipe Aircraft tubing
Hot rolled alloy steel bars	**Cold-finished Alloy Steel Bars**	
Regular quality Aircraft quality Axle shaft quality Bearing quality Cold-headed quality Rifle barrel quality	Regular quality Aircraft quality Axle shaft quality Bearing quality Cold-headed quality Rifle barrel quality	

Carbon levels have a pronounced effect on properties, see Figure 3. Carbon has very limited solubity in iron, and a hard carbide compound Fe_3C (called cementite) forms when carbon is added to iron. The physical form of this carbide can be readily modified and controlled by processing variables with accompanying changes in properties. The cementite carbides may be present as lamellae, plates, needles, or spheres, or the carbon may be retained in supersaturated condition during quenching, which causes the formation of a very hard metastable phase called martensite.

Almost all steels also contain fractional amounts of impurities - phosphorus and sulphur, for example, which are present in raw steelmaking materials such as scrap. While not eliminated entirely, they are present only in such small amounts that they do not adversely affect the properties of the steel, and their presence may then be tolerated in reduced amounts. For instance, many steel specifications permit up to 0.040% phosphorus and 0.050% sulphur to be present. If more than these amounts of phosphorus and sulphur are present, serious limitations in hot forming operations, as well as other mechanical behaviors, are encountered. However, special-purpose steels may contain higher amounts of sulfur (up to approximately 0.20%) to increase the ease of machining or require lower amounts (less than 0.005%) for such applications as gas and oil pipeline in Arctic regions. In like fashion, amounts of phosphorus in excess of 0.040% may be specified to improve the strength and atmospheric corrosion resistance of the steel. Although these specification limits have not changed, present day commercial steel products generally have sulphur and phosphorous contents on the order of 0.010%.

(a) Sparks from AISI 1015 steel

(0.15wt.% Carbon)

(b) Sparks from AISI 1045 steel

(0.45wt.% Carbon)

(c) Sparks from AISI 1095 steel

(1.0wt.% Carbon)

Figure 4. Spark Patterns used to Identify Low, Medium and High-Carbon Steels

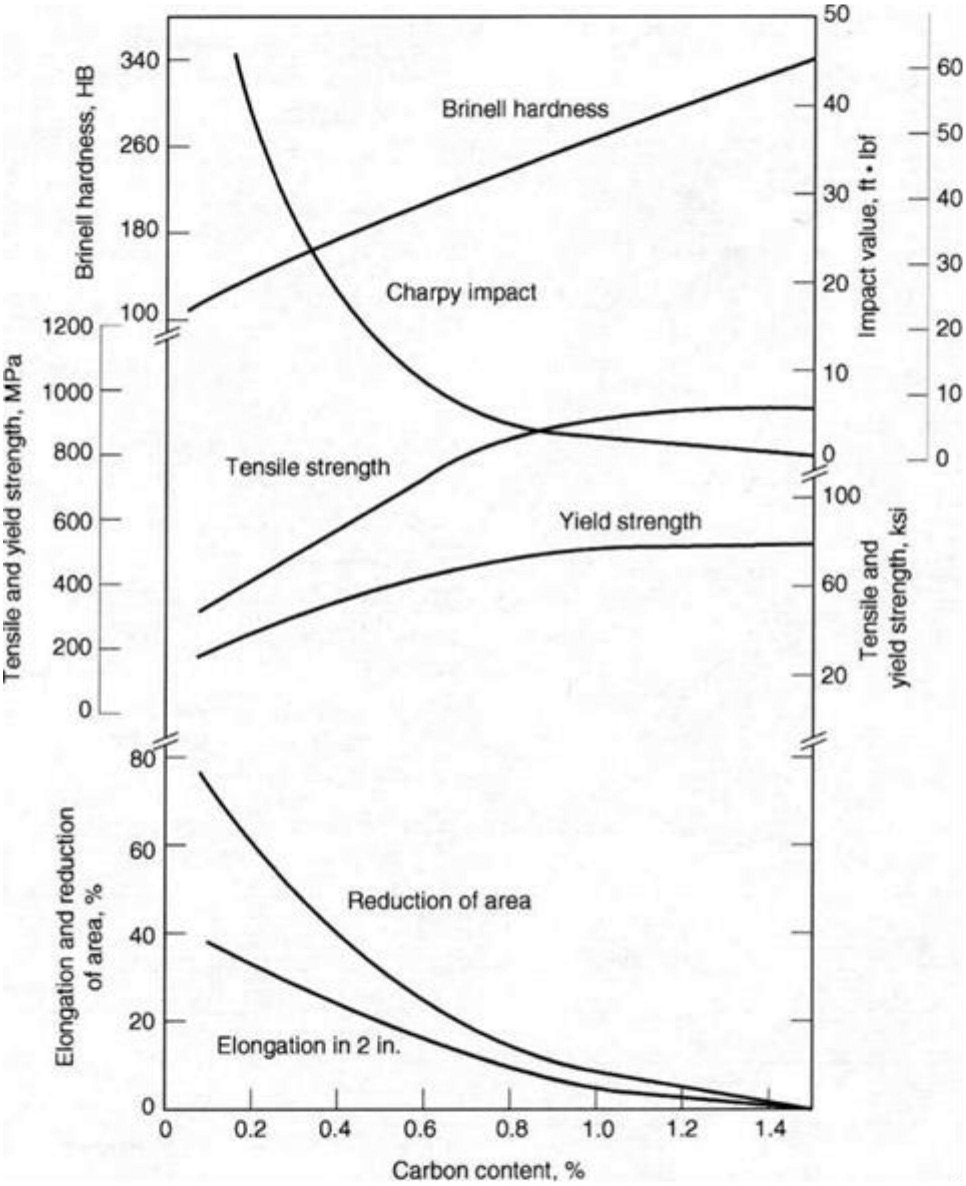

Figure 5. Variations in Average Mechanical Properties of As-Rolled 25mm Diameter Bars of Plain Carbon Steel as a Function of Carbon Content

2.2.6.1 Low Carbon Steels

Low-carbon steels contain up to 0.30% C. The largest category of this class of steel is flat rolled products (strip, sheet or plate), usually in the cold rolled and annealed condition. The carbon content for these high formability steels is very low, less than 0.10% C, with up to 0.4% Mn. Typical uses are in ship plate, automobile body panels, tin plate and wire products. These steels have relatively low tensile values (205 to 240MPa (30-35ksi)) and are selected when enhanced cold formability or drawability is required.

For rolled steel structural plates and sections, the carbon content may be increased to approximately 0.30%, with higher manganese up to 1.5%. This second group of low-carbon steels is commonly referred to as mild steel and has carbon levels ranging from 0.15 to 0.30% C. These steels may be used for stampings, forgings, seamless tubes, and boiler plate. For heat-treating purposes, they are commonly known as carburizing or case-hardening grades. An increase in carbon content of the base steel results in greater core hardness for a given quench. An increase in manganese improves the hardenability of both the core and the case.

Table 3. Composition of Selected Carbon Steels in the UNS (AISI/SAE) System

UNS No.	SAE/AISI No.	Composition, wt. %			
		Carbon	Manganese	Phosphorus	Sulphur
G10060	1006	0.08	0.45	0.040	0.050
G10100	1010	0.08-0.13	0.30-0.60	0.040	0.050
G10200	1020	0.17-0.23	0.30-0.60	0.040	0.050
G10300	1030	0.27-0.34	0.60-0.90	0.040	0.050
G10400	1040	0.36-0.44	0.60-0.90	0.040	0.050
G10500	1050	0.47-0.55	0.60-0.90	0.040	0.050
G10600	1060	0.55-0.66	0.60-0.90	0.040	0.050
G10700	1070	0.65-0.73	0.60-0.90	0.040	0.050
G10800	1080	0.74-0.88	0.60-0.90	0.040	0.050
G10950	1095	0.90-1.04	0.30-0.50	0.040	0.050
Manganese-carbon					
G15130	1513	0.10-0.16	1.10-1.40	0.040	0.050
G15270	1527	0.22-0.29	1.20-1.50	0.040	0.050
G15410	1541	0.36-0.44	1.35-1.65	0.040	0.050
G15660	1566	0.60-0.71	0.85-1.15	0.040	0.050
Free-machining					
G11080	1108	0.08-0.13	0.50-0.80	0.040	0.08-0.13
G11390	1139	0.35-0.43	1.35-1.65	0.040	0.13-0.20
G11510	1151	0.48-0.55	0.70-1.00	0.040	0.08-0.13
G12120	1212	0.13	0.70-1.00	0.07-0.12	0.16-0.23

2.2.6.2 Medium Carbon Steel

Medium-carbon steels are similar to low-carbon steels except that the carbon ranges from 0.30 to 0.60% and the manganese from 0.60 to 1.65%. Increasing the carbon content to approximately 0.5% with an accompanying increase in manganese allows medium-carbon steels to be used in the quenched and tempered condition. The uses of medium-carbon-manganese steels include shafts, couplings, crankshafts, axles, gears, and forgings. Steels in the 0.40 to 0.60% C range are also used for rails, railway wheels, and rail axles.

Medium-carbon steels are used both with and without heat treatment, depending on the application and the level of properties needed. As a group, they are considered good for normal machining operations. It is possible to weld these steels by most commercial methods, but precautions should be taken to avoid cracking from rapid heating or cooling.

2.2.6.3 High Carbon Steels

High-carbon steels contain from 0.60 to 1.00% C with manganese contents ranging from 0.30 to 0.90%. The microstructure is largely pearlitic. They are used for applications where the higher carbon is needed to improve wear characteristics and where strength levels required are higher than those obtainable with the lower-carbon groups. Applications include spring materials and high-strength wires.

In general, cold forming methods are not practical with this group of steels because they are limited to flat stampings and springs coiled from small diameter wire. Practically all parts from these steels are heat treated before use.

2.2.7 Alloy Steels

Alloy steels contain manganese, silicon, or copper in quantities greater than those for the carbon steels, or they have specified ranges or high-alloy steel, depending on whether total alloying content is less than 8%. This is not a hard and fast rule, because some steels with alloying slightly above 8% are sometimes referred to as “medium-alloy” steels. High-alloy steels typically refer to stainless steels, maraging steels, austenitic manganese steels, and some ultrahigh-strength nickel steels.

2.2.7.1 High Strength Low-Alloy (HSLA) Steels

High-strength low-alloy (HSLA) steels are designed to provide better mechanical properties and/or greater resistance to atmospheric corrosion than conventional carbon steels. They are not considered to be alloy steels in the normal sense because they are designed to meet specific mechanical properties rather than a chemical composition. The HSLA steels have low carbon contents (0.05 to ~0.25% C) in order to produce adequate formability and weldability, but also have yield strengths greater than 275MPa (40 ksi). They have manganese contents up to 2.0%. Small quantities of chromium, nickel, molybdenum, copper, nitrogen, vanadium, niobium, titanium, and zirconium are used in various combinations. The types of HSLA steels commonly used include:

- Weathering steels, designed to exhibit sup-rior atmospheric corrosion resistance
- Control-rolled steels, hot rolled according to a predetermined rolling schedule designed to develop a highly deformed austenite structure that transforms to a very fine equiaxed ferrite structure on cooling
- Pearlite-reduced steels, strengthened by very fine grain ferrite and precipitation hardening but with low carbon content and therefore little or no pearlite in the microstructure
- Microalloyed steels, with very small additions (generally <0.10% each) of such elements as niobium, vanadium, and/or titanium for refinement of grain size and/or precipitation hardening
- Acicular ferrite steel, very low carbon steels with sufficient hardenability to transform on cooling to a very fine high-strength acicular ferrite (low-carbon bainite) structure rather than the usual polygonal ferrite structure
- Dual-phase steels, processed to a micro-structure of ferrite containing small,

uniformly distributed regions of high-carbon martensite, resulting in a product with low yield strength and a high rate of work hardening, thus providing a high-strength steel of superior formability

2.2.7.2 Low-Alloy Steels

Low-alloy steels constitute a category of ferrous materials that exhibit mechanical properties superior to plain carbon steels resulting from additions of such alloying elements as nickel, chromium, and molybdenum. For many low-alloy steels, the primary function of the alloying elements is to increase hardenability in order to optimize mechanical properties and toughness after heat treatment. In some cases, however, alloy additions are used to reduce environmental degradation under certain specified service conditions.

Low-alloy steels have a wide variety of compositional categories, and the SAE-AISI designation system defines the major types based on composition (Table 4).

Table 4. Types of Low-Alloy Steels in the SAE-AISI System of Designations (not complete)

Designation	Type of Steel and Nominal Alloy Content, wt. %
Carbon Steels	
10xx(a)	Plain carbon
11xx	Resulphurized
12xx	Resulphurized
15xx	Plain carbon (max Mn range 1.00 – 1.65)
Manganese Steels	
13xx	Mn 1.75
Nickel Steels	
23xx	Ni 3.50
25xx	Ni 5.00
Nickel-Chromium Steels	
31xx	Ni 1.25; Cr 0.65 and 0.80
32xx	Ni 1.75; Cr 1.07
33xx	Ni 3.5; Cr 1.50 and 1.57
34xx	Ni 3.00; Cr 0.77
Molybdenum Steels	
40xx	Mo 0.20 and 0.25
44xx	Mo 0.40 and 0.52
Chromium-Molybdenum Steels	
41xx	Cr 0.50, 0.80 and 0.95; Mo 0.12, 0.20, 0.25 and 0.30
Nickel-Chromium-Molybdenum Steels	
43xx	Ni 1.82; Cr 0.50 and 0.80; Mo 0.25
43BVxx	Ni 1.82; Cr 0.50; Mo 0.12 and 0.25; V 0.03min.
47xx	Ni 1.05; Cr 0.45; Mo 0.20 and 0.35
81xx	Ni 0.30; Cr 0.40; Mo 0.12
86xx	Ni 0.30; Cr 0.40; Mo 0.12
87xx	Ni 0.30; Cr 0.40; Mo 0.12
88xx	Ni 0.30; Cr 0.40; Mo 0.12

The effects of alloying elements are described in the next section. However, some general overlap exists in the wide variety of chemical compositions because compositions of many low-alloy steels are used to develop a response during heat treatment either for hardenability during quenching or the formation of hard metallic carbides.

Another way to define low-alloy steels is to classify them into four major groups:

- low-carbon quenched and tempered (QT) steels
- medium-carbon ultrahigh-strength steels
- bearing steels
- heat-resistant chromium-molybdenum steels

Quenched and tempered (QT) low-alloy constructional (low-carbon) steels combine high yield strength (from 350 to 1035 MPa (50 to 150 ksi)) and high tensile strength with good notch toughness, ductility, corrosion resistance, or weldability. The various steels have different combinations of these characteristics based on their intended applications. Plate is a common product form, but some of these steels, as well as other similar steels, are produced as forgings or castings. In terms of impact toughness, these steels generally outperform mild steel and HSLA steel at low temperature (Figure).

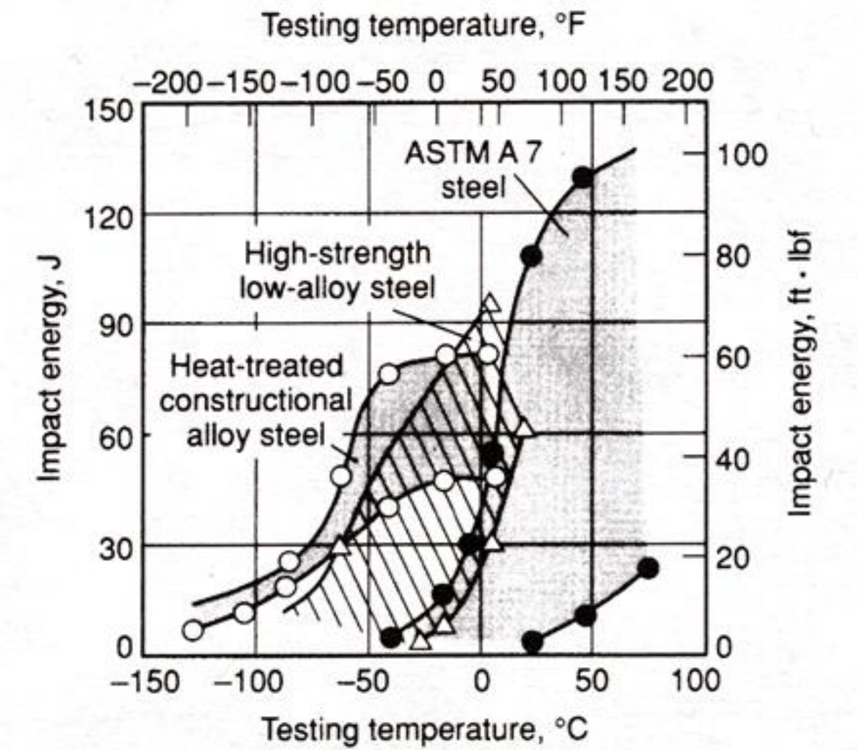

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Figure 6. General Comparison of Charpy V-Notch Toughness for Mild Carbon, HSLA steels and, a Heat Treated Constructional Alloy

2.2.8 Steel Strength and Toughness

The word steel has become synonymous with strength, and the description “strong as steel” is common in everyday language. Steel is usually associated with strength because in many of its uses it is necessary that steel, in one form or another, support a load. The plate in the hull of a ship supports the weight of the internal structure and must be robust enough to cope with the fatigue stresses caused by waves, a car subframe and springs support the weight of the car plus the weight of the passengers, and the car frame must withstand extra forces due to acceleration and deceleration. A bridge must support the weight of cars, trucks, pedestrians, and the weight of the bridge itself.

High-strength carbon and low-alloy steels have yield strengths greater than 275 MPa (40 ksi) and can be more or less divided into four classifications:

- As-rolled carbon-manganese steels
- As-rolled high-strength low-alloy (HSLA) steels (which are also known as microalloyed steels)
- Heat treated (normalized or quench and tempered carbon steel)
- Heat treated low-alloy steels

These four types of steels have higher yield strengths than mild carbon steel in the hot-rolled condition.

The four types of high-strength steels have some basic differences in mechanical properties and available product forms. In terms of mechanical properties, the heat treated (quenched and tempered) low-alloy steels offer the best combination of strength and tough-ness. However, these steels are available primarily as bar and plate products and only occasionally as sheet and structural shapes. In particular, structural shapes (I-beams, channels, wide-flanged beams, or special sections) can be difficult to produce in the quenched and tempered condition because warpage can occur during quenching. Heat treating steels is also a more involved process than the production of as-rolled steels, which is one reason the as-rolled HSLA steels are an attractive alternative.

The as-rolled HSLA steels are also commonly available in all the standard wrought product forms (sheet, strip, bar, plate, and structural shapes). The HSLA steels are an attractive alternative in structural applications because of their competitive price-per-yield strength ratios (generally, HSLA steels are priced from the base price of carbon steels but have higher yield strengths than as-rolled carbon steels). High-strength steels are used to reduce section sizes for a given design load, which allows weight savings. Reductions in section size may also be beneficial in obtaining the desired strength level during the production of structural steel. Whether steels are furnished in the as-hot-rolled or heat treated condition, the strength levels tend to decrease as section size increases. In as-hot-rolled or normalized steel, this results from the coarser microstructure (larger grains and coarser pearlite) that develops from the slower cooling rates on the rolling mill for thicker sections. In quenched and tempered steels, lower strengths result because the transformation temperature increases as section thick increases, and the amount of martensite (the strongest microstructural constituent) progressively decreases. Thus, as the section size increases, it becomes more difficult to obtain the strength levels characteristic of a particular alloy.

Toughness

Steels are generally considered “tough” materials - that is, they can absorb the energy of an impact without breaking. Axle shafts and steering components of an automobile are examples of applications requiring toughness, because fracture of these components during service would be life-threatening. A large impact may bend the axle or steering components and make the automobile inoperative, but at least it is possible to come to a controlled stop.

The most common measure of toughness is resistance to impact as measured in a Charpy V-notch impact test. Carbon content generally increases the strength of steel, but this occurs at the expense of toughness (Figure 3). Consequently, many applications (such as high-strength structural steels) do not depend on just carbon alloying for strength. The toughness of plain carbon and low-alloy steels also is lowered with decreasing temperature (Figure 7). There sharp drop in toughness at a temperature of approximately -40 °C (-40 °F). This is known as the ductile-brittle transition temperature (DBTT). The DBTT is associated with onset of brittle fracture mechanisms in ferritic steels, because the slip systems in the body-centered cubic crystals of ferrite become restricted at low temperature. Austenitic steels (or other face centered cubic - FCC - metals such as aluminium) do not exhibit brittle behavior at low temperature, because their slip systems are maintained at all temperatures.

The DBTT is strongly influenced by microstructural features such as grain size and phase constituents (such as ferrite, pearlite, martensite or bainite). Finer grain size improves toughness and lowers the DBTT, while tempered martensite provides additional toughness at lower temperatures (Figure 8). The maximum energy levels off and is called the “upper shelf energy.” The selection of steel for low-temperature service may be a compromise between strength and impact toughness. The heat treated low alloy structural steels and as-rolled HSLA steels have lower DBTTs than mild steels (Figure 6.), and steels with austenite (FCC) also are tougher without any transition to brittleness

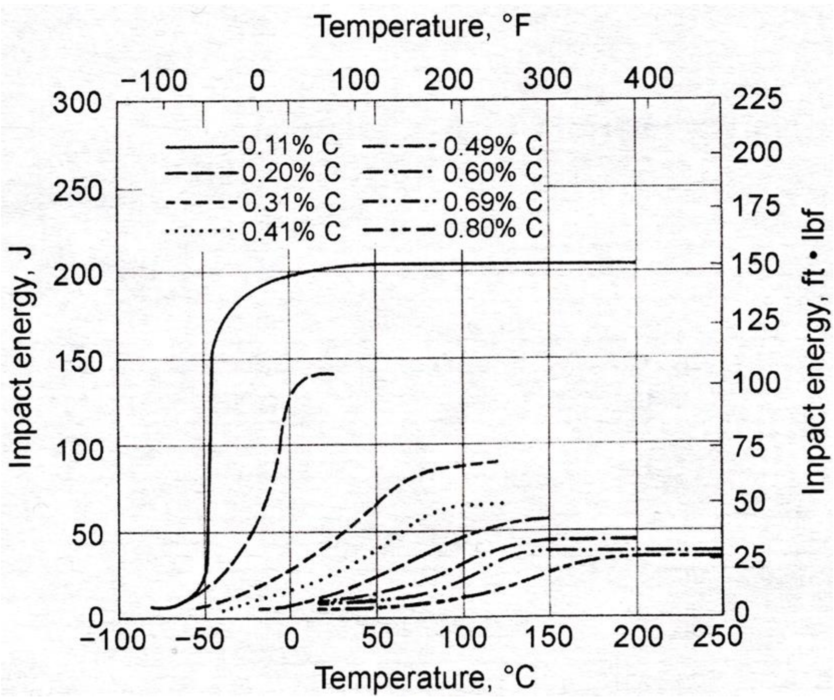
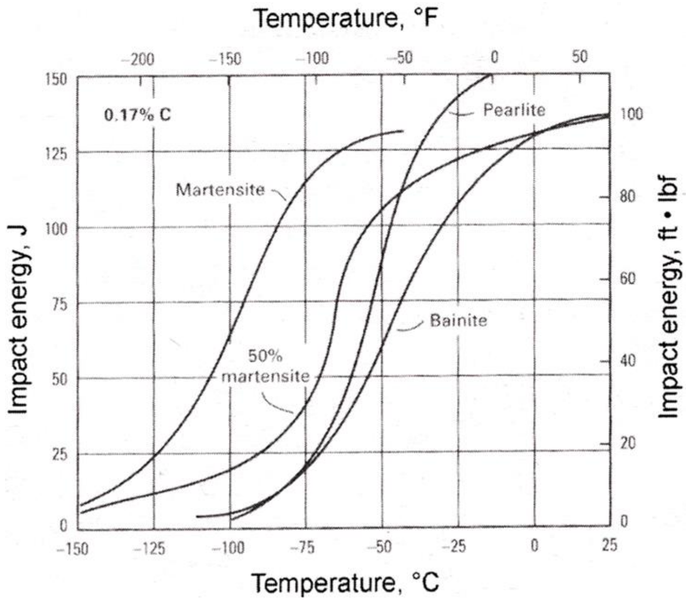


Figure 7. Variation in Charpy V-notch Impact Energy with Temperature for Normalised Plain Carbon Steels

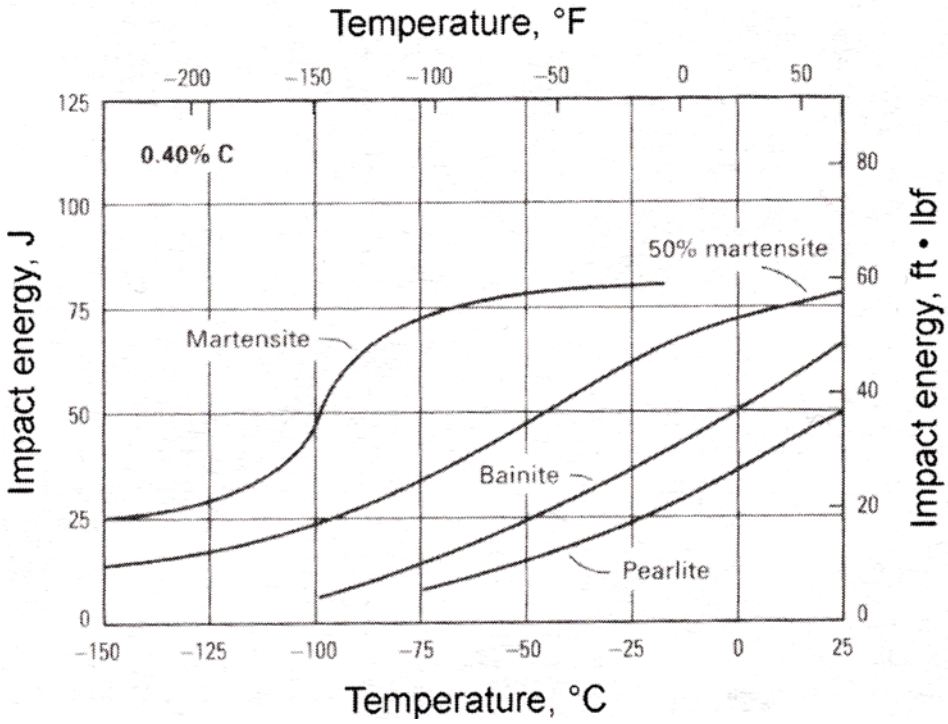
Fatigue Strength

When a steel component is subjected to repeated or cyclic stresses, including vibratory stresses, the part can fail by fatigue, even though the bulk stress levels acting on the part may be below the yield strength of the steel. For this reason it is important to understand the factors influencing fatigue and fatigue resistance and to be able to estimate safe stress levels for a part subjected to repeated stress or strain.

Fatigue failures are frequently encountered in everyday experiences. Bending a steel wire coat hanger or aluminium paper clip many times will result in a fatigue failure in a short time because of the large plastic tensile strain induced in the steel. Automobile axles, gear teeth, steel shafts, springs, railroad rails, pumps, airframes, piping, and numerous other components are susceptible to fatigue failures. In fact, fatigue is the leading cause of industrial failures. Additionally, fatigue behaviour can be influenced by the environment surrounding the component.



(a)



(b)

Figure 8. Variation in Charpy V-notch Impact Energy with Microstructure and Carbon Content (a) 0.17% and (b) 0.40%

For example, steel components exposed to salt water will often fatigue more rapidly than similar components exposed to dry air.

The fatigue resistance or fatigue strength of a steel is usually proportional to hardness and tensile strength, although this generalization is typically not true for high-tensile-strength alloys. Processing, fabrication, and heat treatment techniques, surface treatment, surface finish, and service environment significantly influence the ultimate behaviour of a metal subjected to cyclic stressing. Prediction of the fatigue life is complicated because it depends on many design and material factors such as geometry, loading conditions, stress concentrations, surface finish, residual stresses, and so forth.

The incidence of fatigue failure can be considerably reduced by careful attention to design details and manufacturing processes. As long as the metal is sound and free from major flaws, a change in material composition may not be as effective in achieving satisfactory fatigue life as is the care in design, fabrication, and maintenance during service. The most effective and economical methods of improving fatigue strength involve:

- Designing the part to eliminate stress raisers
- Avoiding sharp surface tears or indentations that may result from punching, stamping, shearing, and even hardness testing
- Preventing the development of surface discontinuities or decarburization (loss of carbon from the steel at its surface during processing or heat treatment
- Improving surface finishes and controlling the details of fabrication and fastening procedures to minimize stress concentrations
- Control of, or protection against, corrosion, service-induced nicks, and other gouges is an important part of proper maintenance to assure that the fatigue strength is maintained during active service.

Fatigue tests performed on small specimens may not be sufficient for precisely establishing the fatigue life of a part. These tests are useful, however, when deciding which steel and heat treatment will be best. The tests must duplicate in-service behaviour as closely as possible. The importance of subtle changes to the fatigue resistance in a component can be illustrated by examining the behavior of heat treated alloy steel crankshafts with and without surface treatment by shot peening (impacting the surface of the heat treated part with steel shot or pellets under controlled conditions). The results of tests on actual crankshafts as well as on separate test bars are shown in, see Figure 9. Shot peening introduced compressive residual surface stresses in the part. These internal compressive stresses reduce the magnitude of the tensile stresses at the surface, thus extending the number of cycles before fatigue failure occurs.

Figure 9 is also useful in that it shows a comparison between the fatigue limit in actual parts (crankshafts) and in standard test specimens. Correlations are reasonable between the ual parts and longitudinal test bars, which re machined with the axis of the specimen in the same direction as the longitudinal axis of the steel bar or forging from which it was made. Test specimens machined with axes transverse to the rolling or forging direction exhibited lower fatigue limits, thus, indicating the influence of steel processing on fatigue resistance.

Other metallurgical variables having pronounced effects on the fatigue behaviour of steels are strength level, ductility, and cleanliness. For most steels with hardness below 400 HB (Brinell hardness), the fatigue limit is approximately half the ultimate tensile strength. Thus, any heat treatment or alloying addition that increases the tensile strength can be expected to increase its fatigue limit. Cleanliness a steel refers to its relative freedom from non-metallic inclusions. These inclusions, especially oxides, have a deleterious effect on the fatigue behaviour of steels. Aggressive environments can substantially influence fatigue resistance. A corroded steel surface has much lower fatigue life than a clean smooth surface.

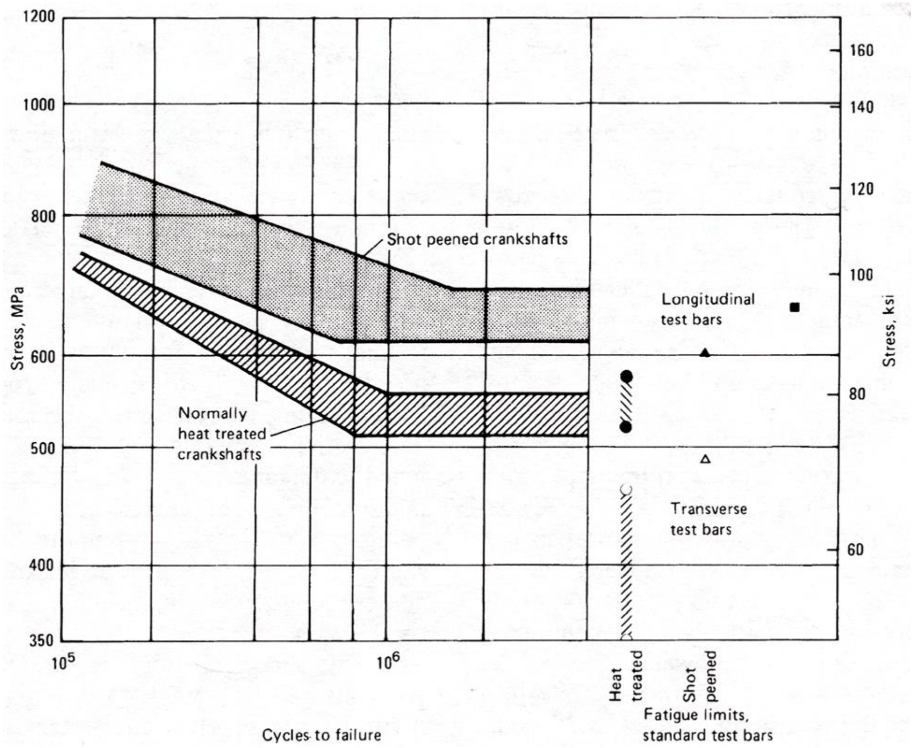


Figure 9. Effect of Shot Peening on Fatigue Behaviour

Corrosion

The corrosion process basically involves electrochemical cells - like the anode and cathode of a battery - that create reactions between a metal and its environment (see Module 8). When the electrochemical cells - consisting of anodes and cathodes - are numerous, small, and close together, uniform corrosion occurs on the metal surface. This is referred to as general corrosion. Corrosion also can occur in localized areas, depending on conditions of the material and the environment. For example, localized forms of corrosion include pitting, crevice corrosion, intergranular corrosion, and stress-corrosion cracking.

General corrosion results in roughly uniform corrosion over the surface. Uniform corrosion is relatively easy to evaluate and monitor. If a material shows only general attack with a low corrosion rate, or if only negligible contamination is present in a process fluid or on the surface, then cost, availability, and ease of fabrication may be the dominant influences on the material of choice. An acceptable corrosion rate for a relatively low-cost material such as plain carbon steel is approximately 0.25 mm/year (10 mils/year) or less. At this rate, and with proper design with adequate corrosion allowance, a carbon steel vessel will provide many years of low-maintenance service.

Carbon steels perform well in dry, rural atmospheres, but the rate of corrosion increases quickly in high-humidity saline or industrial atmospheres. Methods to prevent or control rusting include alloying, coating with a material that will react with the corroding substances more readily than the iron does (as in hot dip galvanized steel), or covering with an impermeable surface coating (such as organic coating systems and tin plating).

Alloying, of course, can improve the corrosion resistance of steel. The effectiveness of these elements in retarding corrosion depends on the corrosive environment. In the case of atmospheric corrosion, the elements generally found to be most beneficial include copper, nickel, silicon, chromium, and phosphorus. Additions of these elements in combination are generally more effective than when added singly, although the effects are not generally additive.

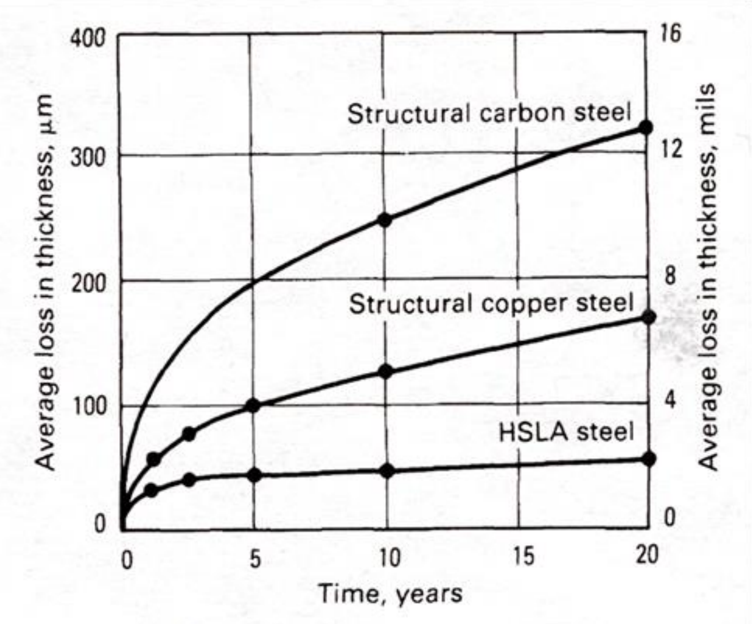


Figure 10. Atmospheric Corrosion Versus Time of Carbon, Copper Steels and HSLA Weathering Steels in a Semi-Industrial or Industrial Environment

Of these, the most striking example is that of copper. Increases from 0.01 to 0.05% have been shown to decrease the corrosion rate by a factor of two to three. Various HSLA weathering steels have also been developed for structural applications. The essential feature of weathering steels is the development of a hard, dense, tightly adherent, protective rust coating on the steel when it is exposed to the atmosphere, permitting it to be used outdoors with or without paint. The rust imparts a pleasing dark surface to weathering steels, and, compared to unalloyed plain carbon steels, weathering steels have significantly reduced corrosion rates in the atmosphere (Figure 10).

2.3 Ship Steel Classifications

Steel for hull construction purposes is usually mild steel containing 0.15-0.23% carbon and a reasonably high manganese content. Both sulphur and phosphorus in the mild steel are kept to a minimum (less than 0.05%). Higher concentrations of both are detrimental to the welding properties of the steel, and cracks can develop during the rolling process if the sulphur content is high.

Steel for a ship classed with Lloyd’s Register is produced by an approved manufacturer, and inspection and prescribed tests are carried out at the steel mill before it is dispatch. All certified materials are marked with the society’s brand and other particulars as required by the rules.

Ship classification societies originally had varying specifications for steel. However, in 1959 the major societies agreed to standardize their requirements in order to reduce the required grades of steel to a minimum. There are now five different qualities of steel employed in merchant ship construction and these are often referred to as IACS steels These are graded A, B, C, D, and E, Grade A being an ordinary mild steel to Lloyd’s Register requirements and generally used in shipbuilding. Grade B is a better quality steel than Grade A and specified where thicker plates are required in the more critical regions. Grades C, D, and E possess increasing notch-toughness characteristics (see section above 2.2.8). Grade C being to American Bureau of Shipping requirements. Lloyd’s Register requirements for Grades A, B, D, and E steels may be found in Chapter 3 of Lloyd’s Rules for the Manufacture, Testing and Certification of Materials, 2020.

2.3.1 High tensile steels

Steels having a higher strength than that of mild steel are employed in the more highly stressed regions of large tankers, container ships, and bulk carriers. Use of higher strength steels allows reductions in thickness of deck, bottom shell, and framing where fitted in the midships portion of larger vessels; it does, however, lead to larger deflections. The weldability of higher tensile steels is an important consideration in their application in ship structures and the question of reduced fatigue life with these steels has been suggested. Also, the effects of corrosion with lesser thicknesses of plate and section may require more vigilant inspection.

Higher tensile steels used for hull construction purposes are manufactured and tested in accordance with Lloyd’s Register requirements. Full specifications of the methods of manufacture, chemical composition, heat treatment, and mechanical properties required for the higher tensile steels are given in Chapter 3 of Lloyd's Rules for the Manufacture, Testing and Certification of Materials. The higher strength steels are available at three strength levels, 32, 36, and 40 (kg/mm^2), when supplied in the as-rolled or normalized condition. Provision is also made for material with six higher strength levels, 42, 46, 50, 55, 62, and 69 (kg/mm^2), when supplied in the quenched and tempered condition. Each strength level is subdivided into four grades, AH, DH, EH, and FH, depending on the required level of notch toughness.

2.3.2 Corrosion Resistant Steels

Steels with alloying elements that give them good corrosion resistance and colloquially referred to as stainless steels are not commonly used in ship structures, primarily because of their higher initial and fabrication costs. Only in the fabrication of cargo tanks containing highly corrosive cargoes might such steels be found.

For oil tankers the inner surfaces, particularly the deckhead and bottom, are generally protected by high-cost corrosion-resistant coatings that require vigilant inspection and maintenance. A recent development in the manufacture of an alloyed shipbuilding steel with claimed improved corrosion resistance properties and its approval by Lloyd’s Register for use in certain cargo tanks of a 105,000 dwt tanker indicate that in the future the need to coat oil cargo tanks might be dispensed with.

2.3.3 Steel sandwich panels

As an alternative to conventional shipyard-fabricated stiffened steel plate structures, proprietary manufactured steel sandwich panels have become available and used on ships where their lighter weight was important. Such panels consist of a steel core in the form of a honeycomb with flanges to which the external steel sheets are resistance spot) or laser (stake) welded. Early use of these bought-in steel sandwich panels was primarily for nonhull structures in naval construction, where their light weight was important. Such panels have also been used for the superstructures of passenger ships, where lightness can allow additional decks and hence increased passenger accommodation. Also, when fabricated using stainless steel their corrosion resistance and low maintenance properties have been utilized.

A proprietary steel sandwich plate system (SPS) has been developed that consists of an elastomer core between steel face plates. Elastomers are a specific class of polyurethane that has a high tolerance to mechanical stress, i.e. it rapidly recovers from deformation. The SPS elastomer also has a high resistance to most common chemical species. Initial application of SPS in shipbuilding has been in passenger ship superstructures, where the absence of stiffening has increased the space available and provided factory-finished surfaces with built-in vibration damping, acoustic insulation, and fire protection. SPS structures have been approved with an ‘A 60’ fire- resistance rating. The main use of this system has been for repair of ships, especially decks. A single steel panel is used to secure the elastomer core to the existing deck. This creates a sandwich panel that is structurally acceptable. The major benefit is in the reduced time required to complete a major steelwork repair, compared to removing and replacing existing, corroded structure. SPS structures can be fabricated using joining technologies presently used in the shipbuilding industry, but the design of all joints must take into account the structural and material characteristics of the metal-elastomer composite. The manufacturer envisages the use of SPS panels throughout the hull and superstructure of ships, providing a simpler construction with greater carrying capacity and less corrosion, maintenance, and inspection. In association with the manufacturer, Lloyd’s Register in early 2006 published provisional rules for the use of this sandwich plate system for new construction and ship repair. The rules cover construction procedures, scantling determination for primary supporting structures, framing arrangements, and methods of scantling determination for steel sandwich panels.

The Norwegian classification society, Det Norske Veritas (DNV), have developed proposals for ship hulls using a lightweight concrete/steel sandwich. They envisaged a steel/concrete/steel composite structure for the cargo hold area of some 600 mm width for the side shell but somewhat greater width for the double bottom area. This sandwich would be much narrower than for a comparable steel- only double-skin bulk carrier, thus increasing the potential carrying capacity, although water ballast may have to be carried in some designated holds as the double skin would not be available for this purpose. DNV consider the other advantages of the concrete/steel sandwich to be reduced stress concentrations with less cracking in critical areas, considerable elimination of corrosion, and elimination of local buckling. The conclusions from the study, a report on which is available for download, are that the sandwich has potential applications for small vessels, for short sea or rivers, and for some offshore structures. It does not appear viable for larger, ocean-going ships at present. Similar panels have been adopted in some offshore applications.

3 Stainless Steels

Stainless steels provide a wide range of strengths and corrosion resistance in seawater environments. Some have limitations that restrict their use to marine atmospheres or require cathodic protection (CP). Others have been developed to a sophisticated level and have extremely high corrosion resistance in seawater. The degree of alloying, temperature, seawater flow, oxygen levels, chlorination, and welding considerations can all influence the performance of stainless steels, and are considered in relation to alloy selection and application.

3.1.1 Characteristics of Stainless Steel

Stainless steels show negligible general thinning in seawater because of a protective, predominantly chromium oxide film that forms immediately on their surface with exposure to air. Oxygen levels present in seawater normally allow the film to repair itself if damaged, in fact, oxygen levels as low as 10 ppb, such as those found in thermal desalination plants, are still sufficient for this to occur.

The film is maintained at very high flow rates, and seawater velocities in excess of 40 ms^{-1} can be accommodated[5]. In practice, however, flow rates in offshore stainless steel pipe systems are often limited to 7 to 10 m s^{-1} in stainless steels as a result of pumping costs and noise restrictions. Even so, the combination of good strength and erosion resistance reduces weight and is economical.

Good manufacturing and fabrication practices are paramount in obtaining the best performance from stainless steel, which is readily fabricated and welded[6-10]. Even the strong duplex stainless steels exhibit good ductility, and there are many suppliers and fabrication shops with experience working with these metals.

Under certain conditions in environments containing oxygenated chloride, the protective surface film on stainless steels can break down locally, leading to pitting, crevice corrosion, or chloride stress corrosion cracking (SCC). Alloy grades can be selected with increased additions of chromium, molybdenum, and nitrogen to significantly improve resistance to crevice corrosion and pitting. Higher nickel levels, or partial or full ferritic structures, increase resistance to chloride SCC compared with 300 series austenitic alloys. Therefore, the situation often faced during material selection is identifying the type of stainless steel that has the correct corrosion resistance required for any given marine environment.

3.1.2 Types of Stainless Steel in Marine Use

3.1.2.1 Applications

Stainless steels are used for a wide range of applications in seawater and for many different reasons. Corrosion resistance in seawater is often only one factor; others include its strength, fabricability, flow velocity, weight saving, and corrosion resistance to other conditions in addition to seawater. Table 6 provides examples of how stainless steels are used in marine environments. They may be part of a mixed metal system and be protected by other less noble alloys, in which case a high corrosion resistance is not the prime requirement.

Alternatively, they may be required to perform on their own merits when attention to corrosion resistance and design is paramount. More details about the range of stainless steels commonly available and their properties can be found in reference 11. Table 5 and the subsequent paragraphs provide details of the grades of stainless steels in marine service, while Table 7 shows the minimum mechanical properties at room temperature.

3.1.2.2 Austenitic stainless steels

Austenitic stainless steels have a tough, ductile structure and are the most commonly available and versatile type of stainless steel. A selection of common austenitic grades is included in Table 5. For welded components, only low-carbon (<0.03%) or stabilised grades should be used, to ensure freedom from intergranular corrosion in the heat-affected zones. The conventional basic austenitic grade used in seawater is 316 (UNS S31600) alloy, which contains 17% Cr, 10% Ni, and 2% Mo; the L grade316L (UNS S31603]) contains low carbon. These have a limited resistance to localised corrosion and, in the presence of crevices or under quiet exposure conditions, require galvanic protection from surrounding components or CP. It should be noted that today 316 (UNS S31600) and 316L (UNS

S31603) are often produced to the minimum chemical composition that has lower corrosion resistance in a marine atmosphere than the more alloyed version used in the past[12,13].

A more highly alloyed austenitic alloy is 904L (UNS N08904), with higher levels of chromium and molybdenum than 316L (UNS S31603). Originally, it was developed for sulphuric acid service, but has seen some use in seawater, particularly desalination.

Increased alloying additions of chromium, molybdenum, and nitrogen can achieve significantly higher resistance to localised corrosion. Over the past 20 years, a number of proprietary 5-7% molybdenum alloys have been developed, with high levels of nitrogen that have the added benefit of stabilising the austenite and enabling the alloys to be produced in thick sections, as shown in Table 5. These are known as super austenitics or 6% Mo alloys.

3.1.2.3 Duplex stainless steels

Duplex stainless steels contain both austenite and ferrite in their structure in roughly 50:50 proportions. They have higher chromium but lower nickel content than the austenitic alloys and low carbon content, as shown in Table 5. The lean duplex stainless steels contain low nickel and molybdenum contents that make them competitive with UNS S31603 (316L) (see Table 5). The lower-molybdenum-containing alloys have a localised corrosion resistance similar to or slightly inferior to that of 316 L (UNS S31603). The higher molybdenum lean alloys are somewhat superior to 316L (UNS S31603) in terms of resistance to localised corrosion.

Duplex stainless steel alloy 2205 (UNS S32205/S31803) with 22% chromium has better localised corrosion resistance than 316 (UNS S31600) grades, and all of the duplex alloys have improved resistance to chloride stress corrosion cracking (SCC). Yield strength for the lean duplex alloys and 2205 (UNS S32205) is about double that of the austenitics; duplex alloys have a strength of 450 MPa compared with 190 MPa for 316L (UNS S31603). Higher (~25%) chromium, molybdenum, and nitrogen-containing superduplex grades, sometimes with copper and tungsten, are also available both in wrought and cast forms and these combine higher strength with the high corrosion resistance of the superaustenitic alloys (Tables 5 and 7).

Table 5. Typical Nominal Compositions for Some Common Wrought Stainless Steel

Type	Common name	UNS No.	Nominal composition (wt%)								PREN[a]
			C	Cr	Ni	Mo	N	Cu	W	Other	
Austenitic	316	S31600	≤0.08	17	10	-	-	-			**17**
	316L	S31603	≤0.03	17	10	2	-	-			**24**
	904L	N08904	≤0.03	20	25	4	-	1.5			**34**
	6% Mo	S31254	≤0.03	20	18	6	0.2	0.7			**43**
		N08926	≤0.03	20	25	6	0.2	0.7			**43**
		N08367	≤0.03	20	24	6	0.2	-			**43**
Duplex	Lean duplex	S32101	≤0.03	21	1	-	0.15	-	-	Mn	**24**
		S32003	≤0.03	20	3	2	0.15	-	-	Mn	**>30**
	Duplex	S31803/ S32205	≤0.03	22	5	3	0.15	-	-		**35**
	Superduplex	S32760	≤0.03	25	7	3.5	0.25	0.7	0.7		**>41**
		S32750	≤0.03	25	7	3.5	0.25	-	-		**>41**
Ferritic	Superferritic	S44735	≤0.03	29	0.5	4	0.045	-	-	Nb	**42**
		S44660	≤0.03	28	1	3.5	<0.04	-	-	Ti, Nb	**40**
Precipitation hardening	17-4 PH	S17400	≤0.07	17	4	-	-	4	-	Nb	**17**
	Grade 660	S66286	≤0.08	14.5	25	1	-	-	-	Ti, V, B	**18**

[a]PREN (pitting resistance equivalent number) calculated from PREN = C + 3.3(Mo + 0.5W) + 16N (elements in wt.%)

Table 6. Typical Stainless Steel Applications in Marine Environments

Conditions	Alloy type	Applications
Marine atmospheres	316 (UNS S31600)/ 316L (UNS S31603); Superduplex	Instrumentation tubing, electrical connectors, instrument housings, rebar in concrete, handrails, cable trays, platform module cladding, fasteners, and boat hardware
Seawater with galvanic protection	316 (UNS S31600)/ 316L (UNS S31603); 2205 (UNS S32205)	Tube sheets, hull-mounted equipment, pump impellers, valves, stems and trim, fasteners for Al and steel, and pump shafts
	Lean duplex Duplex	Thermal desalination plants Subsea flow lines handling wet $C0_2$ and instrumentation tubing
	Precipitation-hardened grades	Special fasteners
Seawater without galvanic protection	904L (UNS N08904)	Pipes, trays, and spray heads in thermal desalination plants
	6% Mo	Power plant condensers, condenser tubing, firewater, ballast and seawater pipes, pumps, valves, and reverse osmosis (RO) desalination
	Superduplex	High-pressure oilfield injection pumps, seawater and firewater pumps, shafting, propellers, retractable bow plane systems, seawater piping and valves, fasteners, heat exchangers (tubes and plates), umbilicals, and RO desalination piping
	Superferritics	Power station condenser tubing
Deaerated brines	316 (UNS S31600)/ 316L (UNS S31603); Duplex	Desalination flash chamber lining and water injection tubing

Table 7. Minimum Mechanical Properties of Wrought Alloys at Room Temperature

Type	Common name	UNS No.	0.2% Proof stress (MPa)	Tensile strength	Elongation (%)	Hardness[3] (HRC)
Austenitic	316	S31600	213	500	45	22
	316L	S31603	213	500	45	22
	904L	N08904	230	530	40	22
	6% Mo	S31254	300	650	35	22
		N08925	300	650	35	22
		N08367	300	650	35	22
Duplex	Lean duplex	S32101	450	650	25	28
		S32003	450	650	25	28
	Duplex	S31803/	450	650	25	28
	Superduplex	S32760	550	750	25	28
		S32750	550	750	25	28
Ferritic	Superferritic	S44735	415	520	18	25
Precipitation	17-4 PH	S17400	750-1450[b]	1030-	5-12[b]	33-45[b]
	Grade 660	S66286	585-650[b]	895-1000[b]	5-15[b]	24-37[b]

3.1.2.4 Precipitation-hardened, martensitic, and ferritic stainless steels

Although austenitic and duplex stainless steels are the most commonly used in marine service, other grades, including ferritic and martensitic stainless steels, are available. While ferritic and martensitic stainless steels do not possess the same levels of corrosion resistance as austenitic and duplex alloys in marine environments, most have much better resistance to atmospheric marine corrosion than carbon and low-alloy steels. Generally they are not recommended for immersed conditions.

Superferritic alloys with high levels of chromium and other alloying additions, such as molybdenum and nickel (Table 5), show good resistance to corrosion both in marine atmospheric and immersion service[14]. However, they are difficult to manufacture in thick sections, and their use is generally restricted to thin sections to avoid toughness problems.

Precipitation-hardened grades have chromium and nickel as the primary alloying elements. They also contain elements such as Al, Cu, Nb, Ti, and Mo. They are principally used because of their high strength, but are seldom used at their highest strength levels because of susceptibility to hydrogen embrittlement (HE) and SCC. Their corrosion resistance is not as good as many austenitic and duplex stainless alloys, so they are only used when strength is the prime requisite, and corrosion- resistance requirements are moderate, or when they are galvanically protected by lower-alloy materials, such as carbon steel.

4 Cast Iron

Cast irons, like steels, are iron-carbon alloys. The difference is that cast irons typically possess higher carbon levels than steels, so that cast irons can take advantage of eutectic solidification in the binary iron-carbon system (Slide section 7a – slide no. 3). The term eutectic is Greek for “easy or well melting,” and the eutectic point represents the composition on the phase diagram where the lowest melting temperature is achieved. The eutectic composition has a distinct temperature where the liquid phase coexists with the two solid phases of austenite and cementite.

For the iron-carbon system the eutectic point occurs at a composition of 4.26% C and a temperature of 1148 °C. Eutectic solidification can begin at a composition of 2.08 % C, which is the point where the maximum solubility of carbon in austenite is achieved. If molten iron has more than 2.08 % C, then the melt does not solidify into just the face-centered cubic (fcc) austenite phase (γ). Instead, molten cast iron solidifies with both austenite and a carbon-rich phase consisting of stable graphite and/or metastable cementite (Fe_3C). This process of eutectic solidification allows cast irons to have a lower melting point and narrower freezing range than steels. This promotes better fluidity to fill complex molds during casting.

Cast irons are often defined as ferrous alloys that contain more than 2% C and 1% or more silicon. Eutectic solidification occurs with carbon content above 2%, but it also is important to note that silicon and other alloying elements may considerably change the maximum solubility of carbon in austenite (γ). Therefore, in exceptional cases, alloys with less than 2% C can solidify with a eutectic structure and therefore still belong to the family of cast irons.

Nonetheless, most commercial irons have carbon contents within the range from 2.5 to 4.0% along with other essential alloying elements, of which silicon and phosphorus are the most important.

Cast irons have a production advantage over steels in that complex shapes can readily be produced without the cost of large-scale machining. Cast irons have a melting range that is approximately 400 °C (720 °F) lower than that for steel, and eutectic solidification of cast iron allows casting of more intricate shapes. Because of its high fluidity when molten, the liquid iron easily fills intricate molds and can form complex shapes. Most applications require very little finishing, so cast irons are used for a wide variety of small parts as well as large ones. Familiar applications include exhaust manifolds and brake drums in automotive applications, gas burners in home furnaces, and frames for electric motors. Special cast irons comprise the wear parts of equipment used to crush and grind coal, cement, and rock. Other special cast irons are used for pumps of all kinds.

Cast irons also comprise a large family of different types of iron, depending on how the carbon-rich phase forms during solidification. The types of cast iron include gray iron, white or chilled iron, ductile (or nodular) iron, malleable iron, and compacted graphite iron. These irons have very different compositions, casting characteristics, and heat treating requirements, which result in a wide variety of physical, chemical, and mechanical properties. The microstructure of cast irons can be controlled to provide products that have excellent ductility, good machinability, excellent vibration damping, superb wear resistance, and good thermal conductivity. With proper alloying, the corrosion resistance of cast irons can equal that of stainless steels and nickel-base alloys in many services.

Shape casting of metal is dominated by cast iron, which constitutes just over 70% of the worldwide production of castings on a tonnage basis. This is followed by steel, copper alloy, and aluminum alloy castings, which make up approximately 25% of the worldwide tonnage of casting production. Magnesium and zinc castings are on the order of 1% or less. The dominance of just a few alloys in shape casting is due to the fact that successful and economic shape casting typically involves alloy compositions near a eutectic.

4.1.1 Classification of Cast Irons

The historical classification of gray and white cast irons, based on fracture appearance, still applies today. Cast irons are also classified as either common or special cast irons. Common cast irons are for general-purpose applications and are unalloyed or low-alloy compositions. Special cast irons, as the name implies, are for special-purpose applications. Special cast irons differ from the common cast irons mainly in their higher content of alloying elements (>3%), which promotes microstructures having special properties for elevated-temperature applications, corrosion resistance, and/or wear resistance.

Table 8. Classification of Cast Irons by Commercial Designation, Microstructure and Fracture

Commercial Designation	Carbon Rich Phase	Matrix	Fracture Surface Appearance	Final Structure Following,
Gray Iron	Lamellar (flake) graphite	P	Gray	Solidification
Ductile (nodular) Iron	Spherical graphite nodules	F, P, A	Silver-Gray	Solidification + Heat Treatment
Compacted Graphite Iron	Compacted vermicular graphite – short fat flakes	F, P	Gray	Solidification
White Iron	Fe3C	P, M	White	Solidification + Heat Treatment
Mottled Iron	Lamellar graphite + Fe3C	P	Mottled	Solidification
Malleable Iron	Temper graphite – irregular shaped nodules	F, P	Silver-Gray	Heat Treatment
Austempered Ductile Iron	Spheroidal graphite	B, AF	Silver-Gray	Heat Treatment

A general classification of cast irons by name and metallurgical structure is provided in Slide section 7b – slide no. 20. For common cast iron, the range of alloying with carbon and silicon varies by the type of iron (section 7b – slide no. 21). As compared with steel, it is apparent that irons have carbon in excess of the maximum solubility of carbon in austenite, which is shown by the lower dashed line. The upper dashed line is the carbon equivalent for the eutectic composition.

The correspondence between commercial and microstructural classification, as well as the final processing stage in obtaining common cast irons, is given in Table 8. With the advent of metallography, the shapes of the graphite phase are classified by types, such as those in ASTM A247[15]. The basic types of graphite shapes include:

- Lamellar (flake) graphite (Type VII in ASTM A247)
- Spheroidal (nodular) graphite (Types I and II in ASTM A247)
- Compacted (vermicular) graphite (Type IV in ASTM A247)
- Temper graphite (TG) from a solid-state reaction called malleabilization (Type III graphite in ASTM A247)

Unacceptable forms of graphite for ductile irons are also classified as Types IV, V, and VI in ASTM A247.

4.1.2 Gray Cast Iron

Gray cast iron is the most common form of cast iron and is characterized by a microstructure with flake (lamellar) graphite embedded in a steel matrix. Gray irons comprise a range of hypoeutectic and hypereutectic compositions (Slide section 7b – slide no. 23).

In a hypereutectic gray iron, graphite forms as the proeutectic phase. In this case, graphite forms in the liquid iron independently of austenite and grows unencumbered by other solid phases. Therefore, it appears as straight plates, with some branching, that grow in size according to the solidification cooling rate. These graphite flakes are entrapped in the structure as solidification progresses, either as characteristic long straight flakes or, in rapidly cooled sections, as lumpy flakes with a starlike distribution. When the temperature has been lowered sufficiently, the remaining liquid solidifies as a eutectic structure of austenite and graphite. Generally, eutectic graphite is finer than proeutectic graphite.

Graphite Shapes in Gray (Flake Graphite) Irons

Standards have been used for many years in the evaluation of graphite size and shape in gray irons. In ASTM A247 (Ref 10.6), for example, the flake graphite in gray cast iron is described by the following types:

- Type A: uniform distribution, random orientation
- Type B: rosette grouping, random orientation
- Type C: superimposed flake sizes, random orientation
- Type D: interdendritic segregation, random orientation
- Type E: interdendritic segregation, preferred orientation
- Type F: Widmanstatten graphite

Type A graphite is generally considered to be the preferred graphite type for gray iron. In general, it is associated with the most desirable mechanical properties and is characteristic of gray cast iron exhibiting good machinability. Type A graphite is uniformly distributed and randomly oriented (Fig. ???). If the cooling rate of the iron is slow, the flakes tend to be larger.

Properties of Gray Cast Irons

Gray irons have relatively low strength and hardness properties (Table 9). Tensile strengths of gray iron range from only approximately 150 to 430 MPa (22 to 63 ksi). Gray cast irons are also brittle due to the inherent notch effect of the flake graphite. Toughness of gray iron is typically lower than other types of graphitic irons, but it is less notch sensitive and does not exhibit a severe drop in toughness at lower temperatures.

Table 9. Mechanical Properties of Gray Cast Irons

ASTM A-48 Class	Tensile Strength, MPa	Shear Strength, MPa	Compressive Strength, MPa	Fatigue Limit	Hardness, HB
20	152	179	572	69	156
25	179	220	669	79	174
30	214	276	752	97	210
35	252	334	855	110	212
40	293	393	965	128	235
50	362	503	1130	148	262
60	431	640	1293	169	302

As a structural material, gray cast iron is selected for its high compressive strength, which ranges from 572 to 1293 MPa (83 to 188 ksi). Gray cast iron also has several unique properties that are derived from the existence of flake graphite in the microstructure. Gray iron can be machined easily, even at hardness levels conducive to good wear resistance. The graphite cavities provide good chip-breaking qualities, thus allowing free machining with short chips. Gray iron also resists sliding wear even when poorly lubricated, because the relatively low coefficient of friction of graphite acts as an excellent solid lubricant.

Gray iron has outstanding properties for vibrational damping (absorbing rather than transmitting vibrations). The dispersed graphite deflects and reflects mechanical vibrations with dampening over a relatively short distance. For the machine housing, gray cast iron is selected because it is relatively inexpensive, can be easily cast, and has the ability to dampen vibrations. Graphitic irons usually also have higher thermal conductivities than steel alloys, and this is an advantage in applications such as automotive brakes where mechanical energy is converted into heat that must be dissipated fairly quickly.

Gray cast irons are used in a wide variety of applications, including automotive cylinder blocks, cylinder heads and brake drums, ingot molds, machine housings, pipe, pipe fittings, manifolds, compressors, and pumps. Specifications typically classify gray irons according to their tensile strength (Table 9). Generally it can be assumed that the following properties of gray irons increase with increasing tensile strength from class 20 to class 60:

- All strengths, including strength at elevated temperature
- Ability to produce a fine, machined finish
- Wear resistance

On the other hand, the following properties decrease with increasing tensile strength, so that low-strength irons often perform better than high-strength irons when these properties are important:

- Machinability

- Resistance to thermal shock
- Damping capacity
- Ability to be cast in thin sections

4.1.3 Ductile Cast Iron (Nodular or Spheroidal)

Ductile iron, also known as nodular iron or spheroidal graphite iron, is very similar to gray iron in composition, but during solidification the graphite nucleates as spherical particles in ductile iron, rather than as flakes. This is accomplished through the addition of a very small amount of magnesium and/or cerium to the molten iron.

The chief advantage of ductile iron over gray iron is its combination of relatively high tensile strength and ductility - up to 18% elongation for ferritic ductile iron with a tensile strength of 415 MPa (60 ksi), as opposed to only 0.6% elongation for a gray iron of comparable strength. This improvement in ductility is due to the shape of spheroidal graphite, which has a lower stress concentration factor than the sharper angular boundaries of flake graphite. Ductile irons tend to be tougher than other types of irons for this reason.

Ductile iron is used in the transportation industry for applications such as crankshafts because of its good machinability, fatigue strength, and higher modulus of elasticity (compared to gray iron), and in heavy-duty gears because of its high yield strength and wear resistance. Ductile iron is stronger and more shock resistant than gray iron, so although it is more expensive by weight than gray iron, it may be the preferred economical choice because a lighter casting can perform the same function. The second-largest end use for ductile iron is for pressurized water and wastewater systems. Since its introduction in the late 1940s, ductile iron has become the industry standard in this application.

Ductile iron also shares and supplements applications with malleable irons, which are as-cast white irons that are annealed to form a temper graphite structure. The energy costs of annealing must be balanced with the cost of additional alloying elements in ductile iron to choose the most economical material at any time. For castings having section thicknesses of approximately 6 mm (0.25 in.) and above, ductile iron can be manufactured in much thicker section sizes than the malleable irons. However, it cannot be routinely produced in very thin sections with as-cast ductility, and such sections usually need to be heat treated to develop ductility.

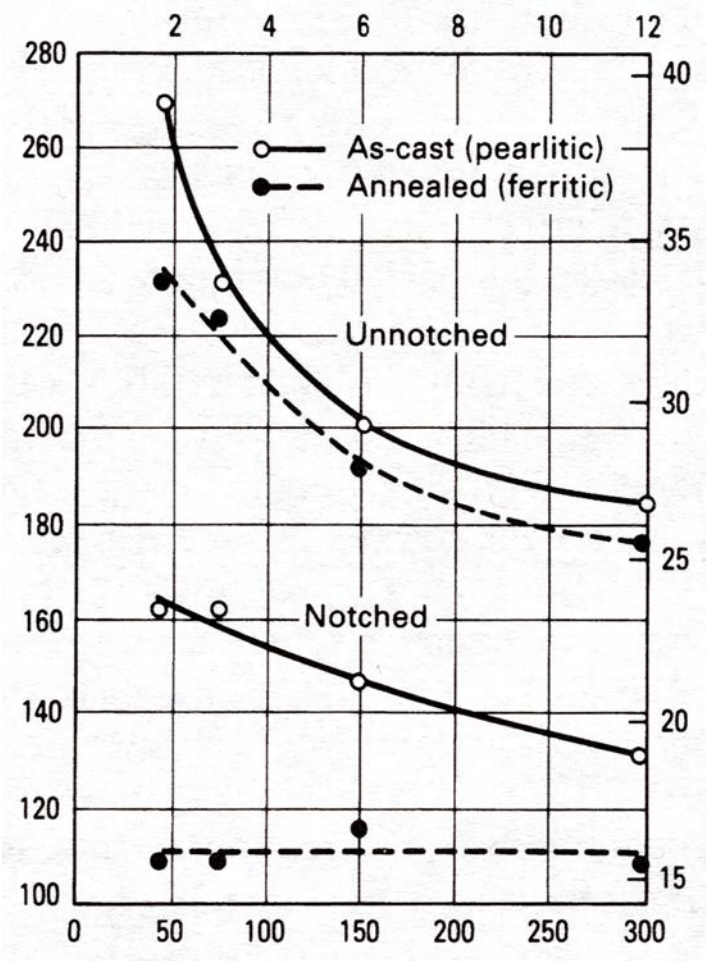


Figure 11. Effect of Cast Section Size on the Fatigue Properties of Pearlitic and Ferritic Ductile Irons

Casting of Ductile Irons

Ductile irons, second only to gray iron in the amount of casting produced, account for over a third of all castings, ferrous and nonferrous. Ductile iron has the advantage, in common with gray iron, of excellent fluidity, but it requires more care to ensure sound castings and to avoid hard edges and carbides in thin sections, and it usually has a lower casting yield than gray iron. Compared to steel and malleable iron, it is easier to make sound castings, and a higher casting yield is usually obtained; however, more care is often required in molding and casting.

directly on casting rather than by heat treatment. The spheroidal form of graphite in ductile iron is made by treating low-sulphur liquid cast iron with an additive containing magnesium (and occasionally cerium). Magnesium content is approximately 0.04 to 0.06%. Sulphur in the iron interacts with magnesium forming magnesium sulfide, which removes the magnesium from the melt and forms a troublesome dross. Therefore, it is important that the iron be low in sulfur' preferably less than 0.02%, when magnesium is added.

Low-sulfur iron melts can be readily achieved in an electric furnace by melting charges based on steel scrap or special-quality pig iron supplied for ductile iron production, together with ductile iron returned scrap. Low sulfur content can also be achieved by melting in a basic cupola, but acid cupola-melted iron has a higher sulfur content and normally needs to be desulphurized before treatment by continuous or batch desulfurization in a ladle or special vessel. In addition to sulfur, the trace presence of lead, titanium, and aluminum can also interfere with the formation of nodular graphite. A small quantity of cerium added with the magnesium minimizes the effects of impurities and makes it possible to produce the iron from raw materials of moderate cost.

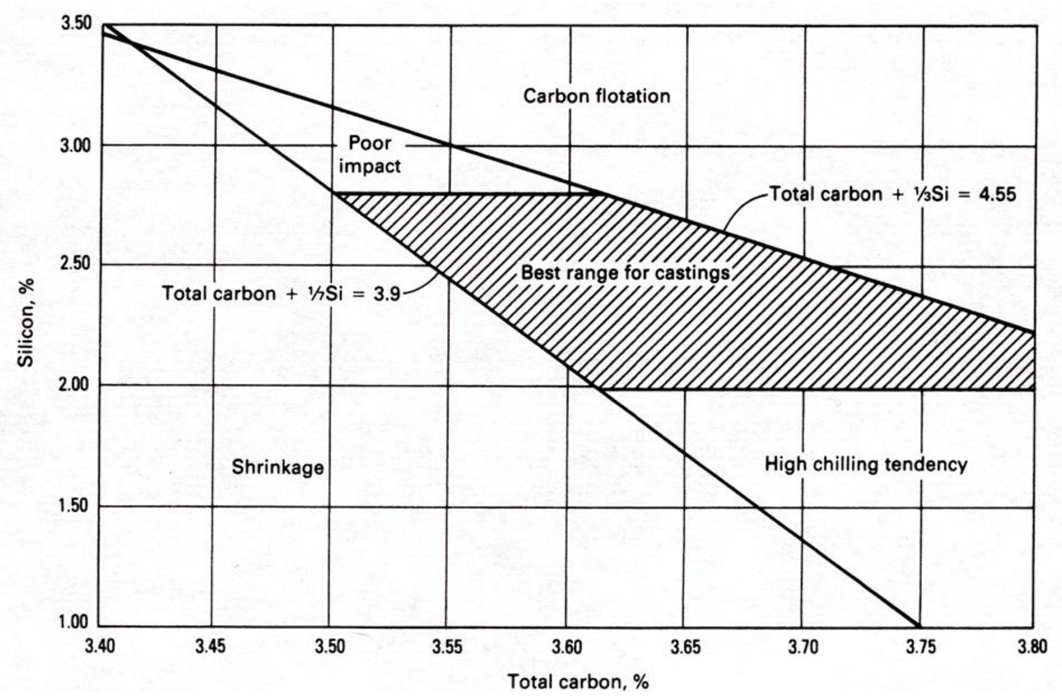


Figure 12. Typical Carbon and Silicon Content for Ductile Cast Irons

The chief advantage of ductile iron is that the preferred spheroidal shape can be obtained

After the magnesium has been added, the melt is usually inoculated just before or during casting with a silicon-containing alloy. Inoculation with silicon promotes the formation of well-shaped graphite nodules. Silicon also increases the number of graphite nodules and reduces the carbide and pearlite content. The silicon content of the base iron is kept low enough so that the silicon from the magnesium alloy and from the inoculation adjusts the final silicon content to the desired range. Alloys used for inoculation include ferrosilicon containing either 75 or 85% Si, a calcium-bearing ferrosilicon with 85% Si, or various combinations of these silicon alloys. The desirable range of carbon and silicon in ductile iron (Figure 12) is a tighter range than that of gray iron (Slide section 7b – slide no. 21).

Heat Treatment and Mechanical Properties of Ductile Iron

Many ductile iron products are used in the as-cast condition, but in some foundries, approximately 50% of the products are heat treated before being shipped. Annealing is mandatory for some grades of ductile iron, and several types of annealing can be employed to reduce the hardness of iron. Figure 13 presents a schematic representation of three types of annealing (high, medium, and low or subcritical) for iron castings and compares them to stress relieving and normalizing. Annealing can relieve residual stresses in castings if the slow cooling is continued to a low enough temperature.

Like gray cast iron, the as-cast matrix micro-structures of ductile iron usually consist of ferrite or pearlite or combinations of both, depending on cast section size and/or alloy composition. Heat treatment varies according to the desired effect on properties. For example, an as-cast pearlitic microstructure (Slide section 7b – slide no. 23) can be annealed to produce a ferritic matrix with lower hardness. Conversely, heat treatment also can induce martensite formation for hardening.

Most of the specifications for ductile iron are based on tensile properties such as tensile strength, yield strength, and percent elongation. In ASTM A536[16], for example, five grades of ductile iron are designated by their tensile properties (Table 10.5). The property values are stated in customary units; 60-40-18 grade designates minimum mechanical properties of 415 MPa (60 ksi) tensile strength, 275 MPa (40 ksi) yield strength, and 18% elongation. The modulus of elasticity of ductile iron varies from 164 to 169 GPa (23.8 to 24.5 xl06psi) regardless of the grade. Although this modulus is higher and more consistent than that of gray iron, it is lower than the modulus of steels.

Good-quality ductile irons produced to meet requirements of a specified grade normally cover a range, as shown in Slide section 7b – slide no. 24. The tensile properties and the Brinell hardness of ductile iron are related because of the nominal and consistent influence of spheroidal graphite. However, the relationship between tensile properties and hardness depends on the alloys used and the microstructure obtained. In ferritic irons, hardness and strength are dependent on solid-solution hardening of the ferrite by the elements dissolved in it, with silicon being the most important and common. Nickel is also a common ferrite strengthener. The lamellar carbide layers are the principal hardening constituent in pearlitic irons. A somewhat higher strength-to-hardness relationship occurs in a uniform matrix of tempered martensite.

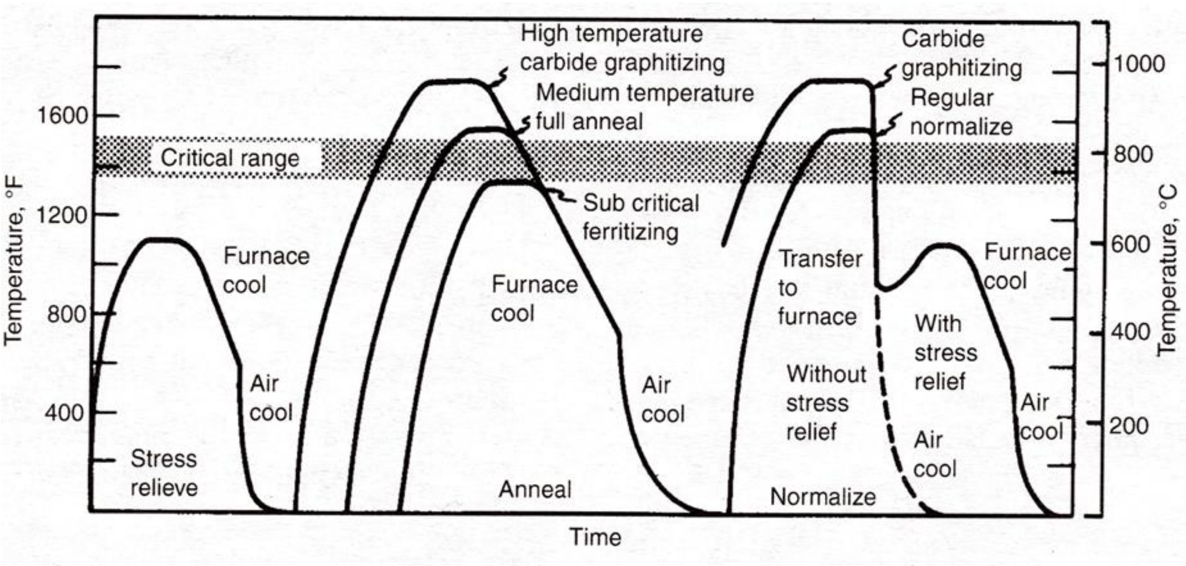


Figure 13. Schematic Representations of Heating and Cooling Cycles used to Stress Relieve, Anneal and Normalize Iron Castings

4.1.4 Austempered Ductile Iron (ADI)

Austempered ductile iron represents a range of cast irons whose properties depend on a heat treatment called austempering. Austempered ductile irons have a matrix with much higher ductility for the same strength than conventionally heat-treated ductile irons (Slide section 7b – slide no. 25). Grades of austempered ductile iron appear in various specifications such as ASTM A897[17].

The austempering process is a special heat- treatment cycle that involves austenitization followed by quenching to an isothermal treatment above the martensite start temperature (Figure 14). The process consists of:

- A-B: heating the part to the austenitic range of 800 to 950 °C(1475 to 1750 °F)
- B-C: holding the parts for a time sufficient to saturate the austenite with the equilibrium carbon level
- C-D: cooling (quenching) the parts rapidly to a temperature above the martensite start temperature (Ms) to avoid the formation of ferrite and pearlite. This temperature is the austempering temperature.
- D-E: austempering the part in the range of 240 to 400 °C (460 to 750 °F) for a time sufficient to produce a stable structure of acicular ferrite and carbon-enriched austenite. This structure, called ausferrite, is the structure that produces the desired high-performance properties.
- E-F: cooling the part to room temperature

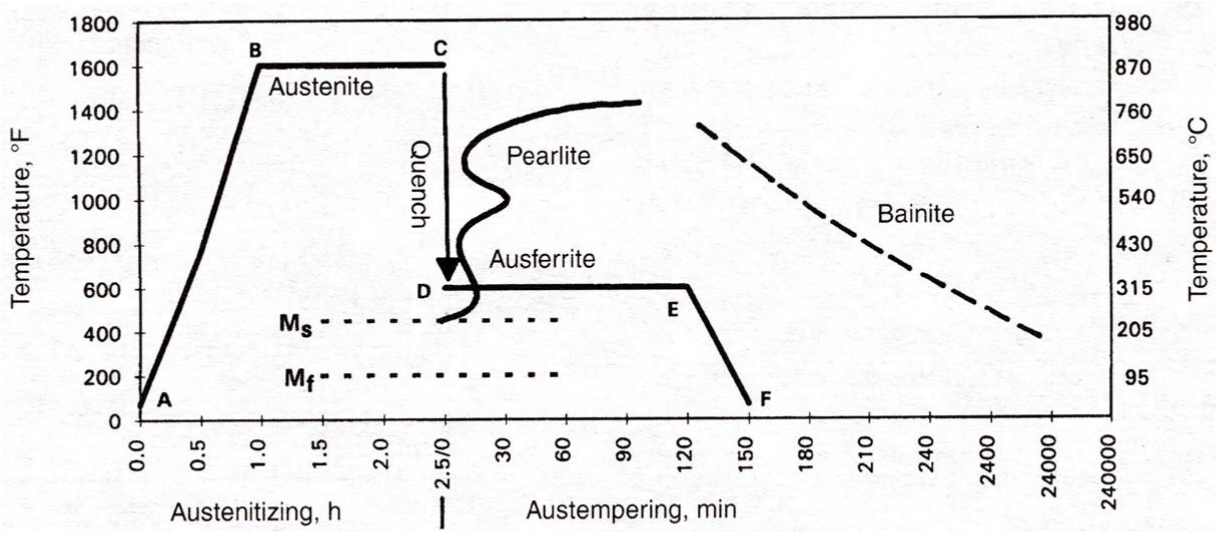


Figure 14. Austempering Process for Cast Irons

The austempering process also applies to gray and malleable irons. In the higher-silicon gray and ductile irons, the resultant structure is ausferrite. In the lower- silicon malleable irons, the structure is either a mixture of ausferrite and bainite or just bainite. Higher austempering temperatures result in coarser structures that exhibit good ductility and dynamic properties. Lower austempering temperatures produce finer structures that have higher tensile and yield strengths and superior wear resistance.

Some of these applications are relevant for the marine environment and include:

- Gears (including side and timing gears)
- Wear-resistant parts, valves etc.
- High-fatigue-strength applications
- High-impact-strength applications
- Automotive crankshafts
- Chain sprockets
- Refrigeration compressor crankshafts

- Universal joints
- Chain links

5 Non Ferrous Alloys

5.1 Copper Alloys

5.1.1 Introduction and Designations

The metal copper is very versatile, having good resistance to corrosion in marine atmospheres and in seawater with moderate flow velocities. Its properties, both in terms of corrosion resistance and mechanical strength, can be further improved by alloying. There are many copper alloys suitable for marine service and the main groups are:

- Coppers
- Copper-nickels
- Bronzes
- Brasses
- Copper-beryllium

All copper alloys can be machined accurately and cost-effectively and to a good standard of tolerance and surface finish. Some copper alloys have excellent machinability as a primary attribute - specifically leaded brasses, which set the standard by which all other metals are judged. Other copper alloys are made with a variety of combinations of properties such as strength, wear resistance, anti-galling and cold formability. These may be less easily machined, but are still easier to machine than many other types of material. For seawater systems, copper-nickel and aluminium bronze are often preferred, although other copper alloys are used in marine service and have their specific advantages. Copper alloys differ from other metals in that they have an inherent high resistance to biofouling, particularly macrofouling, which can eliminate the need for antifouling coatings or water treatment.

European copper and copper alloy material condition (temper) designations are defined in EN 1173. The principal mandatory properties for material condition are defined by a letter. For example, tensile strength R250 indicates the minimum of 250 N/mm², while a hardness of H090 indicates a minimum value of 90 (Vickers for wrought materials and Brinell for cast). Copper and copper alloys may be selected to an R or H value but not both.

Alloys found in marine service are grouped into brasses (copper-zinc), bronzes (copper-tin-phosphorus, copper-aluminium, and copper-silicon), gunmetals (copper-tin-zinc), copper-nickels, and copper - beryllium. There is a wide range of mechanical and physical properties, and many have excellent anti-galling properties. For applications in seawater systems, copper-nickel and aluminium bronze tend to be preferred, although other alloys are used in marine service and have their specific merits. Copper alloys differ from other alloy groups because copper has an inherent high resistance to biofouling, particularly macrofouling, which can eliminate the need for antifouling coatings or water treatment.

5.1.2 Application of copper alloys

Typical marine applications using castings and wrought products for each alloy group are included in Table 10. The range is wide and includes seawater piping, heat exchangers, pump and valve components, fasteners, bearings, propellers and shafts. The compositions of a selection of alloys from each group are shown in Table 11. Associated typical mechanical properties are included in Table 12. Higher values can be achieved by cold working or by thermal treatment called age hardening, depending on the particular alloy, product form, and section size.

Copper and Copper Alloys-Standards, Specifications and Applications[18] provides a detailed range of alloy compositions and mechanical properties. Because of the variety of applications for copper alloys, it is important that designers consult with suppliers to clarify what property values and combinations are available to best fit the purpose of the desired product form. The wrought coppers, brasses and bronzes are low-strength in the soft annealed condition, but can be work hardened well into the medium-strength range.

Age-hardenable alloys such as copper-nickel-aluminium can reach strengths equivalent to ASTM A193[19] Grade B7 bolting steel. Copper-nickel-tin alloys can reach high strengths too, but the highest strength of any copper alloy is provided by the copper-beryllium alloys that may be hardened by a combination of cold working and age hardening to values comparable to any high-strength steel.

Table 10. Typical Applications of Marine Copper Alloys[19]

Alloy group	Alloy type	Applications
Copper	Phosphorus deoxidised, high residual phosphorus (DHP)	Copper tubing, nails
Brass	Aluminium brass,	Seawater tube and pipe
	Naval brass, Muntz metal	Tube sheet
	Al-Ni-Si brass	Hydraulic, pneumatic, and instrument lines
	Dezincification-resistant (DZR) brass	Through hull fittings
	Mn bronze (cast and wrought)	Shackles and cabin fittings, propellers, shafts, deck fittings, and yacht winches
Bronze	Phosphor bronze	Springs, bearings, gears, fasteners, rods and slides
	Silicon bronze	Fasteners (screws, nuts, bolts, washers, pins, lag bolts) staples, and cages
	Aluminium bronze	Sea cocks, pumps, valves, and brushes
	Nickel aluminium bronze (cast and wrought)	Propellers and shafts, pumps, and valves, bushing and bearings, fasteners, and tube plate for titanium tubing in condensers
Gunmetal	Cu-Sn-Zn castings	Pumps and valves, stern tubes, deck fittings, gears and bearings, bollards and fairleads

Copper-nickel	90/10 and 70/30 Cu-Ni-Cr	Heat exchanger and condenser tubes, piping, platform leg and riser sheathing. Seawater cooling and firewater systems. MSF desalination and boat hulls. Seawater cast pump and valve components. Wrought condenser tubing
High-strength copper-nickel	Cu-Ni-Al Cu-Ni-Sn	Shafts, drive bearings and bushes, stab plate connectors and bolting, pump and valve trim, gears and fasteners. Bearings, drill components, subsea connectors, valve actuator stems and lifting nuts, subsea manifold and remote-operated vehicle (ROV) lock-on devices and seawater pump components
Copper-beryllium	Cu-Be	Springs, drill components, subsea cable repeater housings, hydrophones and geophones, subsea valve gates, balls, seats, actuators, lifting nuts, blowout preventer (BOP) Locking rings

Table 11. Nominal Compositions of Selected Copper Alloys[19]

Alloy	EN No. or (DS No.)	UNS No.	Cu	Ni	Fe	Mn	Zn	Al	Sn	Other
Copper-DHP	CW024A	C12200	99.9							0.02 P
Al brass	CW702R	C68700	78				Rem	2		0.04 As
Naval brass	CW712R	C46400	61				Rem		1	
Al—Ni—Si brass	CW700R	C69100	83	1.2			Rem	1		1 Si
DZR brass	CW602N	C35330	62				Rem			2.0 Pb 0.06 As
Mn bronze (high-tensile brass)	CW721R	C67500	58		0.8	1.5	Rem	1	0.7	1 Pb
Phosphor bronze	CW453K CW451K	C52100 C51000	Rem Rem						8 5	0.3 P 0.2 P
Silicon bronze	CW116C	C65500	Rem			1				3 Si
Aluminium	CW302G	C64200	Rem					7.4		2 Si

silicon bronze										
Cast nickel aluminium bronze (NAB)	CC333G	C95800	Rem	5	4.5			9.5		Ni> Fe
	Def Stan 02-747 [3]	-	Rem	5	4.5	1		9.2		
Wrought	Def Stan	-	Rem	4.7	4.2	0.3		9.5		
NAB	02-833 [4]									
	-	C63200	Rem	4.5	3.8	1.3		9.3		
Gunmetal	CC491K	C83600	Rem	1			5		5	5 Pb
Cu-Ni	CW352H	C70600	Rem	10	1.5	0.7				
	CW353H	C71640	Rem	30	2	2				
	CW354H	C71500	Rem	30	0.7	0.7				
Cu-Ni-Cr	Def Stan	-	Rem	30	0.8	0.8				1.8 Cr
	02-824 [5]	C72200	Rem	16	0.7	0.7				0.5 Cr
Cu-Ni-Al	High-strength Cu-Ni	-	Rem	14.5	1.5	0.3		3		
	DS02-835 [6]	C72420	Rem	15	1	5		1.5		0.4 Cr
Cu-Ni-Sn	-	C72900	Rem	15					8	
Cu-Be	CW101C	C17200	Rem							1.9 Be

5.1.3 Coppers

Coppers essentially contain more than 99.9% copper and have been used in marine environments for centuries. They have a high resistance to macrofouling but can be subject to erosion-corrosion when the seawater velocity exceeds certain limits. The typical mechanical property range is shown in Table 12.

Strength and hardness are increased from the annealed condition by cold work. They have excellent thermal and electrical conductivity and good corrosion resistance in marine atmospheres and in seawater, corroding evenly and showing little pitting and crevice corrosion.

These copper-zinc alloys usually have small additions of other elements to enhance their properties, for example, arsenic or tin for inhibition of dezincification, or lead to aid pressure tightness and/or machining operations[20]. They are divided into two groups for seawater service:

- Single-phase (alpha) brasses that have up to 37% Zn.

- Two-phase (alpha beta) brasses that start to form above about 37.5% Zn.

Two main corrosion issues that should be taken into account when selecting and designing with brass alloys are dezincification and ammonia stress corrosion cracking (SCC). Additions of arsenic can successfully inhibit dezincification in alpha brasses, whereas tin can slow down the process in both groups of brass alloys.

5.1.4 Alpha brass alloys

Alpha brass alloys are tough, more ductile than copper, and can be readily cold worked. Their strength increases with zinc levels and cold work. Aluminium brass is one of the more well-known alloys in this group and is sufficiently resistant to erosion-corrosion to be used for piping and heat exchangers/condensers. Alloys with up to about 15% Zn (with the precise content depending on other elements present) are immune to dezincification. Higher-zinc alpha brasses can be successfully used in clean seawater as long as they are inhibited against dezincification by 0.02-0.06% arsenic.

Additionally, UNS C69100 (CW700R) is an alpha brass with about 1% each of aluminium, nickel, and silicon. It has been successfully used in marine environments, particularly for hydraulic control and instrumentation lines up to 35 MPa. It can be precipitation hardened if required, performs well in seawater and marine atmospheres, and has high resistance to dezincification.

5.1.5 Alpha-beta brasses

Alpha-beta brasses are alloys that are hot worked. Other elements can be added, such as lead to improve machineability, and additions of Al, Sn, and Mn produce a range of high-tensile-strength brasses that are readily hot rolled, forged, extruded, and cast. Alpha beta brasses are subject to dezincification[20] in seawater (e.g. Muntz metal; UNS C28000 [CW 509L]), although tin additions (e.g. naval brass: UNS C46400 [CW 712R]) can slow this down considerably.

Cast and wrought manganese bronze alloys also fall into this group; the name is a misnomer as they are essentially high-tensile brasses. Alloys with about 3% Mn and similar amounts of aluminium and nickel provide good service as medium-duty propellers; however, cathodic protection (CP) is required to avoid dezincification.

Table 12. Typical Mechanical Properties of Copper Alloys most Commonly used in Seawater[19]

Alloy	EN No. or DS No.	UNS No.	0.2%Proof strength N mm^{-2}	Tensile strength N mm'^{2}	Elongation %	Hardness HV (or HB)
Copper-DHP[a]	CW024A[a]	C12200	180	240	20	70
Al brass	CW702R	C68700	140	350	30	85
Naval brass	CW712R	C46400	140	370	35	105
Al—Ni—Si brass	CW700R[b]	C69100	223	430	45	130
DZR brass	CW602N	C35330	150	350	20	90
High-tensile brass (Mn bronze)	CW721R	C67500	250 min[c]	50 min[c]	14 min[c]	140
Phosphor bronze	CW453K	C52100	280	450	26	130
Silicon bronze	CW116C	C65500	260	385	40	170
Cast NAB	CC333G	C95800	280 min[c]	650 min[c]	12 min[c]	150 HB
	Def Stan 02-747 [3]	-	250 min[c]	620 min[c]	15 min[c]	
Wrought	Def Stan	-	245 min[c]	620 min[c]	15 min[c]	
NAB	02-833 [4]	C63200	275 min[c]	620 min[c]	15 min[c]	
Gunmetal	CC491K	C83600	110 min[c]	230 min[c]	10 min[c]	65 HB (min)
Cu-Ni	CW352H	C70600	140	320	40	85
	CW353H[b]	C71640	175	450	35	110
	CW354H	C71500	170	420	42	105
Cu-Ni-Cr	Def Stan	-	300 min[c]	480 min[c]	18 min[c]	85
	02-824 (sand cast) [5]	C72200[b] (wrought)	110 min[c]	310 min[c]	46	
Cu-Ni-Al	High-strength Cu-Ni	-	555 min[c]	770 min[c]	12 min[c]	229 min[c]

	Def Stan 02-835 [6]	C72420	430 min^{c}	725 min^{c}	18 min^{c}	170
Cu-Ni-Sn (spinodally hardened)	-	C72900	1035	1137	6	326
Cu-Be	CW101C	C17200	700	860	12	222
	Aged		900 min^{c}	1100 min^{c}	3 min^{c}	354
^{a}Half hard ^{b}Tube only ^{c}Minima where stated can vary with product form and section thickness						

Dezincification-resistant (DZR) brass (UNS C35330 [CW602N]) was developed to provide a brass that is two-phase, and therefore good for hot working, but can be converted to an all-alpha structure by heat treatment. The presence of arsenic makes the alloy resistant to dezincification by stabilising the alpha phase. Although developed for domestic plumbing service, it can be used in seawater, too, and is approved by Lloyds Register for through-hull fittings [7,8] on yachts and small craft.

5.1.6 Bronze alloys

The term *bronze* originally applied to Cu-Sn alloys. This is not as appropriate now because the addition of small quantities of other elements is found to increase its strength as in Cu-Sn-Zn alloys (gunmetals) and Cu-Sn-P (phosphor bronzes).

The search for higher strength alloys also led to alloys that do not contain tin but have adopted the concept of a superior alloy by including the word ‘bronze,’ for example, silicon bronze and aluminium bronze. Bronze alloys have high resistance to ammonia SCC compared with brass alloys[21],

5.1.6.1 Phosphor bronze

Binary copper-tin alloys can be rolled and drawn to increase their strength and hardness by cold work. The mechanical properties can be further increased by small additions of phosphorus (up to 0.4% may be present). Castings may contain more than 8% Sn and if so, may require soaking at temperatures of about 700 °C until a second tin-rich phase disappears, returning it to a more corrosion-resistant single-phase alloy. Phosphor bronze alloys corrode evenly and have little tendency to pit. In general, the higher the tin content, the higher the resistance to seawater corrosion. The higher tin-bronzes have good resistance to seawater polluted with sulphides when compared to other copper alloys[21].

5.1.6.2 Gunmetal

Gunmetals are tin bronze castings containing 2-10% zinc and may be further modified by addition of lead (up to 8%) and nickel (up to 6%). The name gunmetal derives from their use, at one time, for gun barrels. They have been traditionally used for marine components such as centrifugal pump impellers, valve seats, taps and pipe fittings. They are not prone to dezincification, SCC, or pitting, nor is crevice corrosion a problem. For use in seawater, sound casting practices and low levels of porosity are necessary[22], It is preferable to choose a gunmetal with a tin content above 5% and with a low percentage of lead; the more common grades have 5, 7, or 10% tin.

Lead contents of up to 6% have little effect on the corrosion resistance of gunmetal under atmospheric conditions and in normal fresh and seawater at moderate flow rates. When the flow velocity is high, less than 3% lead in such components as centrifugal pump impellers may be advantageous[22]. The addition of lead ensures pressure tightness so they can be used for valve bodies and pump casings. At levels of about 10% lead, so called leaded tin-bronzes make excellent bearing alloys for use in rotating components.

5.1.6.3 Silicon bronze

The most common silicon bronze contains about 3% silicon and 1% manganese and has very good seawater corrosion resistance, and resistance to SCC by ammonia. Silicon bronze has a long history of use as fasteners (screws, nuts, bolts, washers, pins, lag bolts, and staples) in marine environments, including screws used in wooden sailing vessels.

Silicon bronzes have an alpha phase metallurgical structure. They generally have the same corrosion resistance as copper but with higher mechanical properties and superior weldability. The silicon provides solid solution strengthening. They are tough, with high resistance to shock and galling.

5.1.6.4 Aluminium bronze

These alloys are basically copper with 4 - 12% Al and have a thin, adherent surface film of copper and aluminium oxides that heals very rapidly if damaged. They have good resistance to corrosion, erosion, and wear, as well as good mechanical and corrosion fatigue properties.

At less than 8% Al, the alloys are alpha phase and can be readily rolled and drawn. At 8-12.5% Al, a second phase, beta, is formed, and the alloys can be wrought or cast. Additions of iron, manganese, nickel, or silicon can also be present. Generally, the corrosion resistance of the aluminium bronzes increases as the aluminium, and other alloying additions, increase. Thus, nickel-aluminium-bronze (NAB) in both wrought and cast forms is highly corrosion-resistant in unpolluted waters. A derivation, aluminium silicon bronze (UNS C64200 [CW302G]) (also covered by Defence Standard 02-834[23], finds application notably when low magnetic permeability is required.

The metallurgical structure of alpha plus beta aluminium bronze alloys is very complex and described in detail together with corrosion properties and applications by Meigh[24] and Campbell[25,26]. Careful control of chemistry and processing is required to ensure that the structure is maintained in an optimum condition and does not form less corrosion-resistant phases that can promote selective phase attack.

Nickel and iron are two alloying additions which assist this by modifying the transformation of beta phase to less harmful phases to provide and maintain high corrosion resistance. They also increase ductility and improve castability. These alloys are known as the nickel aluminium bronzes (NABs). Those with about 5% each of nickel and iron are widely used for their strength and corrosion resistance and exhibit useful precipitation-hardening characteristics.

Even so, if the NAB cools too quickly, such as occurs during welding or with thinner sections, not all of the beta phase may transform. This became of particular relevance to naval applications and final heat treatments were developed to counteract this; NAB sand castings to Defence Standard 02-747 Part 2 are required to be heat treated for 6h at 675 ± 15 °C and air cooled[27]. Heat treatment is also applied to wrought products; for example, NAB extruded rod and bar stock up to 40 mm, and rolled rod and bar up to 30 mm, in accordance with

Defence Standard 02-833 Part 2, require a heat treatment at 740 ± 20 °C followed by an air cool[28],

5.1.7 90/10 and 70/30 copper-nickel alloys

Of the wrought copper alloys, the copper-nickel alloys, and in particular the more economical 90/10 alloy, are the most widely used for seawater systems (piping and heat exchangers/condensers), and are also used for boat hulls and splash zone sheathing on offshore structures[29], The 70/30 alloy is stronger and can withstand higher flow rates.

General corrosion rates in seawater are normally 0.002 to 0.02 mm year[1], decreasing to the lower pitting, crevice corrosion, and SCC and do not have localised corrosion limitations caused by temperature. Piping typically is used up to 100 °C. Copper-nickels have a high resistance to biofouling, particularly the 90/10 alloy[30].

There is also a modified 30% Ni alloy containing 2% Mn and 2% Fe (UNS C71640 [CW353H]) that is only commercially available as condenser tubing. It was developed for high resistance to erosion-corrosion, particularly in the presence of suspended solids. It is extremely successful in multistage flash desalination plants, notably in the heat rejection and brine heater sections[29].

Ammonia SCC in seawater or sulphide stress cracking/hydrogen embrittlement (HE) are not problem areas with these copper-nickels. However, care is still required in polluted conditions as ammonia can lead to higher corrosion rates and can also cause low-temperature hot-spot corrosion in heat exchanger tubes[21]. Sulphides can cause pitting and higher corrosion rates, usually in situations when aerated water mixes with sulphide-containing waters. An established oxide film offers a good degree of resistance to such corrosion, as does ferrous sulphate dosing[31].

These alloys are ductile and can be welded. If weld consumables are used, the 70/30 Cu-Ni electrodes and filler metals are normally preferred[31]. for both 90/10 and 70/30 alloys. No post-weld heat treatment is required to maintain corrosion resistance. Copper-nickel can also be welded to steel using the appropriate consumables.

Detailed information about the corrosion performance, mechanical properties, fabrication, and biofouling properties of 90/10 and 70/30 copper-nickel can be found in the *Information sources* section at the end of this chapter.

Further, copper-nickel alloys containing chromium have also been developed; a wrought alloy tubing, C72200, to provide higher resistance to erosion corrosion and a cast alloy, Def Stan 02-834[32], which is used by the UK Royal Navy for pumps and valves.

5.1.7.1 High strength copper-nickel alloys

Although copper-nickel alloys have a long history of use in marine environments because of their excellent corrosion properties and good antifouling properties, they have moderate mechanical properties that are improved by cold working. As a means of improving mechanical strength, two principal alloying routes have been followed: the Cu-Ni-Al system in which precipitation hardening allows high strengths and the Cu-Ni-Sn system that relies on spinodal decomposition of the structure. Both types of alloy can achieve high strengths matching that of bolting steel.

In Cu-Ni-Al alloys, the aluminium increases the strength by a conventional precipitation-hardening mechanism, principally consisting of Ni_3Al, otherwise known as gamma prime. Additional elements, such as Fe, Nb, and Mn, are introduced to the basic Cu-Ni-Al ternary alloy to increase the effectiveness of this phase. The 0.2% proof strength levels of about 700 N mm ^{2} are achievable together with good antigalling properties, while retaining low corrosion rates and resistance to HE. The alloys were refined over the years to improve resistance to ammonia SCC[33].

5.1.7.2 Cu-Ni-Sn

Cu-Ni-Sn alloys display spinodal strengthening through the development of submicroscopic chemical composition fluctuations. A significant increase in the strength over the base metal results from the spinodal decomposition, with proof strengths typically 690 to more than 1000 N mm^{2} [34].

The alloys are used subsea where bearing performance, non-magnetic, low-fouling, antigalling, high-strength properties are required, such as for stems, bushes and bearings. Applications with sliding movement and/or good resistance to corrosion and biofouling are favoured. They are weldable with a post-weld heat treatment being required for weldments if strength is a critical requirement. The alloys retain 90% of room-temperature strength at elevated temperatures as high as 300 °C.

Of the copper-based materials available, UNS C72900 is one of the highest strength, low-friction, non-magnetic, non-galling metals that work in most sour service conditions. Its seawater corrosion rate is very low. Resistance to erosion-corrosion in sand-laden seawater is also very good.

5.1.8 Copper beryllium

In its age-hardened condition, copper beryllium attains the highest strength and hardness of any commercial copper-based alloy, while retaining low corrosion rates in seawater and excellent biofouling resistance[35]. The tensile strength can exceed 1300 Nm^{-2} depending on temper, while the hardness approaches HRC 45. It has high galling resistance, and is immune to hydrogen embrittlement (HE) and chloride-induced SCC. Also, in the fully aged condition, the electrical conductivity is a minimum of 22% of the International Annealed Copper Standard (IACS).

5.2 Aluminium Alloys

Aluminium alloys are normally selected for engineering applications as they have advantages in terms of low density, a high strength-to-weight ratio, high thermal conductivity, acceptable weldability, and, depending on the alloy, good corrosion behaviour in seawater. Although aluminium is a reactive metal, its good corrosion resistance is entirely a result of the rapid formation of a thin, stable, and impervious oxide film on the surface. The thickness of this oxide film, as formed in air, varies between 2.5 and 20 nm depending on the time of exposure. Breakdown of this film, for instance, through chemical attack by chloride ions, results in localised attack of the metal substrate, leading to pitting or crevice corrosion.

5.2.1 Nomenclature of aluminium alloys

Pure aluminium metal is of low strength; therefore, it is used for engineering purposes with the addition of various alloying elements. The different types of alloy produced in this way are grouped into non-heat-treatable and heat-treatable alloys, depending on the microstructures that can be developed to give enhanced strength. For instance, the alloying elements magnesium, manganese, and silicon produce alloys that are strengthened using work-hardening techniques.

The alloying elements copper and various combinations of magnesium, zinc, and silicon can produce heat-treatable alloys. These harden after solution heat treatment and quenching through the development of intermetallic particles (or precipitates) in the material, either by naturally ageing at room temperature, or by artificial ageing at elevated temperature.

The common nomenclature system for aluminium alloys is the one devised by the Aluminium Association and uses the first digit of a four-digit number to define the basic alloy type. The list of general aluminium alloy types is provided below:

- 1 xxx - Pure aluminium
- 2xxx - Aluminium-copper
- 3xxx - Aluminium-manganese
- 4xxx - Aluminium-silicon
- 5xxx - Aluminium-magnesium
- 6xxx - Aluminium-magnesium-silicon
- 7xxx - Aluminium-zinc

In the UNS numbering system, the alloys are denoted by the letter ‘A’ followed by five numbers. The first digit following the initial letter ‘A’ defines the type of product. The most commonly used number in this case is 9, which signifies a wrought product. Numbers other than 9 are used to define other products such as castings, ingots, and clad products, among others. The last four numbers are the same as those of the Aluminium Association numbering system listed above.

Table 13. Typical Aluminium Alloy Applications in the Marine Environment

Alloy type	**UNS no.**	**Applications**
5083/5086	UNS A95083/	Yachts, fishing boats, pleasure craft, customs vessels
	UNS A95086	Police boats
5086	UNS A95086	Liquefied natural gas (LNG) storage containers
6005A/6061	UNS A96005/ UNS A96061	Gangways, pontoons, catwalks, ladders and helidecks
5086/6082	UNS A95086/ UNS A96082	Fin tube heat exchangers

Table 14. Composition of Wrought Aluminium Alloys Used in Marine Applications

UNS no.	Nominal composition, wt%								
	Mg	**Zn**	**Si**	**Fe**	**Mn**	**Cu**	**Cr**	**Ti**	**Zr**
A95083	4.5	0.25 max	0.40 max	0.40 max	0.7	0.10 max	0.15	0.15 max	-
A95086	4.0	0.25 max	0.40 max	0.50 max	0.4	0.10 max	0.15	0.15 max	-
A95754	3.0	0.20 max	0.40 max	0.40 max	0.50 max	0.10 max	0.30 max	0.15 max	-
A95456	5.0	0.25 max	0.25 max	0.40 max	0.70	0.10 max	0.1	0.20 max	-
A95059	5.5	0.6	0.45 max	0.50 max	0.9	0.25 max	0.25 max	0.20 max	0.15
A95383	4.5	0.25 max	0.25 max	0.25 max	0.8	0.10 max	0.15	0.15 max	0.2 max
A96005	0.5	0.20 max	0.7	0.35 max	0.50 max	0.30 max	0.30 max	0.10 max	-
A96061	1.0	0.25 max	0.6	0.70 max	0.15 max	0.3	0.2	0.15 max	-
A96082	0.9	0.20 max	1.0	0.50 max	0.7	0.10 max	0.25 max	0.10 max	-

5.2.2 General properties

For seawater applications, the alloys of choice are the 5xxx-series alloys because of their superior corrosion resistance. Some of the 6xxx alloys are also used, but alloys of the other series, particularly those containing copper, show inferior corrosion performance in seawater.

In addition to the alloy number designation, a further designation denoting the temper condition of the alloy is used. This takes the form of a suffix following the alloy number and gives the details of how the material was strengthened. For nonheat-treatable alloys, this is denoted by Hxxx (e.g. 5083-H321). For heat-treatable alloys, it is designated by Txxx (e.g. 6082-T6). If no hardening is done, or the product is fully annealed, then the temper is given by -O (e.g. 5086-0).

Aluminium alloys can be produced as castings or as wrought (hot- and/or cold- worked) products. Because of the significant differences between these two product forms, their numbering system is separate. In as-cast products, the as-cast microstructure normally has low strength and ductility, whereas wrought products offer a recrystallised microstructure (although of a directional nature) giving improved mechanical and engineering properties. Hot-working methods usually take the form of rolling, extrusion, or forging. Sheets of thicknesses below ~2.5 mm are produced by cold rolling.

5.2.3 Aluminium alloys for seawater applications

Aluminium alloys are favoured for uses for which their high strength-to-weight ratio, as well as a high corrosion resistance, are particular advantages[36,37]. Table 13 provides examples of where the higher corrosion-resistant aluminium alloys are used in marine environments.

Table 14 and Table 15 give chemical compositions and mechanical properties, respectively, for many of the aluminium alloys used in seawater service.

5.2.4 Main Corrosion Types

Aluminium alloys in normal use corrode either by a mechanism involving general attack, or by a localised mechanism[38]. In seawater, provided the natural oxide film is maintained, general corrosion is rarely seen, as this type of corrosion mainly occurs when the environment pH is lower than 4 or greater than 8.5. Localised corrosion occurs in seawater because of a breakdown of the protective oxide film in isolated areas, and results in pits developing on the surface. The initiation of such pitting is a chemical attack by chloride ions at defective points in the passive oxide film[39].

Of the aluminium alloys available, the 5xxx alloys possess favourably high corro-sion resistance in seawater[38,40], Generally, the 5xxx alloys are less prone to pitting corrosion than the 6xxx alloys. The presence of copper in aluminium alloys, such as UNS A96061 (6061), produces deleterious cathodic defects in the oxide film. The detrimental effect caused by the presence of copper becomes even greater for 2xxx (Al-Cu) alloys; therefore, these alloys are not suitable for seawater applications. The high-strength 7xxx (Al-Zn) alloys also suffer from excessive corrosion in seawater and are rarely used in marine applications.

There are three advantages that aluminum alloys have over mild steel in the construction of ships. Firstly, aluminum is lighter than mild steel (approximate weights being 2.723 tonne/m^3, mild steel 7.84 tonne/m^3), and with an aluminum structure it has been suggested that up to 60% of the weight of a steel structure may be saved. This is in fact the principal advantage as far as merchant ships are concerned, the other two advantages of aluminum being a high resistance to corrosion and its nonmagnetic properties. The nonmagnetic properties can have advantages in warships and locally in the way of the magnetic compass, but they are generally of little importance in merchant vessels. Good corrosion properties can be utilized, structure are necessary. A major disadvantage of the use of aluminum alloys is their higher initial and fabrication costs. The higher costs must be offset by an increased earning capacity of the vessel, resulting from a reduced lightship weight or increased passenger accommodation on the same ship dimensions. Experience with large passenger liners on the North Atlantic service has indicated that maintenance costs of aluminium alloy structures can be higher for this type of ship and service.

Although aluminum was first used for small craft in 1891 and for experimental naval vessels in 1894, it has not been a significant material for ships until comparatively recently.

A significant number of larger ships have been fitted with superstructures of aluminium alloy and, apart from the resulting reduction in displacement, benefits have been obtained in improving the transverse stability. Since the reduced weight of superstructure is at a position above the ship’s center of gravity, this ensures a lower center of gravity than that obtained with a comparable steel structure. For example, on the Queen Elizabeth 2 with a limited beam to transit the Panama Canal, the top five decks constructed of aluminum alloy enabled the ship to support one more deck than would have been possible with an all-steel construction.

Only in those vessels having a fairly high speed and hence power, also ships where the deadweight/lightweight ratio is low, are appreciable savings to be expected. Such ships are moderate and high-speed passenger liners having a low deadweight. It is interesting to note, however, that for the Queen Mary 2, not having a beam limitation, the owners decided to avoid aluminum alloy as far as possible to ensure ease of maintenance over a life cycle of

40 years. A very small number of cargo liners have been fitted with an aluminum alloy superstructure, principally to clear a fixed draft over a river bar with maximum cargo.

Table 15. Mechanical Properties of Wrought Aluminium Alloys Used in Marine Applications

Alloy	Product form	Alloy temper and condition	PS-0.2%, N mm-2	Tensile strength, N mrrr2	Elongation S_0, %
A95083	Plate/Sheet	O/H111	125	275	15
		H112	125	275	10
		H116	215	305	10
		H321	215	305	10
		Welded	125	275	N/A
A95086	Plate/Sheet	O/H111	100	240	16
		H112	125	250	9
		H116	195	275	9
		H321	195	275	10
		Welded	100	240	N/A
A95754	Plate/Sheet	0/H111	80	190	17
A95059	Plate/Sheet	0/H111	160	330	24
		H116	270	370	10
		H321	270	370	10
		Welded	160	300	N/A
A95456		0	130	290	16
		H116	230	315	10
		H321	230	315	12
A95383	Plate/Sheet	O/H111	145	290	17
		H116	220	305	10
		H321	220	305	10
		Welded	145	290	N/A
A96061	Plate/Sheet	T5/T6	240	290	10
		Welded	125	160	N/A
A96082	Plate/Sheet	T5AT6	240	280	8
		Welded	125	190	N/A
A96005-A	Extruded	profile T5/T6	215	260	6
		profile T57T6 Welded	100	160	N/A
		Closed profile T6/T6	215	250	5
		Welded	100	160	N/A
A96061	Extruded	profile T5/T6	240	260	8
		profile T5/T6 Welded	125	160	N/A
		Closed profile T5/T6	205	245	4
		Welded	125	160	N/A
A96082	Extruded	profile T5/T6	260	310	8
		profile T5/T6 Welded	125	190	N/A
		Closed profile T5/T6	240	290	5
		Welded	125	190	N/A

Smaller naval vessels have often had aluminum superstructures on a steel hull as a weight saving measure. A difficulty is the joining of the two metals, in such a way as to avoid a corrosion cell being set up. Either bolted connections with washers to separate the two metals, or an explosively bonded steel/aluminum transition piece (trade name 'Kelomet' and produced by Nobles explosives) can be used. In the explosively bonded material the interface between the metals remains corrosion free.

The total construction in aluminum alloy of a large ship is not considered an economic proposition and it is only in the construction of smaller multi-hull and other high-speed craft where aluminum alloys of higher strength-to-weight ratio are fully used to good advantage. Aluminum has been used for specialized craft, including hydrofoils, and is currently particularly used for high-speed ferries where weight is critical. The material is also used for small, high-speed military vessels.

One advantage of aluminum is that the material can be extruded to produce a very wide range of profiles. These can have benefits in design of efficient structures. An example is a plate that is extruded with stiffeners as part of the profile. The plates can be joined to assemble deck panels, with minimum welding and hence a lower risk of distortion. The production process is also faster. Specialized extrusions can be expensive so the economic benefits have to be considered carefully.

5.2.5 Riveting

Riveting may be used to attach stiffening members to light aluminum alloy plated structures where appearance is important and distortion from the heat input of welding is to be avoided.

The commonest stock for forging rivets for shipbuilding purposes is a non-heattreatable alloy NR5 (R for rivet material) that contains 3-4% magnesium. Nonheattreated alloy rivets may be driven cold or hot. In driving the rivets cold relatively few heavy blows are applied and the rivet is quickly closed to avoid too much cold work i.e. becoming work hardened so that it cannot be driven home. Where rivets are driven hot the temperature must be carefully controlled to avoid metallurgical damage. The shear strength of hot driven rivets is slightly less than that of cold driven rivets.

5.2.6 Aluminium Alloy Sandwich Panels

As with steel construction, proprietary aluminum alloy honeycomb can offer extremely low weight options for the superstructures of high-speed craft.

5.2.7 Fire Protection

It was considered necessary to mention when discussing aluminum alloys that fire protection is more critical in ships in which this material is used because of the low melting point of aluminum alloys. During a fire the temperatures reached may be sufficient to cause a collapse of the structure unless protection is provided. The insulation on the main bulkheads in passenger ships will have to be sufficient to make the aluminum bulkhead equivalent to a steel bulkhead for fire purposes.

For the same reason it is general practice to fit steel machinery casings through an aluminium superstructure on cargo ships.

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Module 7: Steels and Non-Ferrous Alloys

INDEX (note pages: in black, steel and non-ferrous alloys slide nos. in blue; 'a', 'b' & 'c' refer to slide sections)

Part 2: Steels and Non-Ferrous Alloys: Composition, Properties and Applications

International Institute of Marine Surveying

Professional Qualification
in Marine Corrosion

Presented by **Mike Lewus**

Module 7

(section a)

Ferrous and Non-Ferrous Alloy Designations, Composition, Applications & Testing

Module 7 (section a)

Summary

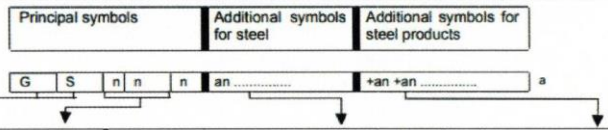
- **Materials Designations**
  - **Steels and Stainless Steels**
  - **Cast Irons**
  - **Non Ferrous Alloys**
    - **Aluminium Alloys**
    - **Copper alloys, nickel alloys**
- **Miscellaneous:**
  - **Carbon equivalent**
  - **Ductile-Brittle transition temperature (DBTT)**
  - **standards**
- **Recap on Mechanical Testing**
  - **Tensile test and associated metrics**
  - **Hardness Tests**
  - **Pendulum Impact Test**
  - **Fatigue and Fracture Toughness (K_{IC})**

Module 7 (section a)

Issues Relating to Metals in Vessel Construction

- **Strength**
  - **Relevance of yield strength, proof strength, tensile strength (UTS), torsional strength, Young's modulus (E)**
- **Toughness**
  - **Fracture toughness, fatigue resistance**
- **Weldability**
  - **Hydrogen cracking, liquation cracking, stress corrosion cracking (SCC)**
- **Formability**
  - **Forming limit diagrams, surface effects, SCC**
- **Corrosion Resistance**
  - **Galvanic corrosion, pitting, SCC, corrosion fatigue etc.**
- **Cost**

BSEN 10027/1: 2016 Designation System for Steels. Steel names.



<table>
<tr><th colspan="2">Principal symbols</th><th colspan="6">Additional symbols</th></tr>
<tr><th rowspan="2">Letter</th><th rowspan="2">Mechanical property</th><th colspan="5">For steel</th><th rowspan="2">For steel product</th></tr>
<tr><th colspan="4">Group 1 [b]</th><th>Group 2 [c d]</th></tr>
<tr><td rowspan="8">G = steel casting (where necessary)

S =structural steel</td><td rowspan="8">nnn = specified minimum yield strength [e] in MPa [f] for the smallest thickness range</td><td colspan="3">Impact property Energy Joules (J)</td><td>Test tempe-rature</td><td rowspan="8">C = Special cold forming
D = Hot dip coating
E = Enamelling
F = Forgings
H = Hollow section
L = Low temperature
M = Thermomechanically rolled
N = Normalised or normalised rolled
P = Sheet piling
Q = Quenched and tempered
S = Ship building</td><td rowspan="8">Tables 16, 17 and 18</td></tr>
<tr><td>27J</td><td>40J</td><td>60J</td><td>°C</td></tr>
<tr><td>JR</td><td>KR</td><td>LR</td><td>20</td></tr>
<tr><td>J0</td><td>K0</td><td>L0</td><td>0</td></tr>
<tr><td>J2</td><td>K2</td><td>L2</td><td>-20</td></tr>
<tr><td>J3</td><td>K3</td><td>L3</td><td>-30</td></tr>
<tr><td>J4</td><td>K4</td><td>L4</td><td>-40</td></tr>
<tr><td>J5</td><td>K5</td><td>L5</td><td>-50</td></tr>
</table>

Hot Rolled Steel Products: Steel name examples

Examples of steel names for structural steels	
Standard	Steel name according to EN 10027-1
EN 10025-2	S235JR S355JR S355J0 S355J2 S355K2 S450J0
EN 10025-3	S355N S355NL
EN 10025-4	S355M S355ML
EN 10025-5	S235J0W S235J2W S355J0WP S355J2WP S355J0W S355J2W S355K2W

BSEN 10025/2: 2019 Hot rolled products of structural steels. Technical delivery conditions for non-alloy structural steels

BSEN 10025/3: 2019 Hot rolled products of structural steels. Technical delivery conditions for normalized/normalized rolled weldable fine grain structural steels

BSEN 10025/4: 2019 Hot rolled products of structural steels. Technical delivery conditions for thermomechanical rolled weldable fine grain structural steels

BSEN 10025/5: 2019 Hot rolled products of structural steels. Technical delivery conditions for structural steels with improved atmospheric corrosion resistance

BSEN 10025/6: 2019 Hot rolled products of structural steels. conditions for flat products of high Technical delivery yield strength structural steels in the quenched and tempered condition

Symbol	Meaning	Mechanical Property	Comment
S	Structural steel	Min. YS	
P	Pressure vessel and lines steel	Min. YS	
L	Steels for pipe and tube	Min. YS	
E	Engineering steels	Min. YS	
B	Steel for reinforced concrete	Characteristic yield	
R	Rail Steels	Min. Yield Case	
H	High Tensile Strength Flat Products	Min. Yield Case	'T' indicates minimum tensile strength
D	Flat products for cold forming		Followed by C, D or X and two numbers characterising steel

Other symbols are added to the category codes to identify any additional compositional requirements, delivery conditions, mechanical properties and impact and temperature codes for structural steels,

Code	Condition
A	Annealed
QT	Quench & Tempered
N	Normalised
SR	Stress Relieved
C	Cold Worked
U	Untreated

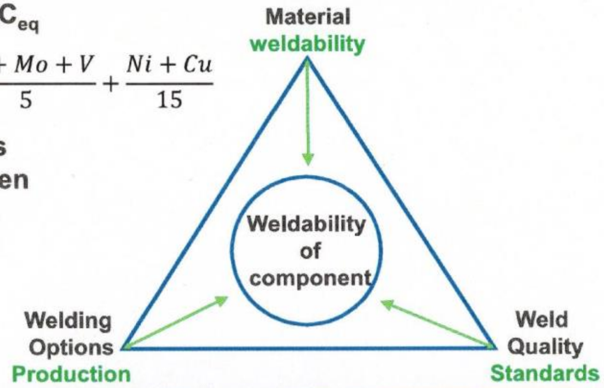
Impact Resistance		Temperature	
Impact Code	Testing Strength	Code	Testing
J	27 J	R	Room Temperature
K	40 J	O	0°C
L	60 J	2	-20°C
		3	-30°C
		4	-40°C
		5	-50°C
		6	-60°C

Weldability of Carbon Steel and C-Mn Steels

- Weldability is closely related to the carbon content
- Weldability is affected by other alloying elements
- The combined effect is given by the materials carbon equivalent value C_{eq}

$$C_{eq} = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

- Generally there is a trade-off between material strength and weldability



Steel Designations: Maximum CEV

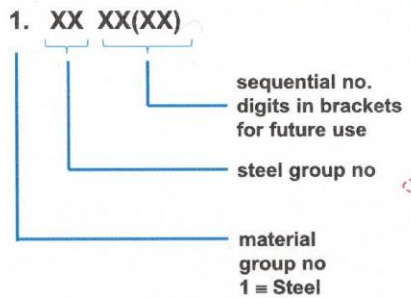
Maximum CEV examples for designated steels and product thickness

Designation		Max. CEV in % for nominal product thickness, mm				
Name	No.	≤ 30	30< t ≤40	40< t ≤150	150< t ≤250	250< t ≤400
S235JR	1.0038	0.35	0.35	0.38	0.40	0.40
S235J0	1.0114					
S235J2	1.0117					
S275JR	1.0044	0.40	0.40	0.42	0.44	0.44
S275J0	1.0143					
S275J2	1.0145					
S355JR	1.0045	0.45	0.47	0.47	0.49	0.49
S355J0	1.0553					
S355J2	1.0577					
S355K2	1.0596					

Stainless Steel Designations

BSEN 10027/2: 2015 Designation System for Steels. Numerical System.

The structure of steel names is set out as follows:



Code	Type
	Non Alloy Steels
00 & 90	Basic steels
0x & 9x	Quality steels
1x	Special steels
	Alloy Steels
2x	Tool steels
3x	Miscellaneous steels
4x	Stainless & heat resistant
5x-8x	Struct., pressure vessel & eng.
08 & 98	Special physical properties
09 & 99	Other purpose steels

Stainless Steel Designations

- BSEN 10027-1: 2005 'Designation System for Steels. Steel names
- Classification of corrosion resisting steels i.e. stainless steels
  - 1.40xx: grades with < 2.5wt. % nickel (Ni), with no molybdenum (Mo) or special additions
  - 1.41xx: grades with <2.5wt.% Ni, with Mo, but no special additions
  - 1.43xx: grades with ≥ 2.5wt. % Ni, without Mo or special additions
  - 1.44xx: for grades with ≥ 2.5wt. % Ni, with Mo, but without special additions
  - 1.45xx and 1.46xx: grades with special additions such as Ti, Nb or Cu

Module 7 (section a) — Common Stainless Steel Grades

Compositions taken from BSEN ISO 10088/2: 2014

Grade	EN No	Composition wt. %						
		C	Si	Cr	Mo	Ni	N	Others
316	1.4401	0.07	1.00	16.5/18.5	2.00/2.50	10.0/13.0	0.10	----
316L	1.4404	0.030	1.00	16.5/18.5	2.00/2.50	10.0/13.0	0.10	----
316L	1.4432	0.030	1.00	16.5/18.5	2.50/3.00	10.5/13.0	0.10	----
316L	1.4435	0.030	1.00	17.0/19.0	2.50/3.00	12.5/15.0	0.10	----
316LN	1.4406	0.030	1.00	16.5/18.5	2.00/2.50	10.0/12.5	0.12/0.22	
316Ti	1.4571	0.08	1.00	16.5/18.5	2.00/2.50	10.5/13.5	---	Ti: 5 x C up to 0.7
316LMN	1.4439	0.030	1.00	16.5/18.5	4.0/5.0	12.5/14.5	0.12/0.22	

Module 7 (section a) — Common Stainless Steel Grades

Compositions taken from BSEN ISO 10088/2: 2014

NOT RECOMMENDED

Grade	EN No	Composition wt. %						
		C	Si	Cr	Mo	Ni	N	Others
304	1.4301	0.07	1.00	17.5/19.5	[illegible]	[illegible]/10.5	0.10	----
304L	1.4307	0.030	1.00	[illegible]	----	8.0/10.5	0.10	----
304L	1.4306	0.030	1.00	18.0/20.0	----	10.0/12.0	0.10	----
304LN	1.4311	0.030	1.00	17.5/19.5	----	8.5/11.5	0.12/0.22	----

Casting Grades: Compositions taken from ASTM A297, A351, A743 etc.

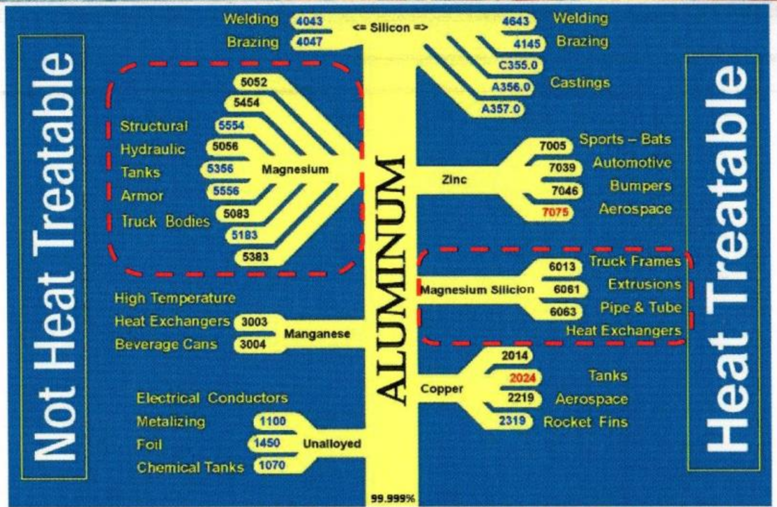
NOT RECOMMENDED

Grade	AISI Equiv.	Composition wt. %						
		C	Si	Cr	Mo	Ni	N	Others
~~CF8~~	~~304~~	~~0.08~~	~~2.00~~	~~18.0/21.0~~	~~----~~	~~8.0/12.0~~	----	----
~~CF3~~	~~304L~~	~~0.030~~	~~2.00~~	~~17.0/21.0~~	~~----~~	~~8.0/10.5~~	----	----
CF8M	316	0.08	2.00	18.0/21.0	2.0/3.0	9.0/12.0	----	
CF3M	316L	0.030	1.00	18.0/20.0	2.0/3.0	10.0/12.0	----	----
CF3MN	316LN	0.030	1.00	17.5/19.5	2.0/3.0	8.5/11.5	0.10/0.20	----

Module 7 (section a) — Stainless Steel: Marine Applications

Condition	Grade (Type)	Application
Marine Atmosphere	316, 316L (austenitic)	Standing rigging, fittings, fixtures and fasteners, railing
Seawater with galvanic protection	316, 316L (austenitic) 2205 (std. duplex) 17-4PH (pptt. hardened)	Hull mounted equipment, pump impellers, prop. shafts, special fasteners, other subsea components
Seawater without galvanic protection	904L (superaustenitic) 6wt. % Mo (superaustenitic) 2507 (superduplex)	Desalination plant, oil and gas platforms

Module 7 (section a) — Aluminium Alloy Designations



Module 7 (section a) — Aluminium Alloy Designations

Aluminium alloys: defined by 1000 to 8000 series

	Series	Major alloying element	Atoms in solution	Work hardening	Precipitation hardening	
WROUGHT ALLOYS*) EN AW-	1XXX	None (min. 99.00% Al)		X		Non-heat treatable alloys
	3XXX	Mn	X	X		
	4XXX	Si	X	X		
	5XXX	Mg	X	X		
	2XXX	Cu	X	(X)	X	Heat treatable alloys
	6XXX	Mg + Si	X	(X)	X	
	7XXX	Zn	X	(X)	X	
	8XXX	Other	X	(X)	X	

	Series	Major alloying element
CASTING ALLOYS*) EN AB- EN AC- EN AM-	1XXX0	None (min. 99.00% Al)
	2XXX0	Cu
	4XXX0	Si
	5XXX0	Mg
	7XXX0	Zn
	8XXX0	Sn
	9XXX0	Master Alloys

*) letters preceding the alloy numbers have the following meaning
EN = European Standard
A = Aluminium
B = Ingot
C = Cast Alloy
M = Master Alloy
W = Wrought Alloy

Module 7 (section a) — Aluminium Alloy Designations

Letter	Condition of Alloy
F	As fabricated
O	Annealed
H	Strain hardened by a cold working process
W	Solution-treated

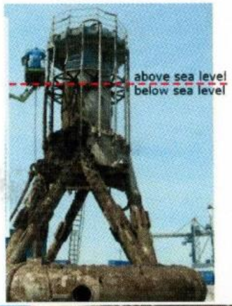
Letter	Code	Description (temper designations)
T	T1	Cooled from fabrication temperature and naturally aged
	T2	Cooled from fabrication temperature, cold worked, naturally aged
	T3	Solution treated, cold worked, naturally aged
	T4	Solution treated, naturally aged
	T5	Cooled from fabrication temperature and artificially aged
	T6	Solution treated and artificially aged
	T7	Solution treated and stabilised by over aging
	T8	Solution treated, cold worked and artificially aged
	T9	Solution treated, artificially aged and cold worked
	T10	Cooled from fabrication temperature, cold worked, artificially aged

Module 7 (section a) — Aluminium Alloy Designations

UNS Number	Composition, wt. %								
	Mg	Zn	Si	Fe	Mn	Cu	Cr	Ti	Zr
Common 5000 Series 'Marine Grade' Aluminium Alloys									
A95083	4.5	0.25	0.40	0.40	0.7	0.1	0.15	0.15	---
A95086	4.0	0.25	0.40	0.50	0.4	0.1	0.15	0.15	---
A95754	3.0	0.20	0.40	0.40	0.50	0.10	0.30	0.15	---
A95456	5.0	0.25	0.25	0.40	0.70	0.10	0.10	0.20	---
A95059	5.5	0.6	0.45	0.50	0.9	0.25	0.25	0.20	0.15
A95383	4.5	0.25	0.25	0.25	0.8	0.10	0.15	0.15	0.2
Common 6000 Series 'Marine Grade' Aluminium Alloys									
A96005	0.5	0.20	0.7	0.35	0.50	0.30	0.30	0.10	---
A96060	0.6	0.3	0.10	0.10	0.6	0.05	0.15	0.10	---
A96061	1.0	0.25	0.6	0.70	0.15	0.3	0.2	0.15	---
A96082	0.9	0.20	1.0	0.50	0.7	0.10	0.25	0.10	---

Module 7 (section a) — Aluminium Alloys: Marine Applications

- North Sea Buoy made from AA5083 sheet and AA6082 extrusions
- Installed 1978, inspected 2010
- No substantial wall thickness reduction on any parts



after cleaning

Module 7 (section a)

Aluminium Alloy: Advantages and Issues

- Aluminium alloys have been used in marine environments for many years with very good results
  - Atmospheric conditions – ship superstructures, oil and gas platform structures, helipads, wind turbine supporting structure
  - Seawater – boat hulls for high performance
- Two most widely used alloys
  - Alloy AA5083 – AlMg alloy
  - Alloy AA6082 – AlMgSi alloy
  - Both alloys seawater resistant
- Few problems with Aluminium Alloys except:
  - Galvanic corrosion
  - Pitting corrosion
  - Over protection by CP systems
  - Stray current corrosion (on ship hulls)

Module 7 (section a)

Copper Alloy Designations

Unified Numbering System (UNS) for copper and copper alloys: Developed by ANSI (1974) and administered by SAE and ASTM

Wrought Alloys		Cast Alloys	
Coppers	C10100-C159999	Coppers	C80000-C81399
High Copper Alloys	C16000-C19999	High Copper Alloys	C81400-C83299
Brasses	C20000-C49999	Brasses	C83300-C89999
Bronzes	C50000-C69999	Bronzes	C90000-C95999
Copper Nickels	C70000-C73499	Copper Nickels	C96000-C96999
Nickel Silvers	C73500-C79999	Nickel Silvers	C97000-C97999
		Leaded Coppers	C98000-C98999
		Special Alloys	C99000-C99999

Module 7 (section a)

Copper Alloy Designations

Alloy	Composition, wt. % Cu	Zn	Ni	Sn	Al	Others	Comment
Copper	99.9						Soft sheet or rivets
Copper-Zinc Alloys (Brasses)							
70/30 cartridge brass	70	30	---	---	---	---	Dezincifies in seawater
60/40 Muntz Metal Brass	60	40	---	---	---	---	Dezincifies in seawater
Red Brass	85	15	---	---	---	---	
Naval Brass	60	39	---	---	---	1 Sn	Inhibited with Tin
Admiralty Brass	70	29	---	---	---	1 Sn+As	Inhibited, good quality
Aluminium Brass	76	22	---	---	2	+ As	High tensile brass; 'best'
Manganese 'Bronze'	58	39	---	---	1	0.25 Mn	High tensile brass. Dezincifies (really a brass)

Module 7 (section a)

Copper Alloy Designations

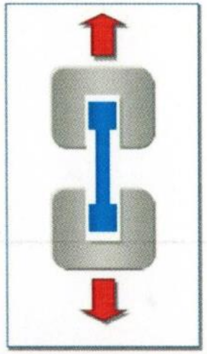
Alloy	Composition, wt. % Cu	Zn	Ni	Sn	Al	Others	Comment
Copper-Tin Alloys (Bronzes)							
Tin Bronze	88	---	---	5-10	---	---	Basic Bronze
G Bronze (Gunmetal)	88	2	---	10	---	---	Good castable bronze
M bronze	88	4	---	6	---	+ Pb	Leaded gunmetal
Copper- 'Zinc Free' Alloys (Bronzes)							
Silicon Bronze	96					1.5/3 Si	Very corrosion resistant
Aluminium Bronze	88				9	3 Fe	Possibility of Al loss
Ni-Al Bronze (NAB)	80		5		10	5 Fe	Tendency of SCC in bolts
Ni-Al-Mn Bronze	75		2		8	+12 Mn	Super propeller material*
Al-Si Bronze	91				6	2 Si	Very Corrosion resistant
Phosphor Bronze	85-95			5-10		+P	Spring Applications

Module 7 (section a) — Copper Alloy Designations

Alloy	Composition, wt. %						Comment
	Cu	Zn	Ni	Sn	Al	Others	
Copper-Nickel Alloys (Bronzes)							
90/10 Copper-Nickel	90	---	10	---	---	(1.5 Fe	
70-30 Copper-Nickel	70	---	30	---	---	(0.4 Fe)	
Hiduron 130	75	---	17	---	2-3	+ Mn, Cr, Fe	Prop. shafts, marine pumps, tow/winch fittings
Nickel Bronze (NBI)	83	---	14.5	---	2.5	---	
Nickel Based Alloys							
Monel 400	32		66			1.5/3 Si	Prop. shafts
Monel Alloy K500	30		67		2.8	3 Fe	Stronger ver. of Monel 400
Monel Alloy 505	30		66		8	+4 Si	Specialised Monel for high pressures & temperatures

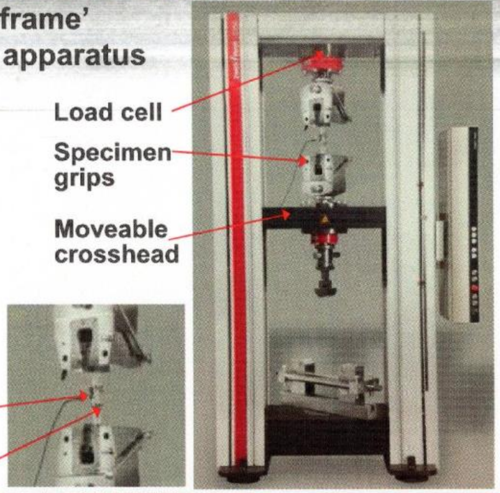
Module 7 (section a) — Mechanical Properties: Tensile Tests

- Tensile testing uses a force measurement system to assess the mechanical behaviour of a component, part or material under axial loading
- Test Principle:
  - A typical 'dog-bone' shaped sample is gripped at the ends and an axially applied force is applied causing the material to stretch, testing may continue until failure
  - During testing test piece extension and applied force data is captured and plotted in a stress-strain curve



Module 7 (section a) — Mechanical Properties: Tensile Tests

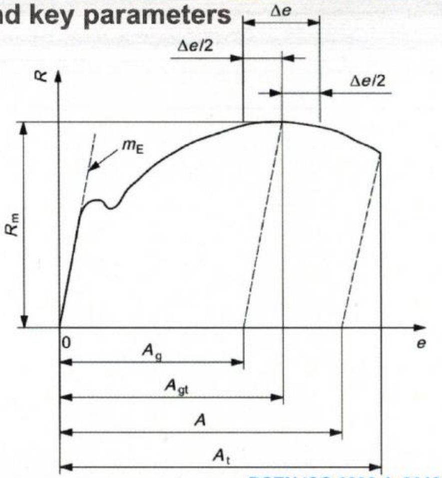
- Key components of 'H-frame' uniaxial tensile testing apparatus
  - Indirect extension measurement: by change in crosshead distance
  - Direct extension measurement: by measuring extension directly from specimen



Module 7 (section a) — Mechanical Properties: Tensile Tests

- Typical Stress-strain plot and key parameters

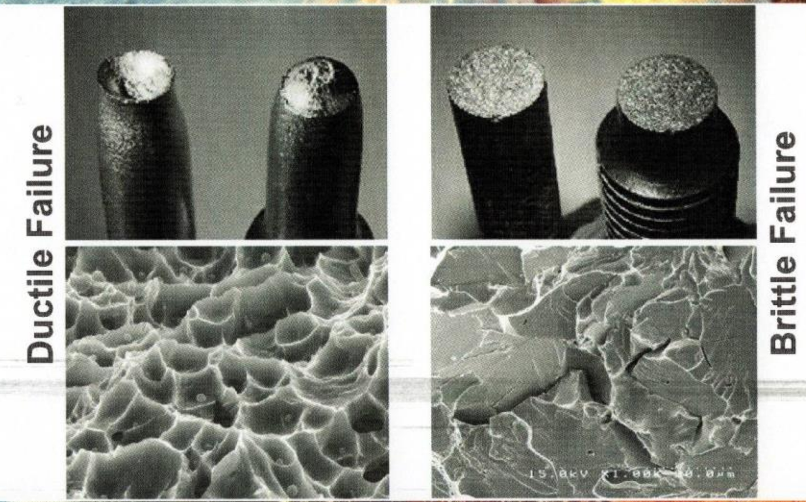
A % elongation after fracture
A_g % plastic extension at maximum force
A_{gt} % total extension at maximum force
A_t % total extension
m_E slope of the elastic part of the stress-strain curve (Young's modulus E)
R Stress
R_m tensile strength (UTS)
Δe plateau extent (for determination of A_g)



BSEN ISO 6892-1: 2019

Module 7 (section a)

Mechanical Properties: TensileTests



Module 7 (section a)

Hardness Measurement: Brinell

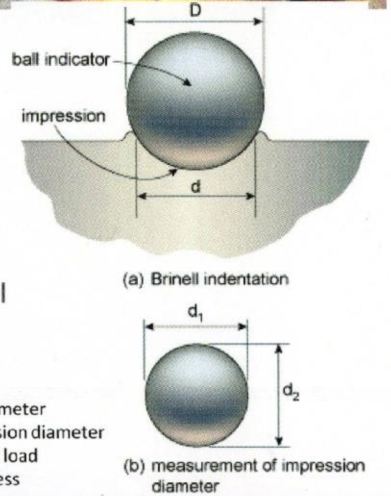
Standard test conditions
- constant force between 500 to 3000kgf (0.5-3 tonne)
- applied for 10-30s
- requires a rough ground surface or better

Indenter material and geometry
- 5 or 10mm diameter hardened steel or tungsten carbide ball

Hardness Formula

$$BHN = \frac{F}{\frac{\pi}{2}D\left(D - \sqrt{D^2 - d^2}\right)}$$

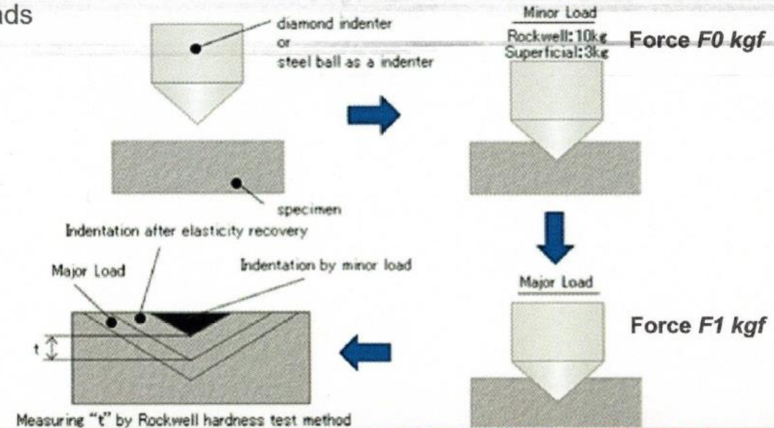
D is the ball diameter
d is the impression diameter
F is the applied load
BHN Brinell hardness



Module 7 (section a)

Hardness Measurement: Rockwell

Measurement Principle:
Relates material hardness to depth differential between two applied loads



Module 7 (section a)

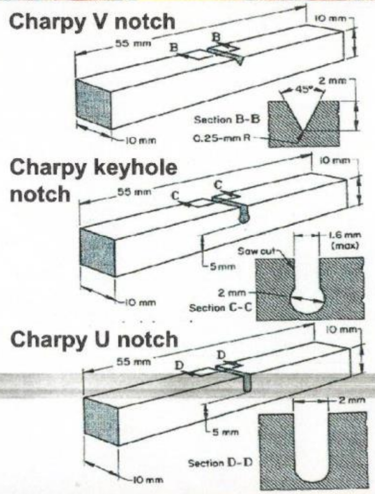
Mechanical Properties: Pendulum Impact Tests

- **Definition:**
  Toughness of a metal is its resistance to crack propagation
- **Note:**
  Metals exhibit high or low toughness depending on a range of factors e.g. heat treatment condition, microstructural features (grain size, precipitates, orientation/texture), composition, service conditions etc.

  Many metals undergo a transition from ductile to brittle failure as the test temperature is lowered

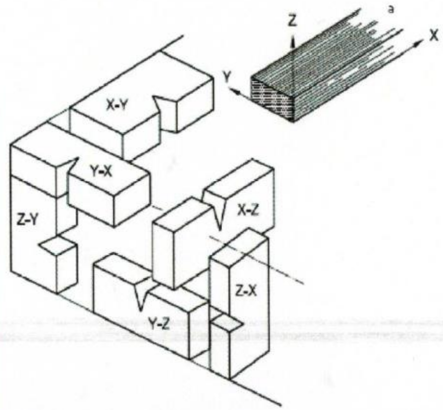
Module 7 (section a) Mechanical Properties: Pendulum Impact Tests

- **Test Requirements**
  - A test sample, which when struck will fracture at a particular location i.e. use notched samples!
  - Notch is generally V- or U-shaped with depths of 2 and 5mm, respectively
- **Two basic tests: Charpy and IZOD**
  - Both involve striking a sample with a pendulum weight ('hammer')



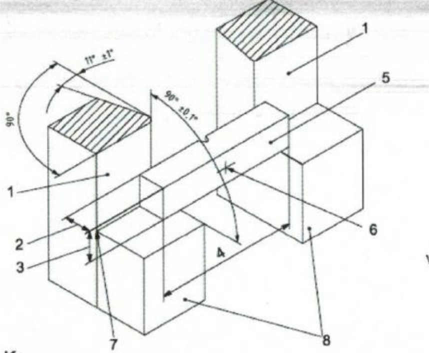
Module 7 (section a) Mechanical Properties: Pendulum Impact Tests

- This diagram shows the standard sampling options for Charpies
- Most material standards require Longitudinal (X-Y) or Transverse (Y-X) sampling, where the length of the notch runs through the plate thickness (Z)
- Grain orientation effects may need to be mitigated with other sample types!



Module 7 (section a) Mechanical Properties: Pendulum Impact Tests

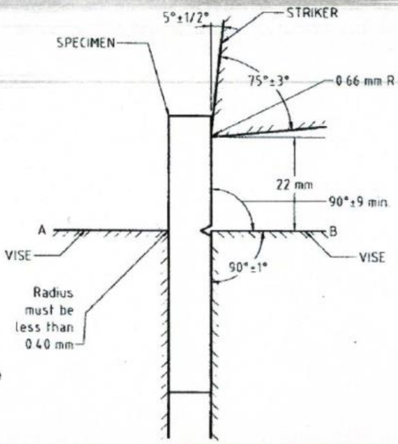
Charpy sample test setup



Key

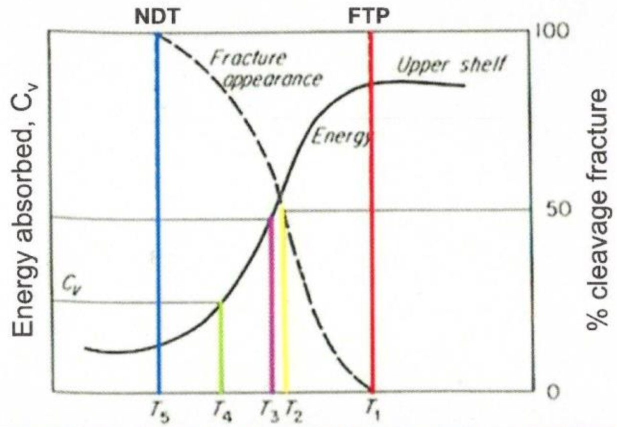
1	Anvil	5	Reference test piece
2	Height of test piece	6	Centre of strike
3	Width of test piece	7	Recess
4	Length of test piece	8	Test piece supports

IZOD sample test setup



Module 7 (section a) Ductile Brittle Transition Temperature

- Fracture Appearance Transition Temperature (FATT)

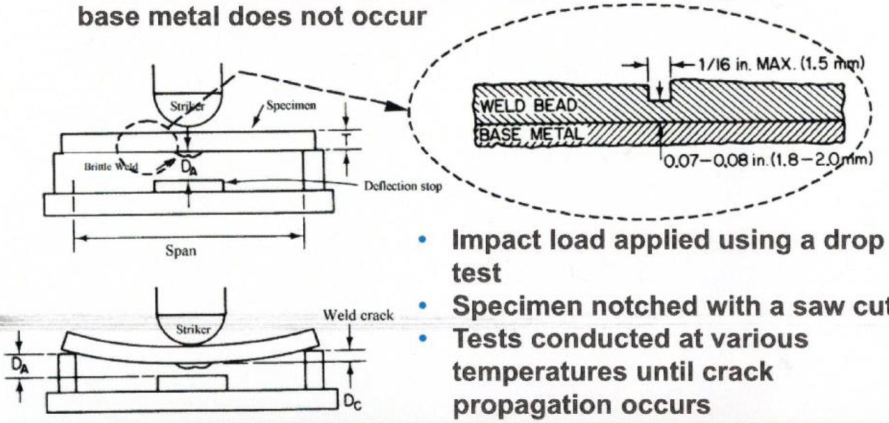


Ductile Brittle Transition Temperature

- Several different criteria have been used to characterise the ductile-brittle transition, including:
  - T_1 : is the temperature at which the test sample absorbs the most fracture energy and possesses 100% fibrous fracture surfaces – called **FTP** (fracture transition plastic), most conservative estimate of ductile-brittle transition
  - T_2 : corresponds to 50% brittle/50% ductile fracture surface; called the **FATT** (fracture appearance transition temperature
  - T_3 : corresponds to average of energy absorbed between upper and lower shelves
  - T_4 : corresponds to temperature at which the absorbed energy (C_v) is **20J**, introduced in World War II
  - T_5 : corresponds to temperature at which there is no sign of ductile fracture, known as the **NDF** (nil ductile temperature)

NDTT Test for High Strength Ship Steels

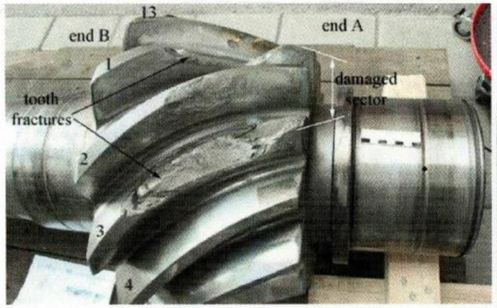
- **Nil Ductility Transition Temperature Test (NDTT) - used to determine lowest temperature when crack propagation in base metal does not occur**



- **Impact load applied using a drop test**
- **Specimen notched with a saw cut**
- **Tests conducted at various temperatures until crack propagation occurs**

Fatigue in Engineered Structures

- **Estimates suggest that 80-90% of all structural failures are caused by fatigue**
- **Catastrophic failure by fatigue often occurs at relatively low stress levels, without warning**



Failure in ship propulsion thruster


Catastrophic structural failure

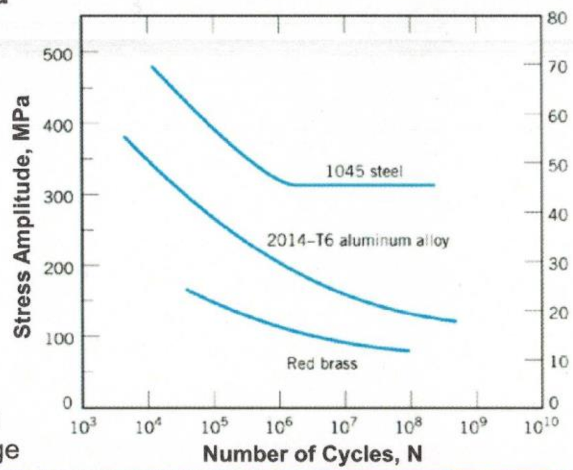
NDTT Test for High Strength Ship Steels

Common terms used with S-N diagrams

'<u>fatigue life</u>':
no. of cycles before failure occurs

'<u>fatigue strength</u>':
S_{Nf}: hypothetical value of stress at failure for exactly N_f cycles

'<u>fatigue limit</u>':
S_f: limiting value of the median fatigue strength as N_f becomes very large



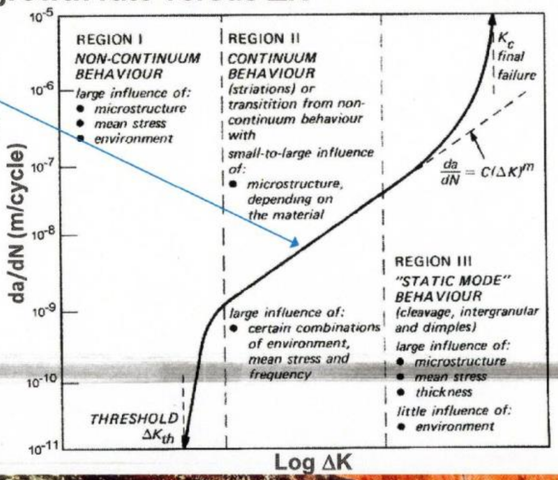
Module 7 (section a)

Fatigue Tests: Fracture Mechanics Approach

- **Fatigue crack growth rate versus ΔK**

Region II corresponds to stable fatigue crack growth and is described by the Paris equation relating crack growth rate to stress intensity factor range (ΔK)

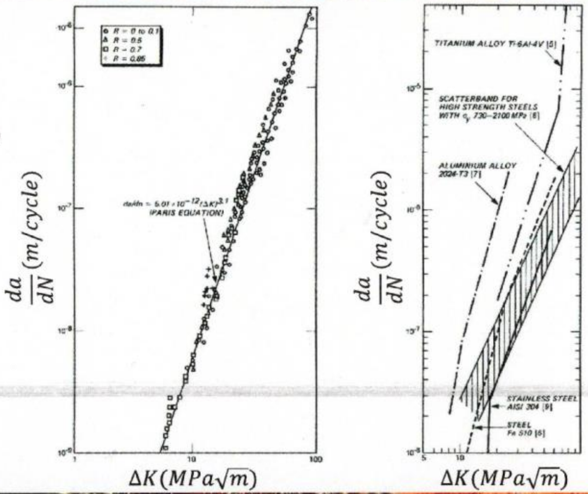
$$\frac{da}{dN} = A(\Delta K)^n$$



Module 7 (section a)

Fatigue Tests: Fracture Mechanics Approach

- **Fatigue crack growth rate (FCGR) vs ΔK for aluminium, titanium and steel alloys**



Professional Qualification

in Marine Corrosion

Presented by **Mike Lewus**

Module 7

(section b)

Ferrous Alloys and their Properties

Module 7 (section b) Summary

- **Steels for Ship Building**
  - **Low carbon mild steels**
  - **High tensile steels**
  - **Impact toughness and fatigue**
- **Stainless Steels**
  - **Tensile test and associated metrics**
  - **Impact toughness and fatigue**
- **Cast Irons**
  - **Grey and white**
  - **Ductile iron**
  - **Impact toughness and fatigue**

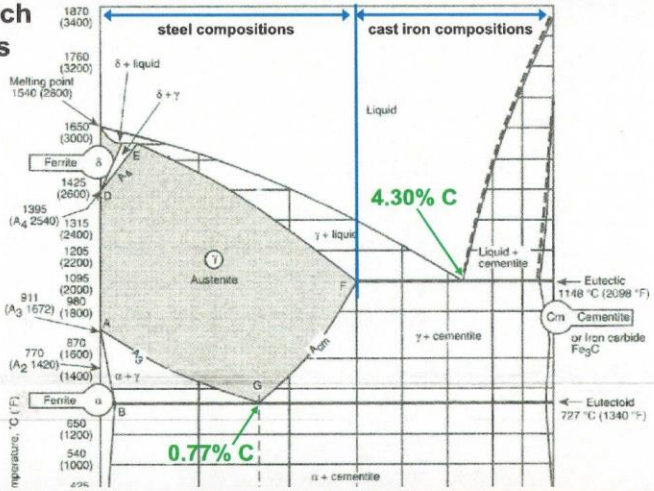
Module 7 (section b) Issues Relating to Metals in Ship Construction

- **Strength**
  - **Relevance of yield strength, proof strength, tensile strength (UTS), torsional strength, Young's modulus (E)**
- **Toughness**
  - **Fracture toughness, fatigue resistance**
- **Weldability**
  - **Hydrogen cracking, liquation cracking, stress corrosion cracking (SCC)**
- **Formability**
  - **Surface effects, SCC**
- **Corrosion Resistance**
  - **Galvanic corrosion, pitting, SCC, corrosion fatigue etc.**
- **Cost**

Module 7
(section b)

Steel Types

- A_1: temp. at which austenite begins to form
- A_3: temp. at which transformation of α-iron to austenite is completed
- A_{cm}: temp. at which the solution of cementite in austenite is completed

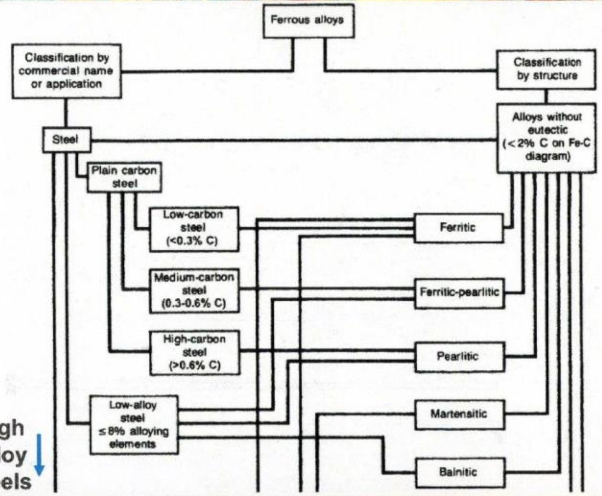


Module 7
(section b)

Steel Types

- Steels in Ship Building
  - Essentially plain carbon and low alloy for hull and internal structural components

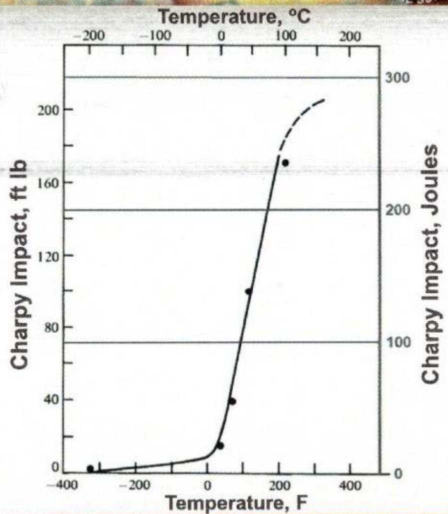
High Alloy steels



Module 7
(section b)

Steel Designations: BSEN 10027-1: 2016

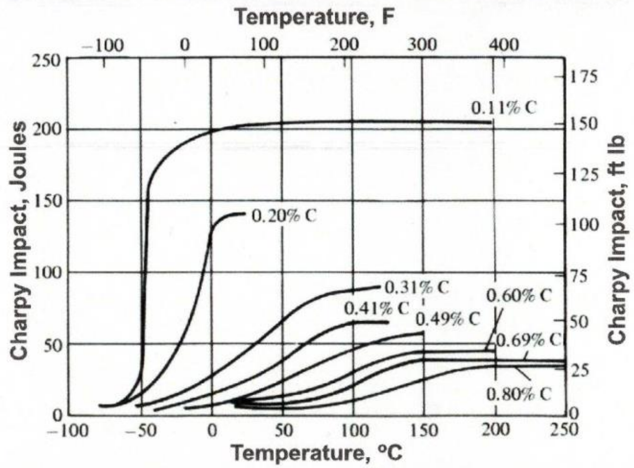
- Ductile-to-Brittle transition temperature for AISI-SAE 1020 hot rolled steel
- The DBTT is of great practical importance. An alloy that exhibits this behaviour loses toughness and is susceptible to catastrophic failure below the transition temperature



Module 7
(section b)

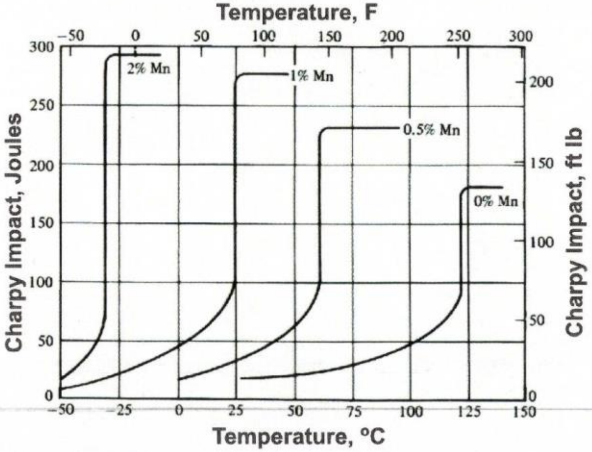
Steel Designations: BSEN 10027-1: 2016

- Effect of steel carbon content on DBTT
- Increasing Carbon content increases DBTT and reduces the maximum 'upper shelf' impact energy



Steel Designations: BSEN 10027-1: 2016

- Effect of steel Manganese content on DBTT
- Increasing Manganese content decreases DBTT and increases the maximum 'upper shelf' impact energy



Ship Grade Steels A, B, D and E

Grade	Plate t, mm	Deoxidation Treatment	Composition, wt. %[5]					
			C	Mn	Si	S	P	Al
A	≤ 50	Any[1]	0.21 max[2]	2.5 x C	0.5 max	0.035 max	0.035 max	
	> 50	Killed						
B	≤ 50	Any*	0.21 max	0.80 min[3]	0.35 max	0.035 max	0.035 max	
	> 50	Killed						
D	≤ 25	Killed	0.21 max	0.60 min	0.10-0.35	0.035 max	0.035 max	0.15[4]
	> 25	Killed + Grain Refine with Al						
E		Killed + Grain Refine with Al	0.18 max	0.70 min	0.10-0.35	0.035 max	0.035 max	0.15[4]

NB Carbon + 1/6 Manganese Content not to exceed 0.6wt. %

Ship Steel Grades A, B, D and E

- Note 1: Grade A, rimmed steel may only be accepted for sections up to a maximum thickness of 12.5mm, provided that it is stated on test certificates or shipping statements to be rimmed steel
- The maximum carbon content for Grade A may be increased to 0.23wt. % for sections
- Where Grade B is impact tested the minimum Manganese content may be reduced to 0.60wt. %
- The total aluminium content may be determined instead of the acid soluble content. In such cases the total aluminium content is to be less than 0.020wt. %
- Where additions of any other elements are made as part of the steel-making practice, the content is to be recorded

Ship Steel Grades: Material Definitions (1)

- Killed
  - Refer to steels that have been deoxidized usually with aluminium and/or silicon. Killed steels have lower porosity levels than semi-killed or rimmed steel
- Rimmed
  - Refer to steels that have not had deoxidizing agents added, such steels are characterised by marked differences in chemical composition across the section and from top to bottom of an ingot; outer rim is lower in carbon, phosphorus and sulphur than the average R
  - Most rimmed steels have been largely replaced by killed steels
- Acid Soluble Aluminium (Al)
  - A limit is placed on acid soluble aluminium as increased amounts can result in presence of Al_2O_3 inclusions

Module 7 (section b)

Ship Steel Grades A, B, D and E

Plate Thickness, t, mm	Material Class					
	I		II		III	
	Mild Steel	H.T Steel	Mild Steel	H.T Steel	Mild Steel	H.T Steel
t ≤ 15	A	AH	A	AH	A	AH
15 < t ≤ 20	A	AH	A	AH	B	AH
20 < t ≤ 25	A	AH	B	AH	D	DH
25 < t ≤ 30	A	AH	D	DH	D	DH
30 < t ≤ 35	B	AH	D	DH	E	EH
35 < t ≤ 40	B	AH	D	DH	E	EH
t > 40	D	DH	E	EH	E	EH

Module 7 (section b)

Ship Steel Grades A, B, D and E

Grade	Thickness, mm	Conditions of Supply			
A and B	t ≤ 50	Any			Note 1
	50 < t ≤ 100	N	NR	TM	Note 2
D	t ≤ 35	Any			Note 1
	35 < t ≤ 100	N	NR	TM	Note 3
E	t ≤ 100	N		TM	Note 4

N = normalised, NR = normalising rolled,
TM = thermomechanically controlled-rolled

Note 1. ''any' includes as-rolled, normalised, normalising rolled and thermomechanically controlled-rolled
Note 2. Plates, wide flats, sections and bars may be supplied in the as-rolled condition, subject to special approval from LR
Note 3. Sections in Grade D steel may be supplied with t > 35mm in the as-rolled condition provided that satisfactory results are consistently obtained from Charpy V-notch impact tests
Note 4. Sections in Grade F steel may be supplied in the as-rolled and normalising rolled conditions provided that satisfactory results are consistently obtained from Charpy V-notch impact tests

Module 7 (section b)

Ship Grade Steels A, B, D and E

- **Mechanical Properties for Acceptance Purposes**

Grades	Yield Stress, (MPa)	Tensile Strength (MPa)	Elongation on $5.65\sqrt{S_o}\%$ (min)	Charpy V-Notch Tests		
				Thickness, mm	Average Energy, J (min.)	
					Long.	Trans.
A, B, D, E	235	400-520	22	≤ 50	27	20
				50 < t ≤ 70	34	24
				70 < t ≤ 100	41	27

Module 7 (section b)

Ship Steel Grades: Material Definitions (2)

- **Normalised**
  - Normalisation is an annealing process designed to produce a steel with a uniform, fine-grained structure and to avoid excess softening in steel. It involves heating the steel to 20–50ºC above its upper critical point (A_3 temperature), soaking it for a short period at that temperature and then allowing it to cool in air
- **Normalising Rolled**
  - Involves two process steps; forming at high temperatures to change shape followed by rolling at lower temperature to minimise grain growth
- **Thermomechanically Controlled Rolling (TM or TMCR)**
  - Involves use of successive temperatures starting at a conventional temperature ~1200ºC, but final hot roll passes are carried out at temperatures below the A_3 temperature i.e. 775ºC. Plastic deformation at these lower temperatures promotes finer recrystallised grain size and hence, higher strength
  - Variables in controlled rolling include material composition, structure, deformation levels, temperatures at various stages, and cool-down conditions

High Strength Steel Grades for Ships

Steel Compositions

Grades	Composition, Wt. % (max.)0.1				
	C	Mn	Si	P	S
AH, DH, EH	0.18	0.9-1.60	0.50	0.035	0.035
FH	0.16	0.90-1.60	0.50	0.025	0.025

Grain refinement elements

Grades0.15	Composition, Wt. %				
	Al (min.)	Nb	V	Ti (max.)	(Nb+V+Ti)
AH, DH, EH, FH	0.15	0.02-0.05	0.05-0.10	0.02	0.12 (max.)

Residual elements

Grades	Composition, Wt. %				
	Ni	Cu	Cr	Mo	N
AH, DH, EH	0.40	0.35	0.20	0.08	----
FH	0.80	0.35	0.20	0.08	0.009

High Strength Steel Grades for Ships

Maximum thickness limits, crack arrest temperature

Steel Designation				Maximum thickness, mm	
				Plates and wide flats	Sections and bars
AH 27S	DH27S	EH 27S	FH 27S	100	50
AH 32	DH 32	EH 32	FH 32		
AH 36	DH 36	EH 36	FH 36		
AH 40	DH 40	EH 40	FH 40		
EH 47					Not applicable

Note 1. Where the thickness of grade EH40 materials exceed 85mm the material is to achieve a crack arrest temperature (CAT) below -10°C. The CAT may be measured directly from large scale isothermal tests or be estimated from small scale tests that determine the Nil Ductility Temperature using,

$$CAT = (NDTT + 10) + \left[\left(\frac{ln\sigma}{0.046}\right) - 105\right] + \left[153\left(B - 5\right)^{\frac{1}{13}} - 190\right]$$

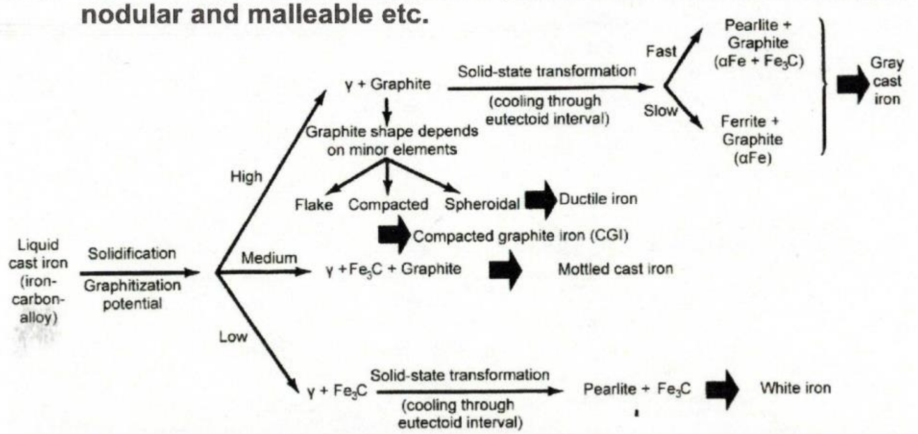
Where CAT = crack arrest temp. in °C, NDTT = nil ductility test temperature in °C
σ = 2/3 of minimum specified yield strength in N/mm², B = plate thickness in mm

High Strength Steel Grades for Ships

Grades	Yield Stress N/mm² (Pa x 10^{-6})	Tensile Strength N/mm² (Pa x 10^{-6})	Elongation on $5.65\sqrt{S_o}$ % (min)	Charpy V-Notch Tests					
				Average Energy, Joules (minimum)					
				t ≤ 50mm		50 < t ≤ 70mm		70 < t ≤ 100mm	
				Long.	Trans.	Long.	Trans.	Long.	Trans.
AH27S, DH27S, EH27S, FH27S	265	400-530	22	27	20	34	24	41	27
AH32, DH32, EH32, FH32	315	440-570	22	31	22	38	26	46	31
AH36, DH36, EH36, FH36	355	490-630	21	34	24	41	27	50	34
AH40, DH40, EH40, FH40	390	510-650	20	39	26	46	31	55	37
EH47	460	570-720	17	----	----	53	35	Note 1	Note 5

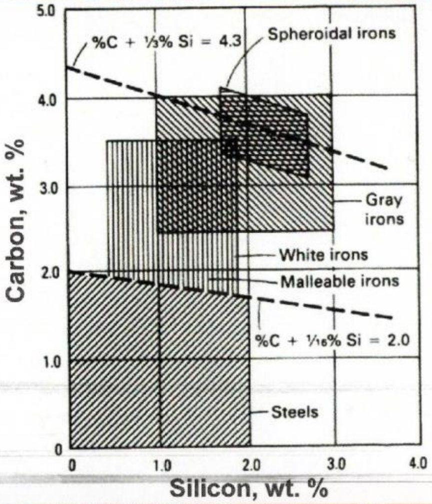
Cast Irons: Gray, Ductile, Spheroidal

- Cast iron types: gray, ductile – spheroidal, nodular and malleable etc.



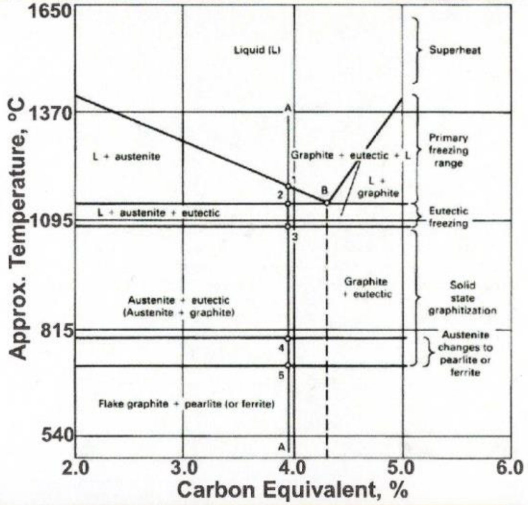
Cast Irons: Grey Cast Iron

- Gray cast iron is the most common form of cast iron and is characterized by a microstructure with flake (lamellar) graphite embedded in a steel matrix
- Gray cast irons comprise a range of hypoeutectic and hypereutectic compositions – see 4.3% carbon equivalent line



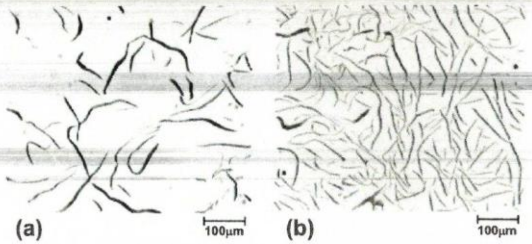
Cast Irons: Grey Cast Iron

- Simplified ternary eutectic diagram taken at 2wt.% Silicon
- Above point 1, iron is molten
- Between points 1 and 2 austenite forms and carbon is rejected and carbon in liquid increases until eutectic composition of 4.3wt. % C is reached
- Remaining liquid between points 2 and 3 transforms to 2 solids; In gray cast irons, graphite and austenite form
- Cooling from points 3 to 4 austenite transforms to pearlite or pearlite & ferrite

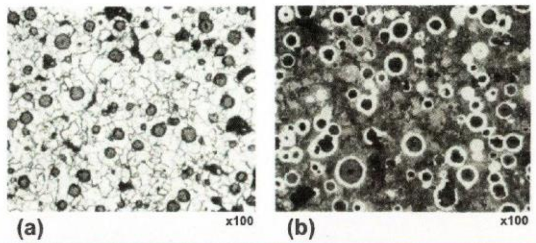


Cast Irons: Grey Cast Iron

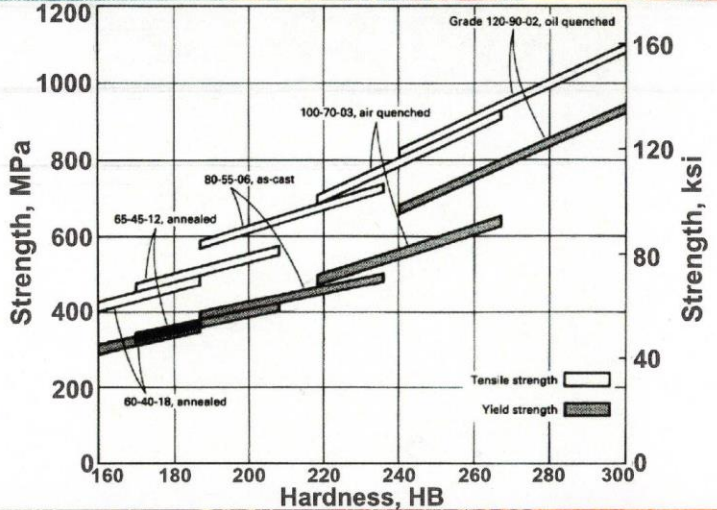
Gray cast iron, Type A structures
(a) Hypoeutectic as-cast gray iron
(b) Hypereutectic as-cast gray iron



As cast and annealed ductile iron microstructures,
(a) as-cast pearlitic condition (grade 85-55-06) with graphite nodules
(b) same, but annealed for 6h at 788°C, furnace cooled



Cast Irons: Ductile Cast Irons



Cast Irons: LR Acceptance Criteria

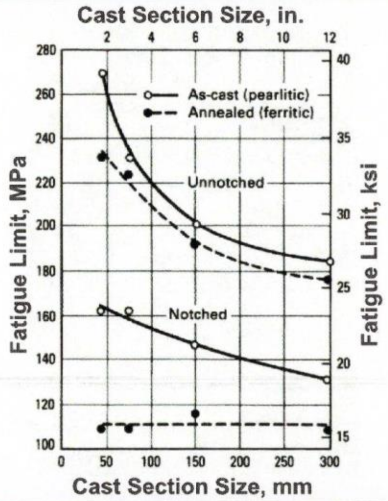
Module 7 (section b)

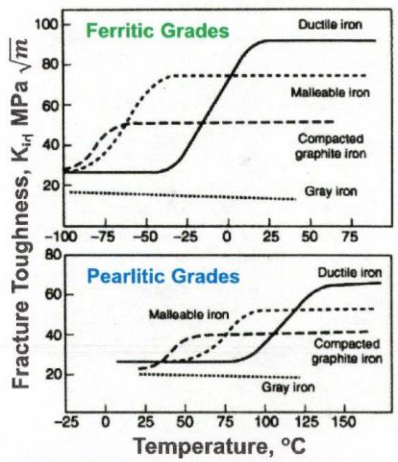
- **Mechanical properties for acceptance purposes of spheroidal or nodular iron castings – LR July 2020**

Tensile Strength, MPa (min)	0.2% Proof Strength, MPa (min)	Elongation on $5.65\sqrt{S_o}\%$ (min)	Typical Hardness Value, HB	Typical Matrix Structure
370	230	17	120 - 180	Ferrite
400	250	12	140 - 200	Ferrite
500	320	7	170 - 240	Ferrite/Pearlite
600	370	3	190 - 270	Pearlite/Ferrite
700	420	2	230 - 300	Pearlite
800	480	2	250 - 250	Pearlite or Tempered Structure

Cast Irons: Fatigue and Fracture Toughness

Module 7 (section b)





International Institute of Marine Surveying

Professional Qualification
in Marine Corrosion

Presented by **Mike Lewus**

Module 7
(section c)

Non-Ferrous Alloy Properties and Applications

Module 7 (section c)

Summary

- **Aluminium Alloys**
  - 5000 Series
  - 6000 Series
  - Impact Toughness and Fatigue
- **Copper Alloys**
  - Bronze alloys; Phosphor, silicon, aluminium etc.
  - Copper-Nickel alloys
  - Copper-Berylium alloy
  - Impact toughness and Fatigue
- **Material Selection: An Introduction**
  - Keel bolt case study
  - Ranking Properties & Cost
  - Digital logic method

Module 7 (section c)

Aluminium Alloys: 5000 Al-Mg and 6000 Al-MgSi Series

- **Benefits of 5000 series, Al-Mg Aluminium Alloys**
  - Excellent corrosion resistance, toughness, weldability and moderate strength (UTS 55-350MPa)
  - Work hardenable
  - 'Work horse' alloys are 5052, 5086 amd 5083; increasing higher strength associated with higher Mg content
- **Disadvantages**
  - Risk of Galvanic corrosion
  - Stiffness
  - Lack of experience in marine applications
  - Lack of design standards

  NB care must be taken to avoid use of 5000 series alloys with >3wt. & Mg content in applications where temperature is above 100°C – such alloys may become 'sensitized' and susceptible to stress corrosion cracking (SCC)

Module 7 (section c)

Aluminium Alloys in Marine Applications

- Issues with exfoliation corrosion and intergranular forms of corrosion in 1960's with 5456-H321 plate led to H116 and H117 tempers for 5086, 5456 and 5083 and, wider application and use

High speed naval vessel

Oil & gas platform helipad

Oil & gas platform stairway

Telescopic gangway

Module 7 (section c)

Aluminium Alloys: Compositions

Aluminium Grade	Alloying Elements	Strengthening Process	Property Rating			
			Strength	General Corrosion Resistance	Workability/ Formability	Joining/ welding
1xxx	Unalloyed	Strain hardening	5	1	1	3
2xxx	Copper	Heat treatable	1	4	4	5
3xxx	Manganese	Strain hardening	3	2	1	1
4xxx	Silicon	Alloy dependent	3	4	1	1
5xxx	Magnesium	Strain hardening	2	1	1	1
6xxx	Magnesium + Silicon	Heat treatable	2	3	2	2
7xxx	Zinc	Heat treatable	1	1	4	3
8xxx	Others	Limited	----	----	----	----

Module 7 (section c)

Copper Alloys: Bronze Compositions

- Bronze Alloys
  - Traditionally bronze alloys were synonymous with copper-tin alloys
  - Today the term refers to Cu-Sn alloys having further alloy additions to give improved strength such as Cu-Sn-Zn (gunmetals) and Cu-Sn-P (phosphor bronzes)
  - The term also covers copper alloys that do not contain tin such as Cu-Si and Cu-Al bronzes

Nickel-Aluminium bronze ship propeller Courtesy Stone Marine Propulsion

Module 7 (section c)

Coper Alloys: Impingement Attack

Resistance of Copper Alloys to Impingement Attack and General Corrosion in Seawater

Alloy	Composition wt. %, bal. copper					28 Day Jet Impinge.	Slow water motion	10ms-1 water flow
	Al	Fe	Ni	Mn	Zn			
Al Bronze	8.2	1.7	---	---	---	0.04	0.15	0.17
Ni-Al Bronze	8.2	2.9	4.3	2.4		0.00	0.04	0.10
Ni-Al Bronze	8.8	3.8	4.5	1.3	---	0.00	0.04	0.16
Mn-Al Bronze	7.6	2.8	3.1	10.0	---	0.01	0.04	0.11
High tensile brass	0.8	0.8	0.2	0.5	37.0	0.03	0.09	0.73
	Sn	Zn	Pb					
Gunmetal	9.7	1.4	0.6	---	---	0.02	0.14	0.74

Copper Alloys: Typical Bronze Alloy Applications

Module 7 (section c)

Alloy	Applications
Phosphor Bronze	Springs, bearings, gears, fasteners, rods, slides
Silicon Bronze	Fasteners: screws, nuts, bolt washers, pins, lag bolts and staples
Aluminium Bronze	Sea cocks, pumps, valves, bushes
Nickel Aluminium Bronze (cast and wrought)	Propellers and shafts, pumps, valves. Bushing and bearings, fasteners, tube plate for titanium tubing in condensers
Gunmetal (castings)	Pumps and valves, stern tubes, deck fittings, gears and bearings, bollards, fairleads

Copper Alloys: Typical Bronze Alloy Applications

Module 7 (section c)

Bronze Alloy	EN No. or DefStan	UNS No.	composition, wt. %							
			Cu	Ni	Fe	Mn	Zn	Al	Sn	Other
Phosphor	CW453K CW451K	C52100 C51000	rem rem						8 5	0.3P 0.2P
Silicon	CW116C	C65500	rem			1				3Si
Aluminium -silicon	CW302G	C64200	rem					7.5		2Si
Nickel -aluminium	CC222G Def Stan 02 0833	C95800	rem rem	4 5	4.5 5			9 10		Ni>Fe
Gunmetal	CC491	C83600	rem				5		5	5Pb

Copper Alloys: Typical Bronze Alloy Applications

Module 7 (section c)

Bronze Alloy	EN No. or DefStan	UNS No.	0.2% Proof Stress, MPa	Tensile Strength, MPa	Elong. %	Hardness
Phosphor	CW453K	C52100 C51000	170-1000	390-1100	1-60	85-270HV
Silicon	CW116C	C65500	200-890	380-900	3-50	90-220HV
Aluminium - silicon	CW302G	C64200	250-350	500-650	10-25	125-160HV
Nickel - Aluminium	CC222G Def Stan 02 0833	C95800 ----	280min 245min	650min 620min	12min 15min	150HB
Gunmetal	CC491	C83600	110min	230min	10min	65HBmin

Copper Alloys: Bronze Compositions

Module 7 (section c)

Silicon Bronze, Rigging Toggle for Mast Support

'Manganese Bronze', Dee Shackle (term a misnomer – not a bronze!)

Copper-Beryllium Alloys

- Copper-Beryllium has a high corrosion resistance and excellent biofouling resistance and can attain the highest strength of any commercial copper-based alloy
- Typical Applications: Springs, offshore drill components, subsea connectors, actuators, valve gates, locking rings, lifting nuts

Alloy	EN No.	UNS No.	Cu	Be	Others
Cu-Be	CW 101C	C17200	Bal.	1.9	0.5

Alloy	EN No.	UNS No.	0.2% Proof Strength, MPa	Tensile Strength, MPa	Elong. %	Hardness HV
Cu-Be	CW 101C	C17200	200-1300	410-1400	2-20	100-240

Inconel, Incoloy & Monel Alloys: Marine Applications

- Difference between Inconel, Incoloy and Monel Alloys
  - High-end alloys - costly relative to mild, high strength and stainless steels
  - Inconel Alloys are nickel-chromium alloys with nickel content > 50%. Incoloy is a nickel-iron-chromium alloy with nickel content < 50%. Iron in incoloy makes these alloys easier to weld
  - Monels are nickel-copper alloys, ~65wt. % nickel - are stronger than pure nickel and can be fabricated readily by hot- and cold-working, machining, and welding
  - Monel alloy K-500 has high strength and corrosion resistance in seawater making it well suited for marine propeller shafts

Inconel, Incoloy & Monel Alloys: Marine Applications

- Inconel and Monel Alloys
  - Used for their high resistance to corrosion in offshore platforms, as well as in power and process plants that use seawater as coolant
  - Inconel 625 very resistant to pitting and crevice corrosion, high corrosion fatigue and tensile strength
  - Monels high resistance to biofouling and MIC makes them a robust alloy for wave protection sheathing for platform risers and steel pylon legs

https://www.corrotherm.co.uk/applications/corrosion-resistant-inconel-incoloy-and-monel-marine-applications

Ni-Cu, Inconel and Monel Alloys

UNS No.	Common Name	Nominal Composition wt. %							PREN
		Ni	Cr	Mo	W	Nb	Cu	Others	
N04400	Alloy 400	65					32	2Fe	----
N04401	Alloy K-500†	65					30	2.7Al	----
N08825	Alloy 825	42	21	3			2	28Fe/0.8Ti	31
N09925	Alloy 925†	44	21	3			1.8	28Fe/2.2Ti/0.8Al	31
N00718	Alloy 718†	54	18	3		5		18.5Fe/1Ti/0.6Al	28
N00625	Alloy 625	61	21	9		3.6		3Fe	51
N07725	Alloy 725†	57	21	8		3.5		7.5Fe/1.5Ti/0.3Al	51
N10276	Alloy C-276	57	16	16	3.5			6Fe/0.35V	75
N06022	Alloy 22	56	22	13.5	3			0.35V	72
N06059	Alloy 59	59	23	16	3			0.5Fe	76
N06686	Alloy 686	58	21	16	3.7		1		80
N06200	Ni-Cr-Mo-Cu	60	23	16			1.6		76

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Ni-Cu, Inconel and Monel Alloys

UNS No.	Common Name	Nominal Composition wt. %							PREN
		Ni	Cr	Mo	W	Nb	Cu	Others	
N04400	Alloy 400	65					32	2Fe	----
N04401	Alloy K-500†	65					30	2.7Al	----
N08825	Alloy 825	42	21	3			2	28Fe/0.8Ti	31
N09925	Alloy 925†	44	21	3			1.8	28Fe/2.2Ti/0.8Al	31
N00718	Alloy 718†	54	18	3		5		18.5Fe/1Ti/0.6Al	28
N00625	Alloy 625	61	21	9		3.6		3Fe	51
N07725	Alloy 725†	57	21	8		3.5		7.5Fe/1.5Ti/0.3Al	51
N10276	Alloy C-276	57	16	16	3.5			6Fe/0.35V	75
N06022	Alloy 22	56	22	13.5	3			0.35V	72
N06059	Alloy 59	59	23	16	3			0.5Fe	76
N06686	Alloy 686	58	21	16	3.7		1		80
N06200	Ni-Cr-Mo-Cu	60	23	16			1.6		76

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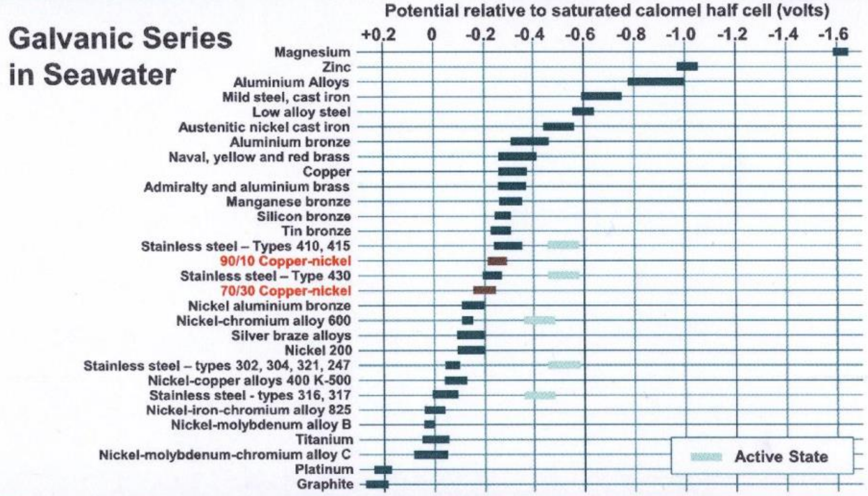
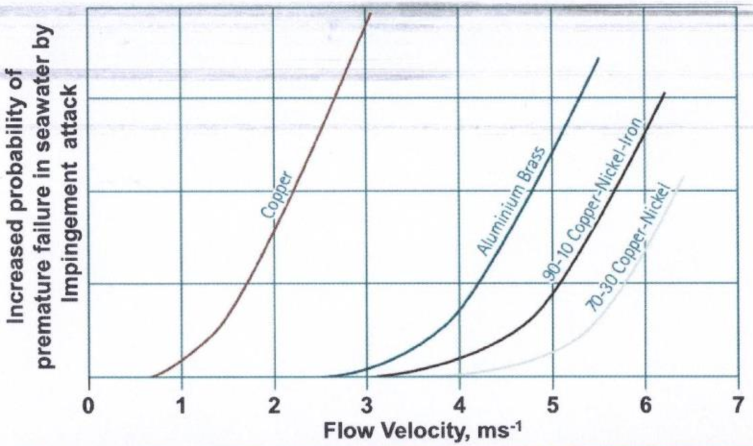
Copper Alloys: Galvanic Series



Module 7 (section c)

Copper Alloys: Breakdown Velocities

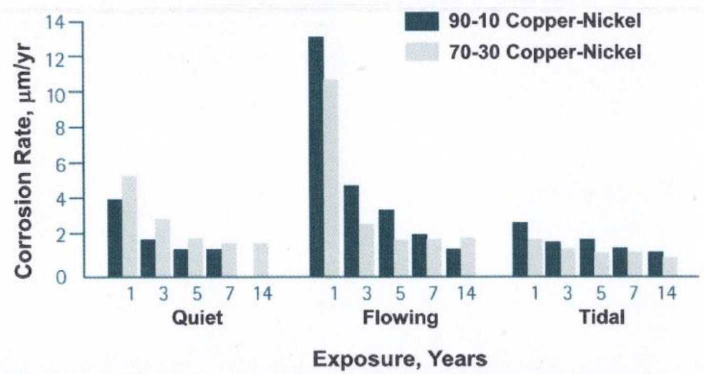
Relative breakdown velocities for copper alloys in seawater



Module 7 (section c)

Copper Alloys: Seawater Flow Rates

Fourteen year corrosion data at LaQue Center for Corrosion Technology, North Carolina[ref]



Common Standards

- **The use of standards is essential in the proper definition of the type, form and condition of an alloy**
  - Standards form part of the technical language used in communication between producers of alloys, manufacturers, designers and stockists and any technical person concerned with materials usage
- **Aluminium Alloys**
  - BS EN 13195: 2013, 'Aluminium and aluminium alloys. Specifications for wrought and cast products for marine applications (shipbuilding, marine and offshore)'
- **Copper Alloys**
  - Defence Standards (called Def Stan) are issued by the MoD (Royal Navy)
- **Nickel Superalloys**

Material Selection: Keel Bolt Example

- **With many ferrous and non-ferrous material options the questions 'which material is best for a specific application'? and 'What material properties should be considered'? Are raised. Important properties include:**
  - Material costs - What are the budget constraints
  - Manufacturability - Is the material readily available and can it easily be used in your product?
  - Environmental impact - How is the material processed in the raw state? Is it recyclable at end of life?
  - Mechanical attributes - Directly affect the durability and performance of the engineered component
  - Chemical and physical properties - affect thermal characteristics, weight, robustness to service conditions i.e. toughness, fatigue, wear and corrosion resistance

Material Selection: Keel Bolt Example

Material options:-

No	Alloy	Typical Composition, wt. %							
		Fe	Cr	Ni	Mo	Cu	C	Mn	Others
1	AISI 1018 Low C Mild Steel	bal	---	---	---	---	<0.02	0.6-0.8	<0.04 P
2	316L (A4-70)	bal	17	12	2.5	---	<0.03	---	---
3	Monel K500	<2	---	63	---	27-33	<0.25		2.3-3.15 Al 0.35-0.85 Ti
4	904L Stainless steel	bal	19-23	23-28	5	---	<0.2	---	---
5	2507 Super duplex	bal	25	7	4	---	---	---	---
6	Hastelloy C276		16	57	16	<0.5	---	---	4 W, 2.5 Co
7	Cu-Ni 90-10 C70600	1	---	10	---	89	---	---	---

Material Selection: Keel Bolt Example

Material properties:-

No	Yield/Proof strength, MPa	Corrosion Resistance Rating†	Fracture Toughness Index*	Elastic Modulus, GPa†	Relative Cost
1	370	7	607	205	1
2	450	5	2300	193	6
3	345	5	2306	179	16.5
4	220	7	1243	190	12
5	552	10	1014	200	12
6	337	9	3870	205	20
7	262	8	548	150	3

* based on (YS + UTS) x ductility (%)/2 (~ area under stress vs strain plot)

† based on potential for localised pitting and crevice corrosion

Material Selection: Keel Bolt Example

For the keel bolt materials listed:-

- List material attributes/properties and assign a weighting
- Assign scaling factors using formulae shown in section 5
- Determine material performance index (γ) using formula defined in section 5

Material Properties: 'weighted properties method'

No	Property	1/2	1/3	1/4	1/5	Ratio	Weight
1	Yield Strength	40	50	80	90	1.0	0.26
2	Corrosion Resistance	60				1.5	0.39
3	Toughness Index		50			1.0	0.26
4	Elastic Modulus			20		0.25	0.06
5	Cost				10	0.1	0.03
					Totals	3.85	1.00

Material Selection: Keel Bolt Example

Or, use 'Digital Logic Method' by determining the relative importance of goals i.e. pair-wise decisions on relative importance of two material properties.

Goals	Number of Pairwise Decisions N=n(n-1)/2										No. Positive Decisions	Rel. Emphasis Coeff.
	1	2	3	4	5	6	7	8	9	10		
1	1	0	1	1							3	0.3
2	0				0	1	1				2	0.2
3		1			1			1	1		4	0.4
4			0			0		0		0	0	0
5				0			0		0	1	1	0.1
										Totals	10	1.0

Material Selection: Keel Bolt Example

Determine scaling factors (β) for candidate material property:-

Material	Yield/Proof strength, MPa (β)	Fracture Toughness Index	Corrosion Resistance Rating	Elastic Modulus, GPa	Relative Cost
AISI 1018 Low C Mild Steel	370 (67)	15.7	50	100	100
316L (A4-70)	450 (82)	59	60	94	16.7
Monel K500	345 (63)	60	70	87	6.1
904L Stainless steel	220 (40)	32	70	93	8.3
2507 Super duplex	552 (100)	26	100	98	8.3
Hastelloy C276	337 (61)	100	90	100	5.0
Cu-Ni 90-10 C70600	262 (47)	14.2	80	73	33.3

Material Selection: Keel Bolt Example

Determine 'material performance index' (MPI):-

No	Yield/Proof strength, MPa	Corrosion Resistance Rating	Fracture Toughness Index	Elastic Modulus, GPa	Relative Cost	MPI ($\Sigma\alpha\beta$)	Rank
1	67 x 0.3 = 20.1	20	3.1	0	10	53.2	
2	82 x 0.3 = 24.6	24	11.9	0	1.7	62.0	3
3	63 x 0.3 = 37.8	28	11.9	0	0.6	59.3	
4	40 x 0.3 = 12	28	6.4	0	0.8	47.2	
5	100 x 0.3 = 30	40	5.2	0	0.8	76.1	1
6	61 x 0.3 = 18.3	36	20	0	0.5	74.8	2
7	47 x 0.3 = 14.1	32	2.8	0	3.3	52.4	

1	2507 Super duplex
2	Hastelloy C276
3	316L (A4-70)