The Power and Peril of Stainless

Despite stainless steel's deserved reputation for corrosion resistance, longevity, and durability, this alloy is prone to a variety of failures depending on its actual composition and application in the marine environment.

Text and photographs by Steve D'Antonio

Above—Even good-quality 300-series stainless steel, such as this steering chain, can suffer crevice corrosion and microcracking, and then ultimate structural failure.
Right—Rust stains running out from under or around stainless hardware nearly always portend crevice corrosion.

If you've worked in a service yard, this list of problems will be familiar: rust from a rub strake leaves streaks on the topsides, or deck hardware stains the gelcoat; a stainless steel chainplate corrodes where it passes

through a cored deck; a pitted stainless steel prop shaft breaks under load; or stainless steel keelbolts require replacement or fail outright from corrosion. And as you explain the failure and propose an appropriate repair, a disappointed owner predictably asks, "How could it corrode? It's stainless." The short and alarming answer is "Very easily." But too often the builders or repairers doing the job have little more understanding of the complexity of stainless steel corrosion than the owner. With growing concerns about our ability to verify the metallurgical quality of

Left—*This stainless steel water tank, built of 304 alloy, corroded and began leaking after just four years of service because it lacked the necessary resistance to corrosion. Uniform discoloration adjacent to the welds also points to weld migration, a result of using inappropriate higher-carbon stainless steel. Water tanks fabricated from 316L (low-carbon) stainless steel alloy are unlikely to fail.* ***Right***—*Raw iron has little resistance to corrosion and thus few appropriate applications in a marine environment. Predictably, this cast iron centerboard rusted after its coating deteriorated.*

stainless steel hardware as yards are forced to source it in an increasingly decentralized global marketplace, it's more important than ever to understand just what we mean when we specify, order, and install stainless steel hardware and components.

In my experience, boat builders and repairers are equally responsible for misapplying various alloys of stainless steel. I've made many such mistakes, and I've also learned from seeing the failures of stainless steel alloys in boats I was servicing.

Recently, an exchange with a colleague reminded me how misunderstood stainless steel is, even within the industry. The broker representing the vessel I had inspected was dumbfounded when I told him its stainless steel water tanks were corroding, leaking, and had to be replaced—a costly proposition, particularly for a four-year-old vessel.

"How could that be?" he said. "They are stainless steel, and stainless steel doesn't rust."

The error is common: the tanks had been built from 304 alloy, which is not the most corrosion-resistant stainless choice and is therefore inappropriate for a water tank. (See page 51 for an explanation of 300-series stainless steel.) Yet the tank was clearly labeled as 304 series stainless steel alloy—proof, I believe, that no subterfuge was intended. It was simply an error in design or selection that no one on the boat's build or maintenance crews caught. It seemed adequate that the tank was stainless, thought to be impervious to decay or corrosion.

This can happen anywhere. I've encountered variations of this scenario repeatedly in Asian-, North American–, and European-built craft. But common stainless steel failure is avoidable when users fully understand the metal's weaknesses in the marine environment.

Iron

Let's start with stainless steel's parent alloying material, iron, which appears in several forms aboard nearly every boat. This metal is a key component in ordinary steel (sometimes referred to as mild steel or low- or high-carbon steel) as well as in stainless steel. It may surprise many that stainless steel is made up of just over 50% iron, compared to conventional carbon steel, which typically contains more than 98% iron.

Cast iron is most commonly employed for manufacturing engine blocks, cylinder heads, and exhaust manifolds and risers. It also serves in some boats as cast or shot ballast. More commonly, lead is chosen for ballast because of its extreme density and resistance to corrosion, but iron is desirable because of its low cost and environmental friendliness. Its primary drawback is vulnerability to corrosion. If applied externally as a sailboat keel or centerboard, for instance, iron will rust severely when its coating is breached. Regular maintenance and preventive action can minimize but not entirely eliminate rust. Wholesale corrective action—stripping, sandblasting, and epoxy priming—can be a significant expense.

For sailing vessels internally ballasted with iron, there's less concern about rust, and no maintenance is required as long as the iron is fully encapsulated within the keel. If water reaches this iron, however, even the smallest intrusion can wreak havoc, as the oxidation and consequent expansion may cause significant and costly damage to the surrounding fiberglass structure.

Mild Steel

Mild, or high-carbon, steel is most beloved by a select few recreational boat builders, although it is by far the most common boatbuilding material for commercial and military vessels. It's called mild because it is ductile, or flexible (rather than brittle), which generally makes it good boat- and shipbuilding material. The carbon

When covered by protective coatings, mild steel is a stout and forgiving building material, especially for commercial vessels. This hull, deformed under lifting stresses during salvage, shows just how ductile the metal is.

Combining mild steel, galvanized steel, and bronze in this raw-water application can lead to a variety of corrosion-induced failures.

content of mild steel is approximately 0.08%. (High-carbon steel, on the other hand, with carbon content up to 0.77%, is strong, a relative term to be sure, yet brittle, and is applied where rigidity is favored over ductility.) Mild steel is inexpensive and strong, and will flex and bend dramatically before fracturing. Consider how much the thin sheet metal in an automobile body distorts before failing. However, mild steel shares an unfortunate weakness with iron: it rusts readily when unprotected, especially in a marine environment.

Despite this, mild steel is used for myriad gear aboard recreational and commercial boats, most commonly in engine beds, fuel tanks, various engine brackets and components, radio and other equipment chassis, chain rode, rudder webbing, and hose clamp screws. Although more desirable, lighter-weight corrosion-proof composite or nonmetallic options now exist for many of these applications, habit and cost will likely dictate mild steel's continued use in select locations aboard small and large vessels. It should be applied sparingly and, with some notable exceptions, never above deck or below the waterline. In most cases, better alternatives include stainless steel alloys.

An unfortunate characteristic of steel, and most alloys for that matter, is that it's impossible to determine the alloy or grade by simple visual inspection. Hose clamps provide an excellent and common example. Clamps designed for marine applications are constructed of *all* 300-series stainless steel—either 304 or 316 alloy—while industrial or automotive-style clamps are usually made with a stainless steel band and a *mild-steel* screw. New mild-steel screws are virtually indistinguishable from stainless steel screws without the aid of a magnet, which is attracted to the iron in non-stainless steel fasteners. Further complicating the issue, some stainless-band/mild-steel-screw hose clamps are labeled "all stainless," evidently referring to the band alone. I've seen boats that were built mistakenly, I presume, with this inferior-style clamp throughout their plumbing systems. Unfortunately, it's up to the builder or service yard to determine the metallurgy of the clamps they install, regardless of the labeling.

Above left—*Although this hose clamp is labeled "ALL STAINLESS," the screw is mild steel, as the rust reveals.* ***Left***—*One way you can identify less-corrosion-resistant stainless alloys, like this 18-8 fastener: they are mildly magnetic.*

Experienced pros who have handled thousands of hose clamps and fasteners of stainless and anodized mild-steel can discern the difference between the two, as plated-steel screws often have a slightly different hue than stainless steel ones. The rest of us have to rely on a magnet.

Hose clamps with plated mild-steel screws will come to grief rather quickly in the marine environment, even when not directly exposed to seawater; the same can be said of some varieties of genuine all-stainless steel clamps (see the photograph of a deteriorated all-stainless clamp below). Although many marine engines have "automotive" mild-steel-screw-equipped clamps, some now have all-stainless constant-tension clamps, which are better mechanically as well as more corrosion resistant. Elsewhere aboard, test with a magnet to determine marine suitability; if it is attracted to *any* part of the clamp, replace the clamp with an all-stainless steel model designed for marine applications.

Galvanized Steel

The other mild-steel category worthy of note is galvanized hardware. Galvanizing is nothing more than zinc plating. Hot dipping, or literally immersing the steel component in molten zinc, typically leaves a slightly mottled or rough surface and is by far the preferred galvanizing method, as the coating it provides is comparatively thick—about 3 mils (a mil is one-thousandth of an inch).

Another popular though inferior method is *electroplating*, where the zinc is applied with electricity much the same way chrome coating is applied to steel. For most marine applications, the 1.5-mil coating is not thick enough for what's referred to as a "class A marine standard."

So-called *flame spraying*, which is essentially spraying molten metal, is a viable alternative, particularly for large objects like entire steel hulls. The alloy often consists of an aluminum/zinc mixture applied at approximately 5 to 7 mils. Galvanized hardware has its place aboard, particularly where it's historically or aesthetically appropriate in wooden vessels. Anchors and anchor chain are galvanized, an application that makes sense for any vessel if the hot-dipped method is employed. Keelbolts were frequently,

Occasionally seen aboard steel vessels, galvanized steel plumbing will have a limited life span. Because the inside of the pipe is inaccessible and unable to be primed and painted, stainless steel or reinforced plastic is more appropriate here.

and sometimes still are, made of galvanized steel. Because the bolt is high-carbon steel, it yields more strength than one of stainless steel, bronze, or Monel (a trademarked alloy of Specials Metal Corp., primarily composed of nickel and copper) for a given size and appreciable longevity, provided the galvanizing is properly applied and not damaged during installation or subsequent use.

Complicating factors can sometimes make other materials preferable for keelbolts. For example, if the bolts are used as a connection point for a bonding or KISS-SSB counterpoise (the wire and terminal will be copper), the zinc coating on the portions of the nuts and studs exposed to seawater or bilgewater may sacrificially, anodically corrode. Galvanizing doesn't last forever, and there are better alternatives, particularly for keel and other difficult-to-access fastenings or hardware.

Galvanized steel's applications aboard small vessels have other downsides. Depending upon environmental conditions, temperature, and salinity, even a hot-dipped-galvanized surface will "waste" at the rate of about 1 mil per year when submerged in still water, and faster in moving water.

Stainless Steel

Since its accidental discovery in 1913, stainless steel has become extremely popular in applications ranging from automobiles and jet turbines to skyscrapers and flatware. The term *stainless steel* encompasses many alloys. Fortunately, for the sake of this discussion, the "marine grades" are a fairly short list.

Much like ordinary mild steel, stainless steel is made up primarily of iron. To this base, chromium and nickel are added in varying amounts, depending on the grade being manufactured. These additions afford stainless steel its unique corrosion-*resistant* (not corrosion-*proof*) properties. Among other things, the nickel enhances the alloy's ability to resist acids. The chromium, when exposed to the elements, specifically oxygen, enables this alloy to form a tough oxide film almost instantly. The result is what was once overoptimistically referred to as rustless or rust-free steel.

The alloying elements, and the effect they have on the strength and corrosion resistance of stainless steel, vary considerably within the grades of stainless. In addition to chrome and nickel, these alloys include sulfur, phosphorus, titanium, molybdenum, nitrogen, vanadium, and others.

There are three basic subcategories of stainless steel. *Martensitic* is applied widely for cooking utensils and sharp cutlery—essentially anything that requires hardening. *Ferritic* is employed for automotive trim and catalytic converters. *Austenitic* is best for marine applications as well as buildings and structures such as the Gateway Arch in St. Louis, Missouri, and New York's Chrysler Building. Nickel is exclusive to the marine grades, which always fall in the 300 series of stainless (see the **sidebar** below).

Austenitic, or marine, grades of stainless steel are further distilled into the American Iron and Steel Institute (AISI) heading of **300 series**. For recreational and commercial vessels, this primarily means two types:

- **304** is sometimes referred to as 18-8, reflecting the percentage of alloying elements chrome and nickel, respectively: 18–20% chromium, 8%–12% nickel; and
- **316** consists of 16–18% chromium,

Stainless steel is not ideal in submerged fastener applications. One alternative is copper alloy such as this hex-head bronze bolt.

Nickel in the Mix

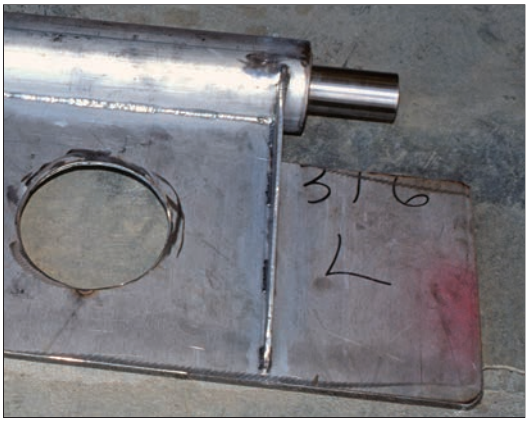
Nickel plays a pivotal role in the durability and corrosion resistance of austenitic stainless steel. With the addition of this alloying element, stainless steel becomes stronger and more stable than ferritic stainless steel at higher temperatures. Less nickel is needed to retain an austenitic structure as the nitrogen or carbon levels increase; when sufficient nickel is added to a chromium stainless steel, the structure changes from ferritic to austenitic.

Adding nickel also improves stainless steel's abrasion resistance, toughness, ductility, and weldability, as well as increasing its resistance to oxidation, carburization, nitriding, thermal fatigue, and acids. It is an important alloying element in stainless steel and other alloys for corrosive and high-temperature applications.

—*Steve D'Antonio*

8%–12% nickel, with an addition of 2–3% molybdenum. That final ingredient enables 316 stainless steel to better resist a phenomenon referred to as *crevice corrosion*, arguably the metal's greatest vulnerability and a menace to those who specify the material for unsuitable applications.

Most stainless steel available to the marine industry and retail purchasers is 304. Stronger than 316, technically it is the least-corrosion-resistant commonly available grade of marine-approved stainless steel. While its corrosion resistance is considerably higher than that of ordinary steel, it's far from corrosion-proof. The popularity of 304



Welded components such as this rudder armature should be fabricated of 316L series stainless, a corrosion-resistant alloy low in carbon and thus less prone to weld decay. The stock should be made of an even more corrosion-resistant shaft stock alloy.

Duplex Stainless Steel: Strength and Corrosion Resistance

Many of the stainless steel alloys familiar to boat builders and repairers include as much tensile strength and corrosion resistance as possible, yet they remain far from perfect. As illustrated in the main text, propeller shafts in particular are run hard in a corrosive environment, making almost any improvement to their alloy worthwhile, especially at the right price.

Although Sweden's Avesta Steelworks—now owned by Finnish metallurgical giant Outokumpu, one of the world's largest and oldest stainless steel manufacturers—cast the first duplex stainless steel close to a century ago, it wasn't really adopted until about 30 years ago. Due in part to the need for stronger, lighter, more corrosion-resistant alloys for the offshore oil and gas industry, duplex stainless steel is now widely used and readily available from several manufacturers and distributors. And because this alloy contains less nickel—whose cost fluctuates considerably—than other equivalent conventional stainless steel alloys, its price is more stable and at times lower.

Common austenitic and ferritic stainless steel alloys are referred to as single-phase austenite or ferrite, respectively, and each has strengths and weaknesses in corrosion resistance, machinability, cost, and tensile strength. In the 1920s it was determined that a hybrid alloy of the two could offer distinct advantages, primarily higher strength pound for pound, good weldability, greater toughness than that of ferritic alone, and better resistance to stress corrosion cracking (SCC), pitting, and crevice corrosion.

As a result of these attributes, the popularity of these so-called duplex stainless steel alloys has grown. Because the alloys are still relatively new, it seems each mill or producer offers its own grade. As volume increases, those that offer the best properties will likely rise to the top.

A key factor in determining the corrosion resistance of stainless steel is its pitting resistance equivalent number, or PREN (see the **table**). While it's not the whole story, a metallurgical law dictates that greater corrosion resistance results in reduced strength. Duplex stainless alloys come close to disproving that law, and are particularly useful for certain applications such as propeller shafts, where SCC is especially common.

With some exceptions, formability and machinability of duplex stainless steel are not as good as those of austenitic and ferritic alloys. Its ductility is also compromised, and its complex metallurgy makes it more challenging to produce. Still, its enhanced corrosion resistance is very attractive. There are three grades of duplex stainless steel: *standard*, which includes 22% chrome; *super*, having 25% chrome and a PREN of 40; and *hyper*, with a PREN of 48. Again, each of these alloys, like most metals, has trade-offs that we must recognize and work with or around.

If your application calls for a highly corrosion-resistant stainless alloy, duplex stainless steel may be worth a closer look.

—*S.D.*

Comparison of Stainless Steel Alloys

Grade	EN No/UNS	Type	Typical PREN
430	1.4016/S43000	Ferritic	18
304	1.4301/S30400	Austenitic	19
441	1.4509/S43932	Ferritic	19
RDN 903	1.4482/S32001	Duplex	22
316	1.4401/S31600	Austenitic	24
444	1.4521/S44400	Ferritic	24
316L 2.5 Mo	1.4435	Austenitic	26
2101 LDX	1.4162/S32101	Duplex	26
2304	1.4362/S32304	Duplex	26
DX2202	1.4062/S32202	Duplex	27
904L	1.4539/N08904	Austenitic	34
2205	1.4462/S31803/S32205	Duplex	35
Zeron 100	1.4501/S32760	Duplex	41
Ferrinox 255/ Uranus 2507Cu	1.4507/S32520/S32550	Duplex	41
2507	1.4410/S32750	Duplex	43
6% Mo	1.4547/S31254	Austenitic	44

This table lists the pitting resistance equivalent number, or PREN, of some duplex stainless steels and a selection of austenitic and ferritic grades.

in the marine trades is a function of cost and availability. It's less expensive than 316 and does a reasonably good job when not called upon to do something it was not designed for. As for availability, a 316 hex-head cap screw, say, is rarely stocked by common chandleries and must be special-ordered from hardware suppliers. Most builders just go with the 304 screw on the shelf.

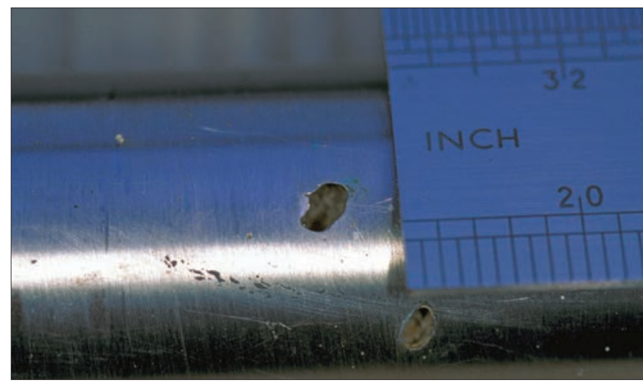
Note that 304 or 316 stainless to be welded must include the suffix "L," as in 304L or 316L, denoting a lower carbon content than in ordinary stainless steel; lower carbon helps prevent weld migration. I'll discuss this later.

Another derivative of stainless steel could be considered a super-corrosion-resistant metal of sorts. Commonly, and often mistakenly, referred to by its well-known trade name, AquaMet, it is simply the best known of a number of proprietary stainless-steel-based shafting alloys.

With slight variations, these alloys possess the basic ingredients of 316 stainless steel plus several other elements such as tantalum, niobium (formerly columbium), and manganese. These formulations are almost exclusively for solid propeller and rudder shafts, although keelbolts and rigging are also available in these or similar alloys. Such shafting comes in several grades, typically 17, 19, and 22, with the last being the most resistant to corrosion, and the first more resistant to yielding, meaning it's stronger.

Because propeller shafts require exceptional strength and corrosion resistance, they are *usually* fabricated from one of these proprietary stainless steel alloys. Ideally, these mixtures yield the preferred combination for the environment in which shafts operate.

As a boatyard manager and now as a marine consultant, I have seen countless severely corroded propeller shafts. I suspect, with some exceptions, that they are made of lower grades of shaft alloys, specifically 17, or less-exotic and thus less-expensive and less-corrosion-resistant non-proprietary shaft alloys such as 304 or even 316. As one might expect, super-corrosion-resistant alloys



Pitting corrosion on a propeller shaft almost certainly fabricated from conventional shaft stock. The need for high strength and corrosion resistance has driven the development of proprietary stainless-steel-based shafting alloys.

come with a justifiably higher price tag, and they still require cathodic protection in the form of zinc or aluminum anodes. Despite that, when comparing the potential cost of shaft corrosion and failure, it's difficult to make an argument for the initially less costly alloys, particularly in recreational vessels where disuse exacerbates crevice corrosion.

Shaft failure includes shafts that pit severely in the region of cutless bearings and stuffing boxes, which while not necessarily in danger of breaking can still be condemned and require replacement. Shafts manufactured from ordinary 304 or 316 stainless frequently suffer from crevice corrosion attacks (discussed in the following section), occasionally within less than a year of service, often beneath cutless bearings and stuffing-box packing, where the damage cannot be easily observed.

When sourcing shafts for your customers, ask for verification, in writing, of the specific alloy and brand your supplier delivers. Again, it's difficult to justify anything other than 22 series shaft alloys unless specifically required by a vessel's naval architect or builder.

Stainless Problems

Although the advantages and popularity of stainless steel make it seem virtually indestructible, it suffers primarily from two types of common corrosion: crevice and carbide precipitation.

Crevice, or pitting, corrosion occurs when stainless steel is exposed to an oxygen-depleted environment for an extended period. The tough, nearly impenetrable oxide film that forms as soon as stainless steel is exposed to air (the term *inox* on many European stainless components is simply an abbreviation for inoxodizable, which refers to stainless steel's resistance to staining) remains intact only as long as the metal is exposed to oxygen. When stainless steel is placed in an environment starved of oxygen *and* is exposed to water, fresh or salt, it becomes susceptible to crevice corrosion, which typically manifests as roughness, valleys, pitting, or worm-like holes. The chlorides in seawater accelerate the destruction of the oxide layer, which is readily replaced as long as oxygen is present. But without oxygen, the chlorides win, the oxide layer diminishes, and the stainless steel starts to corrode more like mild steel.

The most likely location for crevice corrosion is in stainless steel alloys used for raw-water and underwater hardware, most commonly propeller shafts, struts, raw-water intakes and discharges, sanitation plumbing, exhaust systems (particularly diesel exhaust, which when mixed with water becomes acidic), shaftlogs and related fasteners, and bolts and screws installed below the waterline to secure hardware such as struts, seacocks, strainers, swim platform supports, etc.

Because nearly all commonly available stainless steel fasteners are made of 304 alloy, they are exceptionally prone to crevice corrosion when installed below the waterline or in a splash zone. They are particularly vulnerable where they cannot be easily

Left—*This bolt's head and shank parted ways, likely from a combination of a low-quality manufacturing process and subsequent stress corrosion.* ***Right***—*Crevice corrosion, occurring where the metal is simultaneously starved of oxygen and exposed to stagnant water in a bilge or stuffing box, is a common failure mode on T-bolt clamps like this one, manufactured with a metal fold that traps water.*

inspected: as they pass through the hull, for instance. The exposure to water does not require submergence. Stainless steel imbedded in hydroscopic materials such as wood, foam or balsa core, or even fiberglass may suffer from crevice corrosion.

This type of corrosion also occurs on deck where water migrates into penetrations through which stainless steel fasteners pass. Exacerbating this problem is the common practice of bedding the *inside* portion of hardware—washers and nuts—virtually guaranteeing that when deck bedding fails, water will intrude and then stagnate in the void. Without inside bedding, water is more likely to drain, reducing the likelihood of crevice corrosion and core saturation; and the annoying drip lets the boat owner know it's time to re-bed deck hardware.

To avoid installing stainless steel in applications where it is regularly exposed to stagnant or still water for extended periods, builders should choose alternatives such as high-quality silicon-bronze, cupronickel, Inconel 625, Monel, or nonmetallic alternatives. This is particularly true for fasteners

As shown here, crevice corrosion also manifests where fasteners or deck hardware penetrate a cored or solid deck, allowing water to intrude and stagnate around the metal component. Don't rebed these components on the interior, as the bedding will trap water in the bore hole.

and raw-water plumbing. Avoid stainless steel fasteners for struts, strainers, and other underwater hardware installations. Bronze (true zinc-free bronze, not brass) or Monel is a better choice. If stainless steel must be used for a custom-made strut or shaftlog, for instance, it should be fabricated from the most corrosion-resistant, readily weldable marine alloy available, 316L or 317L, primed and antifouled and provided with cathodic protection.

Carbide precipitation, sometimes referred to as weld decay, can occur when the incorrect alloy of stainless steel is used in welded applications. Low-carbon-content stainless steel, noted as 304L, 316L, or 317L, must be used in fabrication. When carbon is not present, chrome carbide will not form when the metal is heated. In common higher-carbon alloys the heat of welding (or any heat between 800°F and 1,600°F/427°C and 871°C) drives chrome ions out of the weld area; the chrome becomes tied up with the carbon, forming chrome carbide, at which point the chrome is no longer available to help the alloy resist corrosion. Essentially, this leaves a strip of what amounts to ordinary mild steel on either side of the weld. This region, known as the heat-affected zone, becomes susceptible to corrosion. This is usually noticeable to even the inexperienced observer as a discolored brownish area extending outward from the center of the weld as much as an inch (25mm). Other than reduced corrosion resistance, the material in the weld area is unaffected.

Related to carbide precipitation is a form of corrosion caused by galvanic or electrical interaction across the metallic grain structure itself, and between the boundaries of grains, impurities, and the alloying elements. Known as ***intergranular corrosion***, this can be caused by welding, overheating, or stress annealing. It can occur also as a result of overly aggressive grinding (which causes local heating), or when the metal is not adequately gas-shielded during welding (in the latter case particularly for

Left—*Corrosion emanating from weld decay, also known as weld migration, on this stainless steel exhaust system led to complete failure.* ***Right***—*Susceptibility to crevice corrosion makes stainless plumbing less than ideal for raw-water applications. In this case, the problem is amplified by the use of the incorrect high-carbon stainless alloy.*

high-carbon-stainless alloys).

While stainless steel owes its corrosion resistance to the oxide layer that forms on its surface when exposed to air, an overly thick oxide layer, often identifiable by its blue hue, can be detrimental and can form as a result of the above-described scenarios. The area beneath the layer is depleted of chrome, impairing its corrosion resistance. To resolve this issue, the oxide layer and the chrome-poor region must be removed, either mechanically or chemically. Ideally, mechanical removal is by fine-grit sanding media or less desirably by shot-blasting or wire-brushing (the alloy of the wire brush can actually exacerbate the problem). Chemical treatment with a mixture of nitric and hydrofluoric acid is another option. A final treatment of chemical passivation will reduce the likelihood of corrosion via anodic interaction.

A final note on stainless steel raw-water plumbing: I often see attractive, intricately welded, and polished raw-water components that are assiduously bonded. I presume builders include these bonding connections for the perceived cathodic protection they offer, but in virtually every case, the anode is located too far from the

The hard-to-identify characteristics of this failure, which is limited to the weld material rather than the parent metal, are most likely caused by intergranular corrosion.

internal plumbing component to offer any protection. Bonding fittings like this may afford some protection from stray-current corrosion; however, when compared to crevice corrosion it is far less common. While such bonding connections can't hurt, they offer little if any protection from crevice corrosion.

Conclusions

Obtain stainless steel stock and components from reputable suppliers, especially proprietary shaft material. Request documentation with shafts that includes the name of the manufacturer or distributor, as well as the alloy from which they are made.

It's also important to specify what's best suited for the application and to know what you are getting. For instance, the most corrosion-resistant, readily available proprietary shaft alloys supplied in North America carry a 22 suffix (they're nonmagnetic); less-corrosion-resistant versions (which are magnetic) carry a 17 and 19 suffix. The less-corrosion-resistant shafts possess greater tensile strength for a given diameter, so they may be specified by naval architects for applications where this strength is required. For most recreational vessels—and those that remain idle for long periods, when oxygen levels are often low in the water surrounding the shafts in the logs and under packing and cutless bearings—greater corrosion resistance is usually of more value. I would be hard pressed to select anything other than a 22 series propeller shaft unless the modest additional strength was absolutely essential.

Not long ago I was involved in a case wherein two propeller shafts aboard the same vessel were afflicted with the same type of corrosion in the same location after approximately six months and 400 hours of operation in tropical water. The corrosion was discovered because of a seemingly unrelated cutless bearing failure. The bearing had been added when the shafts were replaced, a detail that became relevant later in the diagnosis.

During shaft removal to diagnose and replace the failed bearing, we found corrosion where stuffing box packing made contact with the shaft and where the shaft was supported by the added bearing. We confirmed the shaft alloy by sending a sample to a

Slight misalignment caused this shaft to be stressed at a supporting bearing, which led to stress corrosion cracking and the pitting visible here, after just 400 hours of operation over six months in tropical water. High friction and poor water flow raised the temperature of the alloy. Combined with exposure to seawater, these conditions created an ideal environment for this type of corrosion.

lab for analysis. The percentage of each alloy was within the manufacturer's specifications, ruling out an inferior alloy as the culprit.

The ultimate cause of the corrosion was stress corrosion cracking, i.e., being hot, salty, and stressed (it was surmised that slight misalignment was causing the shafts to "work" over the bearing). The boat had long shaftlogs, and while under way, the stuffing boxes and cutless bearings were insufficiently lubricated, causing the shaft to run hot in this region. This condition, exacerbated by the misalignment, led to localized pitting.

Sea trials with the original setup, taken before the corrosion was discovered, confirmed the stuffing boxes were overheating. Subsequent sea trials after the corrosion was discovered confirmed that the added shaftlog bearing was also overheating. When the shafts and bearings were replaced, an added water-injection system reduced the temperature; and shaft-to-bearing interface was adjusted with optical and laser alignment.

Ultimately, to avoid corrosion and failures, one should employ stainless steel only where it's *best* suited for the task, meaning, where it's *better* than other alloys, and specify the right stainless alloy for the job. The tanks mentioned at the beginning of this article were fabricated from 304 series stainless steel; 316L alloy almost certainly would not have suffered a similar fate. For submerged applications such as struts, rudders, and skegs, rely on 316L only as an alternative to other preferred alloys such as bronze, and be sure to coat them with epoxy primer and antifoulant. And always use and maintain cathodic protection. PBB

About the Author: *For many years a full-service yard manager, Steve now works with boat builders and owners and others in the industry as "Steve D'Antonio Marine Consulting." He is the technical editor of* Professional BoatBuilder*, and is writing a book on marine systems, to be published by McGraw-Hill/International Marine.*