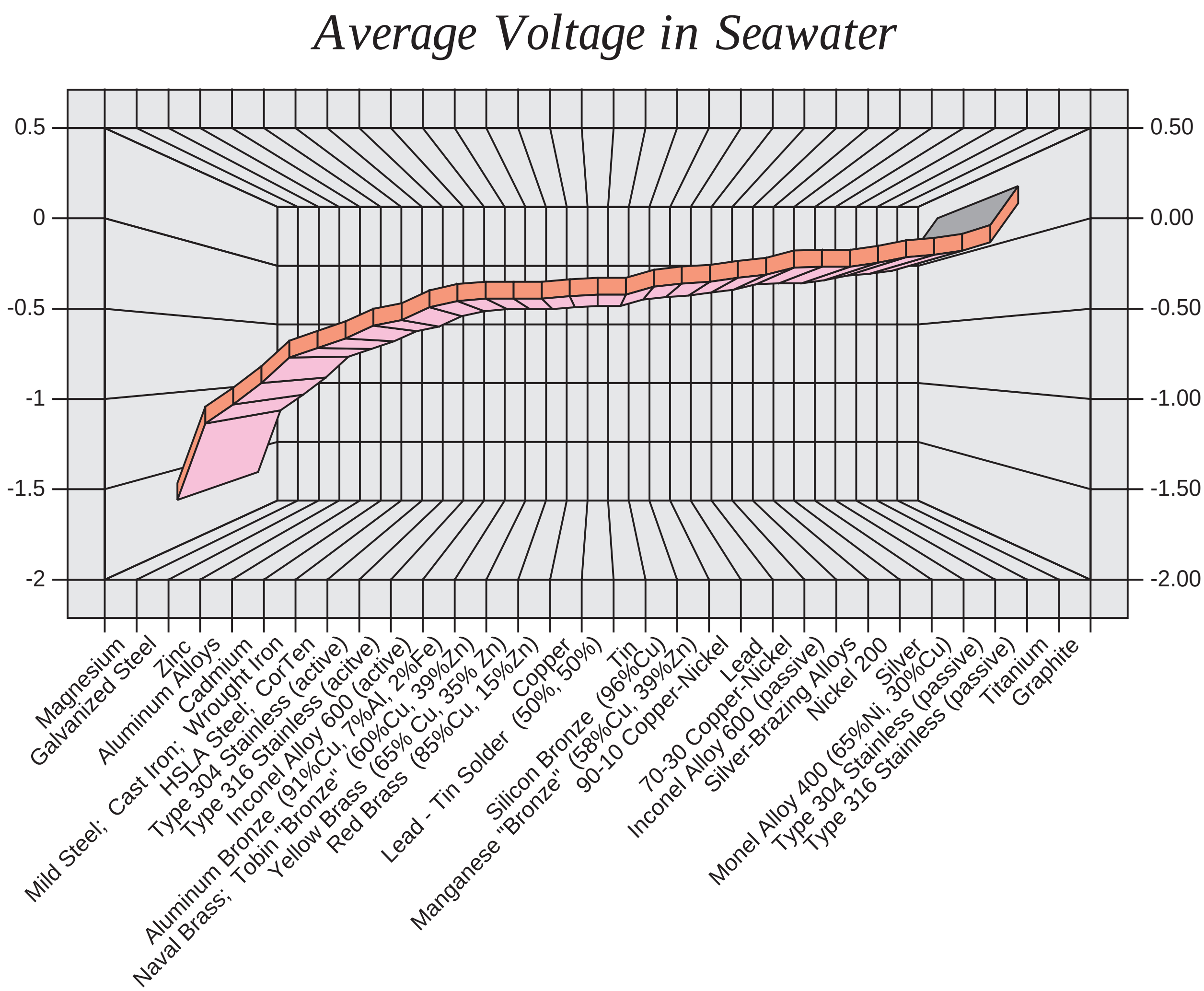
Metal Boat Quarterly

Marine Metals Reference



Summer 1997

Special Edition

The Metal Boat Society

6251 Goodhew Road
Sedro-Woolley, Wa. 98284

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*Our officers meet periodically to conjure and scheme how to keep the MBS alive. Our members meet once a year at the annual Festival, **and every three months right here through the Metal Boat Quarterly.***

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The Metal Boat Quarterly

PO Box 991
Port Townsend, Wa. 98368

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The Metal Boat Quarterly is published during January, April, July, and October, by The Metal Boat Society.

Deadlines for contributions to the Quarterly are the middle of the month prior to publishing, as above. MBQ Classified Ads have the same deadline.

Send all editorial contributions, letters, questions for the Boat Doctor, articles, drawings, boat designs, recipes, cruising stories, advertising (classified or otherwise), etc. to:

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Membership in the Metal Boat Society includes receiving the Metal Boat Quarterly.

Marine Metals Reference Edition

Summer 1997

This material was originally developed as a series of classes taught in Port Townsend, Washington at the Northwest School of Wooden Boatbuilding, entitled *Metals In The Marine Environment*.

This little booklet is part of a larger manuscript called the *Guide to Marine Metals*. It awaits a slot of "free time" so I can create a series of illustrations before it is published in book form.

My goal has been to provide a clearly presented resource which is accurately researched, for use not only by boat designers and boat builders, but also clear enough for boat owners to benefit from. This quick guide is therefore arranged mostly in outline form.

The illustrations on the front and back cover are the galvanic series—an important chart to keep in the forefront of your decisions about metals. A table of metal physical properties is at the end.

Although there are other marine metals reference books (currently out of print) this little guide presents only the basics, as a quick reference.

As boaters, one of our main concerns is with the preservation of our boats and the the various metal parts on them. Toward this end, a working knowledge of the different metals and their alloying components is rather essential.

Having done boat designing, boat building, boat repair, and boat surveying, I've seen many times over that this information is sorely needed by everyone working with boats, owning boats, or even just *planning* to own boats.

The mess one can get into through ignorance of the marine metals and their correct uses is often beyond belief. A badly corroded piece may be what keeps your boat afloat. If it goes, so goes the boat! Foreknowledge and vigilance are essential.

Throw metals and electricity into salt water and you have an interesting potential for trouble. The basic rules for preventing Galvanic Corrosion by appropriate use of zincs or bonding are summarized only briefly. These rules are based on my own experience and a fair bit of research. I will be pleased to receive feedback from others.

There is much difference of opinion regarding bonding, and the reasons to use it (and the reasons not to use it). The main issues are not what one would expect!

Corrosion and bonding are therefore a large part of the full manuscript. They are not explored here, however, and will instead be thoroughly covered in a series of articles in the *Metal Boat Quarterly* during coming issues. *Stay tuned!*

Michael Kasten
Port Townsend, Washington
1997

Marine Metals Reference

A Metals Guide, by Michael Kasten

Excerpted froma larger work by Michael Kasten, the "Guide to Marine Metals." This is just the core information specific to the metals properties. It is presented here as a service of the Metal Boat Society, for use by members for informed decisions during their boat building and repair, boat designing, and most importantly, for safe sailing.

Metals are what holds a wood boat or a ferrocement boat together. In a metal boat, it's the whole boat. In a fiberglass boat, it is still used for any parts requiring great strength, fine tolerances, or resistance to wear.

At normal temperatures, most metals exist as crystals. The metal crystals are more or less regularly shaped and are arranged in a fairly ordered recurring pattern. When metal is heated to its melting point, the crystalline matrix loses its organization and becomes fluid. When the molten metal cools, crystal patterns are reformed. Crystal growth begins in the first areas that cool. Crystal clusters begin to form in several areas simultaneously. These clusters may or may not share the same orientation. The clusters of crystals are called grains. As they grow, these crystal grains bump into one another, forming irregular grain-boundaries.

In the fully solidified metal, the grains are joined one to the next along their grain boundaries. The metal crystal grains are interlocked by the irregular shapes of the grain boundaries. When the piece is worked, larger crystals get broken into smaller ones. More grain boundaries are created. The usual result is that the metal becomes tougher and harder to work. This is ***work-hardening.***

A similar thing happens when metal is rapidly cooled, or quenched. The crystal grains don't have time to gradually grow from a few clusters in an organized pattern. Instead many small non-oriented grains are formed with much more irregular grain boundaries. This is ***tempering.***

If the metal is given a longer time to cool, the crystals will be more likely to align themselves into a more organized lattice. The crystal arrangement will contain small vacancies which facilitate crystal movement and so contribute to malleability. This process is ***annealing.***

Some nonferrous metals, when held at annealing temperatures will form a more perfect arrangement. The result is a less malleable material. This is ***heat hardening.***

Most metals are available in either "cast" or "wrought" form. These two production methods might sometimes share the same alloy composition, or more often would be made from slightly different alloying elements, when cast vs. when wrought.

In the ***cast*** form, the alloy would be poured into a mold. In the ***wrought*** form, the metal would be "hot worked" by being shaped by a series of rollers into bars, rods, angles, sheet or plate.

Forged metal is hot worked under extreme pressure. "Forge Welding" is to join two pieces of metal by hammering them together while heated to a semi-fluid condition.

The following metals list illustrates the need for clarity when specifying a kind of metal for a job. Only the metals likely to be encountered for marine use are listed. Some are desirable, others are less so. Some are not appropriate for marine use, or have a restricted use, as noted.

—Michael Kasten

THE COPPER ALLOYS

Copper: Metals with a minimum copper content of 99.3 %. The uses for copper of this purity on a boat are usually restricted to wiring, and to under-water sheathing for a wooden boat.

Brass: Alloyed with zinc primarily, plus other metals. Brasses should be restricted in use to those areas not likely to be immersed in sea water. The high zinc content renders them subject to "de-zincification" in sea water. Brasses are not easily weldable, also due to the high zinc content. Brasses can be soldered and brazed. Zinc fumes are poisonous, and care must be taken to avoid breathing welding fumes. Some Brasses are incorrectly called Bronzes, as noted.

Common types of Brass: Listed in order of increasing zinc content.

Commercial "Bronze": 90% Copper, 10% Zinc.

Red Brass: 85% Copper, 15% Zinc. There are electrodes made for stick-welding Red Brass. Pre-heat is required. Brazing or Soldering are preferred.

Tin Brass / Admiralty Brass: 70% Copper, 28% Zinc, 1% Tin.

Cartridge Brass: 70% Copper, 30% Zinc. Ductile while cold.

Yellow Brass: 65% Copper, 35% Zinc.

Muntz Metal: 60% Copper, 36.5% Zinc, 3.5% Lead. Ductile hot.

Manganese "Bronze": 58.5% Copper, 39.25% Zinc, 1% Iron, 1% Tin. Manganese "Bronze" is not for use below the water. Leaded Mang. "Bronze" adds lead for machinability.

Naval Brass / Tobin "Bronze": 60% Copper, 39.25% Zinc, .75% Tin.

Bronze: These are copper alloys in which the major alloying elements are neither zinc nor nickel. The major alloying elements are silicon, aluminum, and tin. Weldability is compromised somewhat by the addition of lead, when added for machinability. These are the metals of choice below the water. All are somewhat expensive, but less so than copper nickel or monel.

Wrought Bronze alloys:

Phosphor Bronze: 94% Copper, 5% Tin, .25% Phosphorus. High strength. Weldability is considered to be good with stick, but only fair with TIG and MIG. Pre-heat is required. Resistant to fatigue. Resistant to cavitation. Used for hardware, bearings, pumps, springs. Leaded Phosphor Bronze has lead added for machinability.

Aluminum Bronze: 91% Copper, 7% Aluminum, 2% Iron. High strength. Easily welded with TIG or MIG. Stick welding is possible, but is rated only fair. Wear resistant. Machinable. Resistant to cavitation. Used for propellers, sheathing, wire rope, hardware.

Silicon Bronze: 96% Copper, 3% Silicon, 1% Manganese. Strong. Corrosion resistant. Machinable. Ductile. Easily weldable with TIG and MIG. Stick welding is considered fair. Used for everything from hardware to shafting and props.

Cast Bronze alloys:

Tin Bronze: Cast equivalent to Phosphor Bronze. Same qualities apply. Leaded Phosphor Bronze used for machinability.

Aluminum Bronze: Cast Equivalent to Aluminum bronze above. Same qualities.

Silicon Bronze: Again, as above. Used for casting struts, rudders, stuffing boxes, through-hull valves.

Copper Nickel: Usually available in wrought form. The primary element is copper, and the main alloying element is nickel in varying amounts. More expensive than Bronzes.

70-30 Copper Nickel: 70% Copper, 30% Nickel. Readily formed and welded. Extremely ductile. Extremely corrosion resistant. More expensive than 90-10 CuNi, but 30% stronger. Less expensive than Monel, but Monel is much stronger. Cathodic to most metals. Used for salt water piping, tanks, heat exchangers, exhaust systems, hull plating, fittings, struts, etc. Does not need antifouling.

90-10 Copper Nickel: 90% Copper, 10% Nickel. As above, but not as strong, and not as ductile. Very corrosion resistant. Less expensive. Cathodic to most metals. Used for salt water piping, tanks, heat exchangers, exhaust systems, hull plating, fittings. Makes great marine stoves. Does not need antifouling.

To summarize the Copper alloy group, remember the following, whether cast or wrought:

If copper is alloyed with Zinc, it is brass.
If alloyed with Nickel, it is copper-nickel.
If alloyed with Aluminum, Tin, or Silicon, it is bronze.

THE NICKEL ALLOYS

Most commonly available in wrought form.

Monel: Mostly nickel, with the main alloying element being copper.

Monel 400: 65% Nickel, 30% Copper. High strength, very ductile. Easily weldable by MIG, TIG, stick. Extremely corrosion resistant, retains strength over a wide temperature range. Generally free from stress corrosion and crevice corrosion. Cathodic to most metals, so it is galvanically stable. Ideal for underwater fittings. Used for fastenings, fittings, valves, heat exchangers, tanks, exhaust systems. Very expensive.

Inconel: Nickel alloyed with chromium and molybdenum.

Inconel 617: 54% Nickel, 22% Chromium, 12% Cobalt, 9% Molybdenum. Readily formable and weldable. Excellent high temperature strength. Highly corrosion resistant even at elevated temperatures. Used for exhaust systems. Expensive.

Inconel 625: 57% Nickel, 22% Chromium, 9% Molybdenum, 5% Iron. Readily formable and weldable. High temperature strength. Exceptional fatigue strength. Highly corrosion resistant even at elevated temperatures. Almost completely immune to stress corrosion. The preferred metal to use for exhaust systems. Expensive.

THE FERROUS ALLOYS

These alloys are made up mostly of iron. Less "noble" galvanically than most metals. Must be protected with zinc anodes when used below the water. Inexpensive.

Iron: Usually available in cast form. Both wrought and cast iron contain 2% to 4% carbon. Hardenable. Can be joined by forging. Must be pre-heated for welding, and cooled slowly to avoid brittleness and cracking in the weld zone. Use special nickel electrodes for welding, or use brazing to join. Corrosion of iron is considered to be slower than corrosion of steel. Must be *thoroughly* protected either by sand blasting and painting, or by sand blasting and flame-spraying with zinc, or by hot dip galvanizing. Used for engine blocks, galvanized fittings, ballast. Forging used for high strength.

Steel: Lower carbon cntent than iron. Usually available in wrought form, but also made into cast parts. Abrasion resistant. Can be easily cut with oxy-acetylene torch, plasma torch, metal cutting bandsaw, nibbler, or a jig-saw with a metal blade. Can be joined by forging, gas welding, and all types of arc welding. Machinable. All mill scale should be removed before painting or galvanizing. Must be *thoroughly* protected by sand blasting and painting, or by sand blasting and flame-spraying with zinc, or by hot dip galvanizing.

Medium Carbon Steel: Iron with a carbon content from 0.30% to 0.45%. The hardenability of steel increases with carbon content. These steels serve where hardness, wear-resistance, or higher strength is required. These characteristics, though, make the medium and high carbon steels more difficult and more costly to weld. Pre-heat is required for welding to prevent cracking, and some may require postweld stress relief. Not often used in small craft, and not usually suitable for all-around use.

Mild Steel: (Low Carbon Steel) and Structural Steel (A-36). These steels contain from 0.15 to 0.30% Carbon. The preferred range is from 0.15% to 0.20% carbon for general use. Very easily formed and welded. Cannot be tempered. Resistant to work hardening. These qualities are an advantage for welded structures. Very malleable and resistant to fatigue failure. Used successfully for just about everything, from fabricated parts to whole boats. Adequate protection *must* be provided, and long term maintenance must be possible.

"CorTen" Steels: (A-242; A-441). Properly called High Strength Low Alloy (HSLA) Steels.

"CorTen" is the trade name of an alloy from one manufacturer, which has become the common name for the type. This family of steels have a carbon content of 0.09% to 0.24%, and add around 0.20% to 0.40% copper.

These HSLA steels have 15% to 20% higher strength, and two to four times more corrosion resistance than mild steel. Generally not hardenable.

"CorTen" usually refers to A-242. For low temperature toughness, A-441 would be preferred.

The "Corten" steels are useful for hull plating in small steel boats where the plating thickness is smaller than around 5/32". This is for the added stiffness mostly, in order to control distortion due to welding and due to impact in service. A lesser consideration is the somewhat greater corrosion resistance, since these steels must be painted and protected, just like mild steel, and will require a more aggressive sand blasting to achieve the same "tooth" for paint. A higher strength filler metal is used for welding, as will be recommended by the steel manufacturer.

Stainless Steel:

Steel alloyed with 16 - 26% Chromium, and 6 - 22%Nickel. These "Chromium-Nickel" Stainless Steels are the types most commonly used for fabricating.

Stainless Steels have high strength. Stainless is very abrasion resistant, and is best cut with a plasma arc cutter, or a metal cutting bandsaw. Stainless is easily arc welded by stick, TIG, and MIG. Stainless is relatively inexpensive.

Due to its high expansion rate and poor heat conductivity, stainless is subject to high distortion levels when welded, or when cut with a plasma torch. Matching electrodes should be used for all stainless welding, according to stainless type.

The Chromium-Nickel Stainless Steels are not readily heat treatable for hardening. These stainless steels are, however, subject to work-hardening, which can create a locally hard section in an otherwise annealed piece, effectively creating a "notch" in the piece, reducing its strength considerably. This makes stainless subject to fatigue failure. These stainlesses are generally non-magnetic in their fully annealed condition.

Stainless is subject to stress corrosion in areas of high localized stresses, when in a corrosive environment.

Stainless depends on Oxygen to repair itself, to create an oxide film. Stainless is subject to crevice corrosion where it is unable to have ready access to Oxygen.

Stainless steels each occupy two locations in the galvanic series of metals. Stainless can be both passive and active. The same piece of stainless can be both in different parts. Stainless is usually passive when it has enough oxygen available to create a tough oxide on the surface. Stainless usually becomes active when there is insufficient oxygen, as when embedded in sea water soaked wood.

Due to its tendency toward crevice corrosion, stainless steel of any kind should never be used as a fastening material below the waterline, especially in a wooden vessel! Stainless should not be used as a fastening material for any part of the hull structure of a wooden boat, even above the waterline. Stainless should not be used for keel bolts on any kind of boat.

Stainless is subject to pitting corrosion in salt air.

Stainless is subject to carbide precipitation in the heat affected zone adjacent to any welding, or other high heat source, such as exhaust. Carbide precipitation occurs at a temperature range between 800° and 1500°F, and results in definite impairment of corrosion resistance. In this temperature range, carbon precipitates out of the solid solution to the grain-boundaries in the heat affected zone, where it combines with chromium to form chromium carbides. Depletion of chromium in the grain boundaries creates a local area of preferential attack for inter-granular corrosion, which will accelerate all of the above conditions.

It should be noted that carbide precipitation is *not* prevented in the low carbon types (304-L and 316-L) but is greatly reduced. Carbide precipitation is prevented in the stabilized types, which contain alloying elements that will keep the chromium and carbon in solution.

Stainless must be protected by zincs when immersed in sea water.

Type 302 or 18-8 Stainless (18% Chromium, 8% Nickel). Type 303 adds Phosphorous and Sulphur for relatively easy machining, and is used to make fastenings. Should be used on boats only with *extreme* care.

Types 302 & 303 will develop a rust film after exposure to salt water. Used as a fastening in wet wood, they will bleed rust. Used below the water, they will freely corrode, especially where buried in wet wood, due to crevice corrosion. High stress will accelerate the process. *Not* for use below the water.

Type 304 has less Carbon to reduce carbide precipitation when welding. Most of the above also applies, though Type 304 has somewhat greater corrosion resistance.

Type 304-L is an extra low carbon version, to further reduce carbide precipitation in the weld-zone. This is the alloy that should be specified where the piece will be a welded fabrication, even if it will be used below deck inside a boat. The above cautions all apply, however.

Types 304 and 304-L will develop a rust film with exposure to salt water. Below the water, they can freely corrode, especially where oxygen starvation is likely. These corrosion processes will be accelerated where subject to high stress, and will be highly accelerated in the active zone just below the surface of the water. Types 304 and 304-L should *not* be used below the water.

Types 316 & 316-L contain added molybdenum for higher corrosion resistance. Type 316 is used for fastenings above the water, and will not develop a rust film. Very resistant to pitting in the salt air. Type 316-L is an extra low carbon version used for fabricated structures where carbide precipitation would present a problem.

Types 316 & 316-L are considerably more resistant to crevice corrosion than types 302 & 304. However, Type 316 cannot be recommended as a fastening material for any structural part below the water, on a wooden hull, even above the waterline. Type 316 is sometimes used as a sea cock material below the waterline on aluminum boats. Isolation of the two metals must be thorough. Can be successfully used as a shafting material below the water, and must always be protected with zinc anodes.

Type 321 Stabilized by the addition of Titanium to prevent Carbide Precipitation. This is an excellent choice anywhere above the water. Welding is easily accomplished by any of the processes.

Type 347 Stabilized by the addition of Tantalum and Columbium to prevent Carbide Precipitation. An excellent choice for use above the water. Easily welded by all processes.

Various Shafting Alloys - Aquamet; Aqualloy.

Weldable, and corrosion resistant. Some alloys permit heat treatment to gain higher strengths, usually due to addition of Nitrogen.

Carbide precipitation is minimal in Aquamet 17, due to addition of Tantalum and Columbium, though welding creates an un-tempered region of lower strength. As a rudder shaft, this would be a fairly good choice, but welding it to mild steel will contribute added carbides in the weld zone.

Other Aquamet alloys are subject to carbide precipitation, and if welded, must be annealed to remove the chromium carbides from the grain boundaries in the heat affected zone, and put them back into solution.

THE ALUMINUM ALLOYS

Aluminum is light, strong, corrosion resistant, non-sparking, conducts electricity and heat well, and is weldable. Aluminum is not abrasion resistant, and can be cut with carbide tools.

Aluminum alloys for use on boats are generally limited to the 5000 and the 6000 series. These two alloy groups are both corrosion resistant in the marine environment due to the formation of a tough aluminum oxide. These alloys are subject to pitting, but the pitting action slows as the oxide film thickens with age.

Aluminum alloys are subject to crevice corrosion, since they depend on the presence of Oxygen to repair themselves. What this means is that wherever aluminum is in contact with anything, even another piece of aluminum or zinc, it must be painted with an adhesive waterproof paint like epoxy, or it must be protected with a waterproof adhesive bedding, or both.

Paint preparation is critical. Thorough cleaning, and sand blasting provide the best surface for adhesion of paint or bedding. Alternately, cleaning and then grinding with a coarse 16 grit disk will provide enough tooth for the paint to stay put. Grinding is not as good as blasting for paint adhesion, and is not as thorough for cleaning the metal.

If the surface finish must be extra fine, as on an aluminum spar, then sanding, cleaning and etching with a product like Alodine before painting will give adequate results. A plastic wafer alone as an isolator is not enough. Salt water must be prevented from entering the crevice, or crevice corrosion *will* result. More detailed information about protecting aluminum can be found in *Metal Boat Quarterly #3.*

Anodizing is a process of electrically causing the formation of a tough oxide film on the surface of aluminum. Anodizing will slow down pitting, but will not prevent it. Anodizing will *not* prevent crevice corrosion.

Aluminum is very active galvanically, and will sacrifice itself to any other metal it contacts either directly or indirectly. Aluminum is anodic to everything except zinc and magnesium, and must be electrically isolated from other metals. In this case, paint, bedding, and a non-conductive plastic or rubber isolator should all three be used together.

The Wrought Aluminum Alloys

5000 Series:

Non Heat Treatable. Aluminum alloyed with magnesium. Usually available only as sheet or plate. Alloys in the 5000 series are used for plating hulls and superstructures of boats. In the 5000 series, the H-116 temper is less susceptible to inter-granular corrosion and is the only temper certified for marine use.

Being non-heat-treatable, these alloys retain more strength across the weld joint than the 6000 Series alloys. An 11% to 20% loss in tensile strength in the heat-affected zone is typical, along with a 30% to 45% loss in yield strength. This loss of strength must be compensated for in designing the weld joint.

5052-H32 Strain Hardened and Stabilized. Lowest strength. Formable. 45% yield strength loss and 20% tensile strength loss as-welded. Lowest cost

5083-H116 Strain Hardened. Higher strength than Alloy 5086. 42% yield strength loss as-welded.

5086-H116 Strain Hardened. As below but lower strength. Not as strong as Alloy 5083. Resistant to stress corrosion. 32% yield strength loss as-welded.

5454-H-116 Strain Hardened and Stabilized. Low strength. Extremely resistant to stress corrosion, even at elevated temperatures. (Exhaust stacks, etc.)

5456-H-116 Strain Hardened. Highest Strength. Best as-welded tensile and yield strength among the marine aluminum alloys. Not as formable.

6000 Series: Heat Treatable. Aluminum alloyed with silicon and magnesium. Usually available in shapes, occasionally in plate. Highly corrosion resistant. Being heat-treatable, these alloys suffer a loss of strength in the weld zone of around 40%, which must be compensated for in the design of the welded joint.

6061-T6 Solution Heat Treated & Artificially Aged. The preferred alloy for shapes. Used for nearly all shapes such as rod, bar, angle, tube and pipe.

6063-T6 Solution Heat Treated & Artificially Aged. Not as strong or as corrosion resistant as 6061. Lower cost. Extrusions are rod, bar, angle, tube, and pipe.

Cast Aluminum Alloys:

356 (AlMag 35) Aluminum alloyed with magnesium or copper. Similar to the 5000 series of wrought alloys.

Welding Aluminum

Both the 5000 and 6000 series alloys, and alloy 356 are easily weldable with both TIG and MIG processes, but are not easily solderable. They can be joined by brazing. Stick welding is possible, but results in a very low strength joint. TIG and MIG are the preferred processes. Weld zone cleanliness is critical for being able to achieve maximum as-welded strength. The oxide film must also be removed prior to welding, as it is a contaminant which reduces the strength of the welded joint. The rather large inherent loss of strength in the weld zone with either alloy group must be compensated for in the design of the weld joint (see physical properties chart p. 18 - 19). It is usual for backing plates to be used, and then fully welded, or for structural members to be located in way of the weld joint.

TITANIUM

Not frequently used, except occasionally for extremely high strength combined with extreme lightness as in a racing sailboat mast. Most common alloys use Aluminum and Tin, or Aluminum and Vanadium. Very resistant to corrosion. More noble than nickel and copper. Easily welded by MIG and TIG. Very expensive.

ZINC

High purity zinc is used to make sacrificial anodes. These cast anodes protect other metals to which they are electrically attached. Zinc is less noble than, and will sacrifice itself to all other metals except magnesium.

Zinc is used to hot dip galvanize steel. It provides a very slowly corroding coating, and affords excellent galvanic protection. Hot dip galvanizing, as a coating, is inexpensive and lasts a very long time, especially if painted for further protection.

The strength of steel parts may be lessened during galvanizing, due to the 790° F. temperature of the dip, and its slightly annealing effect. A rule of thumb (not true for *all* steels) is to allow for a 15% strength loss. The higher carbon steels, such as in high test chain, are affected more than the more typically used low carbon mild steels.

Some iron or steel fastenings, and some pieces of hardware are merely electro-plated with zinc. Some hardware and fastenings are available with a cadmium plating. Both treatments are thin and inadequate in the marine environment. The coatings will not last, and the piece will have to be either replaced very soon, or have an adequate protective paint coating applied.

Zinc can also be applied to steel by flame spraying. This is a process of melting off a wire of zinc in an oxy-acetylene flame, and blowing it onto a perfectly prepared surface. This is called metallizing. The steel must be sand blasted to “white metal” to thoroughly clean the surface, and to provide adequate tooth to the surface for adhesion of the molten zinc droplets.

The American Welding Society has done a nineteen year controlled test of steel panels which compared hot dip galvanized pieces with metallized pieces. The pieces received varying thicknesses of galvanizing, and varying thicknesses of flame-sprayed zinc. The results showed that the two galvanizing methods have an equivalent longevity. It made little difference whether a part was hot dip galvanized, or metallized with a coating of zinc or aluminum, it was the thickness of the zinc that was important for the coating to last.

If below the waterline, a galvanized fitting should be protected from potential rapid depletion of the galvanizing by also attaching one or more sacrificial anodes to the piece.

LEAD

High purity lead is used as ballast. Lead has very low strength, and is extremely formable. Lead is used as an easily worked material on deck, and primarily as a heavy non-corroding ballast material. Antimony is added for hardness, to allow free cutting and threading without the lead becoming gummy.

Lead ballast *must* be fastened by a more noble metal fastener. Silicon bronze or monel fastenings would be a good choice. Of the two, silicon bronze would be better, since it is closer on the galvanic scale. Phosphor bronze will also be encountered, and should be a good keel bolt material, provided that no welding or hot forging is done to them.

Galvanized steel fastenings, though common, should not be used. The lead is more noble, and the fastenings will be sacrificed to the lead keel.

Stainless steel of any kind should never be used as a keel bolt, due to its ability to become “active”, and its vulnerability to both stress corrosion, and crevice corrosion. In its active mode, the stainless keel bolts would sacrifice themselves to the lead keel!

It is interesting to note that Lloyds of London approves Type 316 Stainless as a keel bolt material for an Iron keel. In spite of Lloyds’ very capable judgement, and in spite of Type 316 being somewhat more resistant to crevice corrosion, it can hardly be recommended to use stainless of *any* kind as a keel bolt, even for an iron keel!

Appropriate Uses of Metals

Hull Structure - Steel; aluminum; copper-nickel (many boats have been built of iron and some of stainless).

Ballast - Lead; iron; steel as ballast box to enclose lead pigs in mortar.

Hull Fastenings - Silicon bronze; monel; galvanized steel.

Interior Fastenings - Silicon bronze; brass; galvanized steel; stainless.

Rudder Fittings / Rudder Stock - Silicon bronze; monel; galvanized or painted steel; sometimes stainless, but usually only as a bearing surface.

Through-hull Valves - Silicon bronze; monel; sometimes Type 316 stainless (on aluminum hulls).

Superstructure - Painted steel; aluminum.

Masts - Painted steel; aluminum.

Mast Fittings - Silicon or manganese bronze; galvanized steel; sometimes Type 316 stainless (316-L if welded); aluminum welded on fittings for an aluminum mast.

Rigging Wire - Galvanized steel; phosphor bronze; Type 316 stainless (oversize & replace often).

Tanks - Monel; copper-nickel; aluminum; galvanized steel; 316-L stainless. Stainless is ***not*** USCG approved for fuel tanks, due to corrosion problems.

Salt Water Plumbing & Pumps - Bronze; copper nickel; monel.

Fresh Water Plumbing & Pumps - Galvanized steel; brass; stainless; occasionally aluminum.

Fuel Piping - Steel; stainless; bronze; brass fittings; aluminum or SS fittings for aluminum tanks.

Engines & Machinery - mostly cast iron; steel; sometimes aluminum.

Exhaust Piping - Inconel; monel; copper nickel; galvanized steel (used because it's cheap to replace, and then only in a dry exhaust).

Hardware Above Water - Silicon bronze; manganese bronze; monel; copper nickel; galvanized steel; Type 316 stainless (316-L if welded); aluminum.

Hardware Below Water - Silicon bronze; monel; copper nickel; galvanized steel.

** See the Back Cover for ideal maximum voltage difference for metals in contact with sea water.*

Welding

Methods & Materials

In general, welding is an easy process. If anything, the hard part is to get the machinery and the materials together in a good work place, that is also safe and easy to use. The next major hurdle is to get the machinery set up correctly, and adjusted for the type of welding to be done. Welding methods are many, but the practical methods for everyday boatyard use are not that far out of reach.

To begin, if you are completely unfamiliar with the processes, the machines, and the materials, the best thing would be to find someone who will steer you in the right direction for the type of welding you need to do. To get set up with the machinery is the main thing, and then it is just a matter of " burning rod." Get some guidance, and then burn rod. Get some more guidance, etc. Not a big deal...

The welding methods of use to boat builders, as well as the machinery required are usually different than what may be used in the shipyards. The following is not an attempt at a complete treatise. This is just an outline of the materials and the machinery which would be needed for any given project. It is a reminder of what is required in each case. This is only a"guide." Your own experience will fill in the rest.

Gas Welding: An oxy-acetylene flame generates the heat for fusion. Wire filler metal is hand fed to the weld puddle. Slightly carburizing flame creates shielding of the molten puddle. Oxy-propane is also used, with special propane welding tips. This is a *welding* process because it uses metal of the same alloy as that being joined for filler-metal in the joint.

Gas Brazing: An oxy-acetylene flame generates heat for fusion, just as with gas welding. Wire filler metal of a *different* alloy than the parent-metal is hand fed to the weld puddle. A slightly carburizing flame creates shielding of the molten puddle. Oxy-propane is also used, with special tips. ***Brazing*** is done at temperatures above 800° F. ***Soldering*** is done below that temperature.

Arc Welding: An electric arc generates the heat for fusion.

Stick Welding: A stick is both electrode and filler metal. Machines are Constant Current. You set the amperage, and the voltage is varied by the machine. Machines are AC or DC, or both AC and DC.

Currents used are:

- DCRP (reverse polarity) usually preferred. Electrode is positive.
- DCSP (straight polarity) Electrode is negative.
- AC for all around use.

A flux coating on the stick electrode creates shielding at the weld puddle. Differences in the flux coating are what define the types of electrodes. The first two numbers of the electrode name refer to the minimum strength, in thousands of lbs. per sq. inch. As an example, for 6011, the minimum strength would be 60,000 lbs.

Most Commonly Used Electrodes:

- 6011 for AC or DC. Deep penetration, more spatter.
- 6013 for AC. Smoother operation, less spatter.
- 7018 for DC. Higher strength, low hydrogen. *Must* be kept in an oven to eliminate moisture uptake.

MIG Welding: (Metal - Inert Gas) A small wire is both the electrode and the filler metal. The wire electrode is fed by drive rollers to the weld puddle through a torch. Inert Gas is fed through the same torch, and shields the weld puddle from oxygen.

MIG machines are Constant Voltage (Constant Potential). You set the voltage (potential), and the machine varies the amperage (Current) depending on the arc length and wire speed. DCRP (reverse polarity, electrode positive) is nearly always used.

Electrodes and Shielding Gasses for MIG welding:

Steel Short Arc:
Used for welding thinner sections.
Shielding is CO_2 or Argon / CO_2 mix.
Solid Wire Electrode. (E70-S6 best for CO_2)
Steel Spray Arc:
Used for welding heavier sections. Higher wire speed, requires more current and produces deeper penetration.
Solid Wire used with Argon / 5% Oxygen.
Tubular Flux-cored Wire is made for use without shielding.
Tubular Flux-cored Wire is used with CO_2, as well. (E70-T2 for use with CO_2)
Steel Pulsed - Spray Arc:
Pulsing used to reduce current and heat while maintaining spray mode. The above electrode wires and gas combinations are used, but with higher wire speeds, and more current.

Stainless Short Arc: 90% Helium / 7.5% Argon / 2.5% CO_2.
More than 2.5% CO_2 adversely affects corrosion resistance.
Solid wire electrodes used should match the SS alloy being welded.
Stainless Spray Arc: For welding heavy sections. Argon / 1% Oxygen. Same solid wire electrodes as above for short arc.

Aluminum: Argon or Argon / Helium mixes.
Always use spray mode. Pulsed spray mode used for thinner sections. Solid Wire. 5356 is a good all-around wire, but other wires are used for special purposes.

Bronze, Copper-Nickel: Argon shielding gas. Electrode wire should match alloy. Short arc or spray arc is used, depending on thickness of the piece.
Phosphor Bronze: Helium shielding gas. Wire should match alloy. Stick welding produces a better weld on Phosphor Bronze.

TIG Welding: (Tungsten - Inert Gas) A Tungsten Electrode creates the arc, but is not consumed. The tungsten is held in a torch. Inert gas is fed through the torch. Filler Wire is hand fed into the weld-puddle. Machines for TIG are usually capable of both AC and DC.

Steel / Stainless: Argon shielding gas. DCSP (electrode negative), with a sharp tungsten.
Aluminum: Argon. Argon / Helium used for very thick sections. AC is used to balance cleaning and penetration. Use rounded tungsten. 5356 filler wire is most common.
Bronze, Copper Nickel: Argon shielding gas. Use DCSP (electrode negative), with a sharp tungsten.
Use AC on Aluminum Bronze, with a rounded tungsten.
Use electrodes of a matching alloy.
Phosphor Bronze: Use Helium. Use DCSP (electrode negative) with a sharp electrode. Stick welding is better.

Marine Metals Book List

Metal Boats and Metal Work

Thomas Colvin, *Steel Boat Building.*
Gilbert Klingel, *Boatbuilding in Steel.*
Smith & Moir, *Steel Away.*
Roger Pretzer, *Marine Metals Manual.*
Nigel Warren, *Metal Corrosion in Boats.*
Lincoln Electric Co, *Arc Welding Handbook.*
Allegheny Ludlow Steel Co, *Stainless Steel Fabrication.*

Use of Metal Hardware on Traditional Vessels

Howard Chapelle, *Boatbuilding.*
Howard Chapelle, *American Fishing Schooners.*
Pete Culler, *Skiffs and Schooners.*
Harold Underhill, *Masting and Rigging.*
Eric Hiscock, *Cruising Under Sail.*
Mystic Seaport, *Restoration of the Smack Emma C. Berry.*
L.F. Herreshoff, *Common Sense Yacht Design.*
Tom Cunliffe, *Hand Reef & Steer*

Hull & Rig Design

Larsson & Eliasson, *Principles of Yacht Design.*
Howard Chapelle, *Yacht Designing and Planning.*
Phillips-Birt, *Sailing Yacht Design.*
Henry & Miller, *Sailing Yacht Design.*
Kinney, *Skene's Elements of Yacht Design.*
Brion Toss, *The Riggers Locker.*

Metal Supply Catalogs

Alaskan Copper & Brass Co, *Catalog.* Seattle, Wa.
Pacific Metal Co, *Catalog.* Seattle, Wa.
Metal Goods, *Metalog.* Alcan Aluminum Co, St. Louis, Mo.
Kilsby Tube Supply, *Catalogs.* Seattle, Wa.

Bonding and Electrical Wiring

Charlie Wing, *Boatowners' Illustrated Handbook of Wiring.*
Edgar J. Beyn, *The 12 Volt Doctor's Practical Handbook.*
Miner Brotherton, *The 12 Volt Bible for Boats.*
Nigel Calder, *Boatowner's Mechanical and Electrical Manual.*
Nigel Warren, *Metal Corrosion in Boats.*

The first two have the most to say about corrosion and bonding.
The other three fill in a few areas not covered in the first two.

Classification Societies

American Boat and Yacht Council, *ABYC Standards Manual.*
American Bureau of Shipping, *Rules for Building and Classing Steel Vessels Under 61 Meters.*
American Bureau of Shipping, *Rules for Building and Classing Aluminum Vessels.*
American Welding Society, *Guide for Steel Hull Welding.*
American Welding Society, *Guide for Aluminum Hull Welding.*
Lloyds Register of Shipping, *Rules for the Hull Construction of Steel Yachts.*
Lloyds Register of Shipping, *Rules for the for the Classification of Yachts and Small Craft.*

Metals and Structure

Salvadori & Heller, *Structure in Architecture,* Prentiss - Hall.
Oberg & Jones, *Machinery's Handbook,* Industrial Press.
Parker & Ambrose, *Simplified Mechanics and Strength of Materials,* Wiley.
James Ambrose, *Building Structures,* Wiley.
Den Hartog, *Strength of Materials,* Dover.
Lincoln Electric Co, *Arc Welding Handbook,* (Chapter on Structure).

The excellent book by Parker and Ambrose, Simplified Mechanics and Strength of Materials, gives a clear presentation of the mathematics involved in working out the practical aspects of structure. Machinery's Handbook is a nearly indispensable reference. For the terminally curious, the math intensive Strength of Materials, by Den Hartog will probably be of interest. Structure in Architecture, by Salvadori and Heller, provides an extremely clear overview without resorting to mathematic equations.

Preventing Galvanic Corrosion

* Use metals below the water that are as close to each other as possible on the galvanic scale. Don't mix metals.

* Fasteners must always be more noble than the fitting they're used on.

* With a simple boat, or a wood boat of any kind, it would be best to electrically isolate all underwater metal fittings from each other, and then.....

* Put a zinc on it. Weld the zinc on if possible, or bolt the zinc directly to the piece.

* Never paint a zinc anode!

* Painting the cathodic metals is beneficial.

* Never use graphite-bearing lubricants. Graphite is noble to almost everything!

* When bringing AC shore power aboard, it should pass through an isolation transformer.

* Battery chargers must be an isolation transformer type.

* Use bonding with a highly complicated electrical system in order to reduce the electrical shock hazard.

* Do everything possible to avoid stray currents in the water, and to prevent them aboard.

Marine Metals Physical Properties

METAL ALLOY	Ultimate Tensile	Minimum Yield	Elong.	Compressive Yield	Ultimate Sheer	Fatigue Strength	Elastic Modulus	Poisson's Ratio
Units Used:	psi	psi	%	psi (= @ yield)	psi (@ 75% UTS)	maximum psi load for duration of 500 Million Cycles	millions of lbs. (tensile)	
Ingot Iron - 99.9% Fe	45,000	18,000	47	18,000	33,700			
Gray Cast Iron - 2 to 4% C	27,000	25,000		75,000	37,800		25.0	0.21
Wrought Iron - 2 to 4% C	42,000	27,000		27,000	34,500		28.0	0.27
Mild Steel - 0.2% C	60,000	36,000	23	36,000	45,000		28.9	0.30
CorTen A-242	70,000	50,000	22	50,000	52,500		28.9	0.30
SS Type 304	84,000	42,000	55	42,000	63,000		28.0	0.29
SS Type 304-L	81,000	39,000	55	39,000	61,000		28.0	0.29
SS Type 316	84,000	42,000	50	42,000	63,000		28.0	0.29
SS Type 316-L	81,000	42,000	50	42,000	61,000		28.0	0.29
SS Type 321	90,000	35,000	45	35,000	68,000		28.0	0.29
SS Type 347	95,000	40,000	45	40,000	71,000		28.0	0.29
5052 H-32 Alum	31,000 / 25,000	23,000 / 13,000	12	23,000 / 13,000	21,000 / 16,000	17,000	10.3	0.33
5083 H-116 Alum.	44,000 / 39,000	31,000 / 18,000	12	31,000 / 18,000	26,000 / 23,000	23,000	10.3	0.33
5083 H-32 Alum.	45,000 / 39,000	34,000 / 23,000	12	34,000 / 23,000	30,000 / 24,000	23,000	10.3	0.33
5086 H-116 Alum.	40,000 / 35,000	28,000 / 19,000	12	28,000 / 19,000	24,000 / 21,000	23,000	10.3	0.33
5086 H-32 Alum.	42,000 / 35,000	30,000 / 19,000	12	30,000 / 19,000	25,000 / 21,000	23,000	10.3	0.33
5454 H-32 Alum.	36,000 / 31,000	26,000 / 16,000	12	26,000 / 16,000	24,000 / 19,000	24,000	10.2	0.33
5456 H-116 Alum.	46,000 / 41,000	33,000 / 24,000	12	33,000 / 24,000	30,000 / 25,000		10.3	0.33
6061 T-6 Alum.	45,000 / 30,000	40,000 / 19,000	17	40,000 / 19,000	30,000 / 20,000	14,000	10.0	0.33
6063-T6 Alum.	35,000 / 20,000	31,000 / 12,000	18	31,000 / 12,000	22,000 / 15,000	10,000	10.0	0.33
Cast A-356 T-6 Alum.	33,000 /	24,000 /	3.5	24,000 /	26,000 /		10.5	0.33
Phosphor Brz Rod - 510	80,000	55,000	20	55,000	60,000		16.5	0.35
Aluminum Bronze - 642	80,000	40,000	20	40,000	60,000		18.0	
Silicon Brz, Everdur - 655	55,000	20,000	30	20,000	41,000		16.0	0.33
Manganese Brz Rod - 675	80,000	50,000	20	50,000	60,000		15.0	0.34
90-10 Copper Nickel - 706	42,000	18,000	35	18,000	31,500		22.0	
70-30 Copper Nickel - 715	52,000	20,000	45	20,000	39,000			
Monel 400	90,000	50,000	40	50,000	67,500		26.0	0.32
Inconel 617	106,000	42,900	70	42,900	79,500		31.0	0.29
Inconel 625	120,000	60,000	40	60,000	90,000		30.0	0.31
Lead	3,000						1.5	0.43
Zinc	20,000						12.4	0.33

Aluminum: Second Value is "As Welded" Strength.

Marine Metals Physical Properties

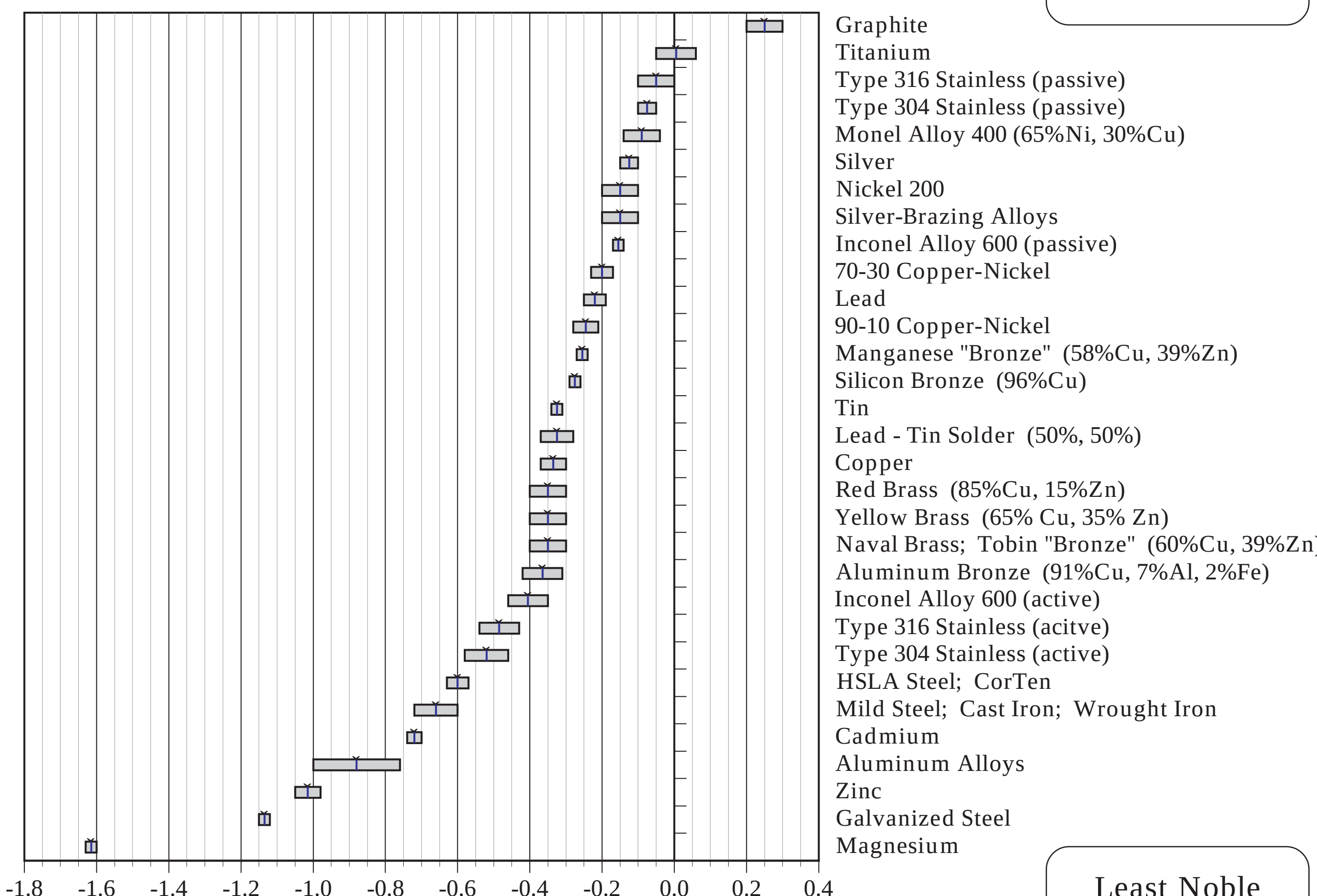
METAL ALLOY	Weight	Hardness	Impact	Melting Pt.	Thermal Exp.	Thermal Cond.	Heat Cond.	Elect Cond.
Units Used	lbs. per cubic foot	Brinell (avg.)	Ft. Lbs. (Izod)	deg F. (avg.)	in / in / deg F.	BTU / Sq.Ft. / Hr / deg.F / Ft.	Percent Copper = 100%	
Ingot Iron - 99.9% Fe	480	50		2,800	0.0000059	40	15	12
Gray Cast Iron - 2 to 4% C	460			2,800	0.0000062	30	12	15
Wrought Iron - 2 to 4% C	480			2,750				
Mild Steel - 0.2% C	490	60		2,500	0.0000065	31	12	15
CorTen A-242	490	85			0.0000065	31	12	15
SS Type 304	501	170	85	2,600	0.0000092	9.2	3.6	2.8
SS Type 304-L	501	170	80	2,600	0.0000092	9.2	3.6	2.8
SS Type 316	501	200	70	2,525	0.0000089	9.4	3.6	2.8
SS Type 316-L	501	180	80	2,525	0.0000089	9.4	3.6	2.8
SS Type 321	501	200	80	2,575	0.0000092	9.4	3.6	2.8
SS Type 347	501	200	80	2,575	0.0000091	9.4	3.6	2.8
5052 H-32 Alum	167	60		1,150	0.0000132	96	40	32
5083 H-116 Alum.	166			1,120	0.0000132			
5083 H-32 Alum.	166			1,120	0.0000132			
5086 H-116 Alum.	167.5	64		1,135	0.0000132	87	36	31
5086 H-32 Alum.	167.5	67		1,135	0.0000132	87	36	31
5454 H-32 Alum.	167	73		1,155	0.0000131			
5456 H-116 Alum.	166	80		1,120	0.0000133			
6061 T-6 Alum.	169	95		1,130	0.0000141	116	48	43
6063-T6 Alum.	169	73		1,170	0.000013	139	58	53
Cast A-356 T-6 Alum.	167.6	80		1,150	0.0000125	96	40	
Phosphor Brz Rod - 510	552.9	80		1,800	0.0000099	36		15
Aluminum Bronze - 642	499.2	153				44		14
Silicon Brz, Everdur - 655	537.6	60			0.0000098	21	30	17
Manganese Brz Rod - 675	519.5	100		1,700	0.000012	69		24
90-10 Copper Nickel - 706	576	64		2,000	0.0000093			
70-30 Copper Nickel - 715	600	75		2,200	0.000009	17		4.6
Monel 400	551.2	130		2,400	0.0000064	15	6.6	4
Inconel 617	521.8	133		2,480	0.0000049	94	3.5	16
Inconel 625	527	175		2,410	0.0000055	68	3.5	16
Lead	708.5			621	0.0000163		9	8
Zinc	445.8			787	0.000022		29	28

Metal Boat Quarterly

The Galvanic Series

Average Voltage in Seawater

Most Noble
Cathodic



Least Noble
Anodic

Maximum Recommended Voltage Difference is 0.2 Volts

The Metal Boat Society
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Sedro-Woolley, Wa. 98284