Close attention to design and best practices can simplify construction and extend the working life of a high-speed aluminum boat.

by John Kecsmar

Creating the complex structure and graceful curves of an aluminum boat requires the profound transformation of flat, square, virgin plate. It is rolled, bent, forged, bashed, scored, heated, welded into shape, and painted. Done incorrectly, any one of these processes can seriously compromise the fatigue life of the resulting structure. Such failings can be exacerbated by original designs that overlook the simple details needed to accommodate the properties and peculiarities of the material.

The relationship between aluminum fabrication practices and fatigue failure is complex. While I cannot possibly cover all its aspects in a brief article, I’ll highlight some of the common causes of failure in aluminum boats that are too often overlooked during planning and construction.

To better understand why such mistakes are made and how to correct them, let’s take a look at a common fatigue failure in a series of high-speed aluminum powerboats I worked on in the early 1990s: cracking in the aluminum structure in transoms and around waterjets.

At the time, the popularity of waterjet propulsion was booming, and with it came a troubling rise in these cracks. They were common enough to almost be expected. The problems have now been well documented and,
In contrast, aluminum has no fatigue limit. Constant exposure of aluminum to repeated loading will ultimately lead to failure, no matter how low the actual stress magnitude experienced for all practical purposes.

Faced with numerous failures, we were beginning to think that aluminum was a poor choice for a lightweight boatbuilding material; it seemed cursed. It turns out that many of our problems—and those of other builders—were caused by applying steel design and building methods to aluminum, a very different metal. Steel, a forgiving material, has been around for centuries, and the techniques and procedures for working it are highly developed and widely employed. As a boatbuilding material, aluminum is just decades old, so correct, consistent aluminum-fabrication methods are not as commonly shared. It is imperative that we teach best practices for aluminum to fabricators, especially those who are accustomed to building in steel.

**Basic Aluminum Fabrication**

During fabrication, steel is not affected and/or changed to the same degree as aluminum, but aluminum has the undeniable advantages of lightweight and resistance to corrosion. So, how do we reconcile these differences? It’s important for designers and fabricators to recognize aluminum’s characteristics so they can maximize its desirable properties, and avoid the sort of failures that plagued our waterjet structures and transoms.

**Fatigue**

In this context, fatigue is best described by metal fatigue expert L.P. Pook: “a failure of a metal under repeated or otherwise varying load which never reaches a level sufficient to cause failure in a single application.” In simple terms: When you apply a force to a structural member, it will bend and become stressed. So long as the stress from static loading is below the material’s yield stress, the member will not fail. If you now repeat this loading many times, although each specific load applied does not overstress the member, the simple repetition can initiate a failure owing to the dynamic or cyclic nature of the loading.

In troubleshooting our transom failures, or any fatigue failure of an aluminum boat, there’s an important distinction to be made between fatigue in steel and fatigue in aluminum. Below a particular level of stress, steel reaches its fatigue limit. No damage or loss of strength will occur below that fatigue limit, regardless of the number of cycles (Fig. 2).
Material-specific quality assurance (QA) is the key to consistently successful design and construction of aluminum boats. Whether you’re the designer, the plater, or the welder, your awareness of the alloy’s physical properties and limitations is the first step in recognizing what can compromise an aluminum structure, what can go wrong in build, and ultimately how you can avoid such faults. That understanding also clarifies the necessity of different fabrication processes for steel and aluminum, and helps you avoid the common errors caused by not differentiating between the two materials.

You may ask, “Is strict quality control really that necessary? I’m only building a small yacht; won’t it add time and cost? Surely this is only for large commercial builds.” Regardless of size or complexity, once the boat enters service, simple unforeseen vibrations from numerous sources will expose any flaws unintentionally built into the hull due to lack of attention to detail during design

Let’s start with a few fabrication practices that best accommodate aluminum’s principal characteristics.

Avoid marking the plate with scribing tools; these leave marks on the surfaces and can create a slight flaw where a crack can develop and become the site of crack initiation under high loads. Similarly, don’t write on aluminum stock with pencil, as the carbon in it is higher up (more noble) on the galvanic corrosion series.

If aluminum is too coarsely cut, its rough surface can result in potential sites of crack initiation. Cutting with a rotary saw can create considerable heat at the blade tips (Fig. 3). This heat buildup can locally reduce the strength of heat-treatable 6000-series aluminum as well as annealing a strain-hardened 5000-series non-heat-treatable alloy.

Another desirable property of aluminum that differentiates it from steel is that it requires no special tools for bending. It is important to ensure that the bending tools are free of irregularities, which could cause marks or score the surface of the plate. The effects that notching or scoring have on aluminum are shown in Fig. 4. Ranging from minor to major, notches in the plate can reduce the fatigue strength by as much as 75% from its pristine condition.

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and fabrication. And the cost of repairing a finished and flawed vessel can equal a large percentage of the initial build cost.

In steel construction, applying the correct filler wire or painting the bare metal surface to prevent obvious corrosion have become standard best practices, so ingrained and accepted than no one questions either the need or the expense. This is QA at its best. By learning and adhering to similar rules and standard practices, and recognizing that steel and aluminum require different approaches that should not be universally applied to both, the same high quality can be achieved in aluminum construction.

—John Kecsmar

Shaping should be performed in the O temper (annealed) or H111 (another temper designation) alloys to avoid excessive localized strain-hardening. Simple processes such as rolling and bending will work-harden the alloy, which in turn reduces its capacity for deformation and load-carrying. For this reason the United Kingdom Ministry of Defense accepts only O-temper alloys, which are the softest and most ductile. A typical value of proof stress of 5083 alloy in the O temper is nominally 120–140 MPa (Fig. 5). Strain-hardening the same 5083 alloy to a temper of H2 increases this proof stress to roughly 240 MPa. That sounds good, as the allowable design stress limit has increased. But closer inspection reveals that the same strain-hardening has reduced the margin from yield to ultimate tensile strength (UTS), or failure. Fig. 6 illustrates that strain-hardening each temper also increases the UTS, but at what cost? Thus, the UTS of O temper is approximately 300–330 MPa, whereas in H9 temper, the UTS is 420. As strain hardening increases, the percentage over the base yield proof stress the temper can carry, decreases. It ranges from 107% for O temper, down to a paltry 14% in the H9 temper.

This means that if the alloy is overloaded from its design-allowable stress in O temper, the amount of reserve capacity is 107%, or double the design limit—an inbuilt safety factor of 2. But in the H9 temper, for example, the margin from yield to overload is so small that an overload can cause instant failure of the structural member.

In addition, O temper is easier to bend for hull plating; and the resulting temper—after factoring in strain hardening from rolling—leaves sufficient overload capacity in the finished hull components. With O temper, it’s likely that simple rolling of hull plating can increase temper to, say, H116. But an already strain-hardened alloy, say H321, is significantly more difficult to roll, and once rolled is strain-hardened possibly to a temper of H2 or more, depending on the curvature’s complexity. This leaves little capacity for deformation in the event of overloading.

Some old-school fabricators will apply the heat method common in steel fabrication to straighten a buckled or bent aluminum plate. This is poor practice. Heat can significantly affect aluminum’s proof strength.

Even if the metal has been perfectly handled, cut, shaped, and fixed into position, it must still be welded. This process alters aluminum’s fatigue strength, sometimes dramatically if...
Welding reduces fatigue properties even further than those shown in Figs. 2 and 4. When aluminum is immersed in a corrosive environment like seawater, its fatigue life is reduced yet again, as shown in Fig. 7. A welded joint does not have to be immersed in seawater for its fatigue life to be reduced. If it is wetted just once with seawater in a bilge or unventilated compartment, and then dries, the effect is the same: the salt deposits are deliquescent, meaning that in damp conditions the salt crystals attract water in the air to form a highly saline drop of liquid, probably more corrosive than seawater.

Fig. 7 illustrates that when aluminum is welded, the reduction in fatigue strength “in air” is approximately 50%, and when that weld is immersed in seawater, reduction can be as much as 90% of the static unwelded strength. So, static design limits appear to be rather meaningless for a welded aluminum boat that is constantly exposed to or immersed in seawater. To avert failures, designers must carefully position welded joints, and builders must practice comprehensive quality control.

Frame Design

Proper structural analysis is always necessary in planning a complex structure. Incorrectly identifying load paths in connecting structure can cause serious problems in the framing for aluminum boats. When a typical stringer/longitudinal passes through a main transverse frame, cutouts are required so both structural members can be continuous. The size, shape, and connection detail of these cutouts requires care and an understanding of the true forces the frames will be subjected to. In Fig. 8, a typical arrangement shows an angle bar stringer, which could just as easily be a T or a bulb bar.

In the connection between the web of the transverse frame and the web of the longitudinal, seen in section, there is a 0.6” (15mm) radius. This prevents the weld of the transverse frame web (left to right on the page) from coming in contact with the weld of the web of the stringer. That’s important for two reasons: first, to avoid locating a weld over a weld (more on this later); second, the weld in the frame web carries a correct procedures are not followed.
load transversely, and the web of the stringer carries a load longitudinally. When these two welds join, the weld at the intersection is being “pulled” in two directions. If a load in each weld has a unit value of 1, then owing to the connection, the resulting maximum load is the square root of the triangle of forces: $\sqrt{2}$, or 1.41. Thus, the weld at the intersection has an increase in stress of 41% over “as designed” stress. Overlay an increase of 41% in expected stress onto Fig. 7, and the resulting weakness and likely failure is apparent, commonly called a biaxial stress riser. (A triaxial is a joint in three directions). The size of this radius needs to ensure that the two welds don’t touch.

The weld on the frame web must also return around and be continuous. If the cutout is an odd shape/size, this too can increase the local stress as a discontinuity.

An example of a poor weld return is shown in Fig. 9. Weld returns are important because as the shear load in the weld runs out, the load has nothing to pass into. (FEA can establish the structural load path to illustrate the phenomenon.) But more importantly, the end of a weld always has too much heat without a runoff plate and creates a heat sink as the weld solidifies, and eventually leaves a classic “crater,” or start-stop, crack. This is visible in the poor joint shown in Fig. 9, as indicated by the circle. The arrow is pointing at the heat sink and small pore, a microscopic flaw, which eventually becomes a crack that propagates under repeated loading. This type of flaw is also called a hot crack.

Shown in Fig. 10, a good return at the ends of a joint will prevent the heat sink, thus eliminating the flaw, and will provide a direct path around the joint to distribute the shear load when the vessel is in service.

If stringers are highly loaded, sniped ends will also exacerbate the fabrication problem. A snipe is the common method of finishing a structural member if an end doesn’t attach to another member. For example, when an angle bar stops short of a frame and it’s not possible to attach a bracket to the frame, the bar is cut back at an angle of 30°. This gradually reduces the change of section, thus lessening any stress concentration from loads in the member. The designer must ensure that the shear and bending loads are not excessive in any loading conditions in a sniped-end structural member.

Weld Flaws

Cracks in welds are the most common fatigue failure. They are generally the result of poor welding practice and not performing the standard checks to maintain quality. One of the most common is a simple start-stop crack initiated when too much heat is concentrated in one location for too long, or not long enough to fully penetrate. Considered to be too time consuming, good welding practices are too often abandoned when a builder is under the pressure of production. A classic example is when a welder makes a long run and neglects to grind back the stop to prevent a void (Fig. 11). If the weld has gone cool or cold, a new weld run on top, or if performed too quickly, will rarely fuse deep into the root and so leaves a void—a ready-made crack waiting to propagate.

Another common site for cracks is the intersection of the flange of a longitudinal and the web of a transverse frame. You can see in Fig. 8 that the flange of the angle bar has a defined gap between it and the frame web. Some designers and yards leave no gap, thinking that for a really stiff joint it’s often best to weld them together. This is incorrect. The resulting joint is very stiff; however, the problem that manifests in service is similar to, but worse than, the biaxial stress riser on the lower-radius web connection, discussed above. The weld of the frame web is carrying shear transversely, and the flange in the longitudinal direction carries tensile load. The shear strength of aluminum is much less than its tensile strength by a factor of $\sqrt{3}$; therefore, the allowable stress that the weld can take is reduced by 58% ($1/\sqrt{3}$)—the difference between the tensile and shear load capacity. Since the stringer
is constantly subjected to wave loads, it flexes with each passing wave in this extreme fatigue environment. As a result, the weld will crack, as shown in Fig. 12. Again, if the designer overlaid the calculated stress, with the √3 increase at this joint, onto the graph in Fig. 7, the implications for longevity are obvious. (While Fig. 7 shows a drop in strength at fatigued welds of roughly 90% in 5000-series aluminum, the results would be slightly worse in 6000 series.)

Poor fit-up is another common problem. If the plate is incorrectly sized, a large gap will result when it’s fitted up to the hull. Far too often, the welder will gap-fill to make it fit. A classic example of this is shown in Fig. 13, a cross section of the connection of a stern tube passing through a waterjet duct, exhibiting a large void. The stern tube must be fitted to exact tolerances to ensure the correct gap for welding. Though the drawing called for just three weld beads, or passes—a root and two caps—numerous beads are visible on the finished and failed structure. This excessive gap-filling led to the inevitable lack of penetration (LOP) and lack of fusion (LOF). Inadequate penetration means the weld pool does not reach the weld root, and therefore a root gap remains. Finally, where the minimum cross-sectional area and heat-affected zone (HAZ) coincide, there’s the resulting fatigue crack at the weld toe (the line where the base metal meets the weld metal on the surface). The stern tube shown in Fig. 13 failed within a few months of going into service. Despite being a small joint, it was a very costly repair, because the vessel had to be put in dry dock. Poor training or just a fabricator’s momentary lapse in attention necessitated this expensive correction.

Apart from being extremely unsightly, LOP/LOF seriously impacts the fatigue life of a welded joint, as illustrated in Fig. 14. That graph highlights several other welding defects as well. As the void size increases, the number of cycles to failure decreases significantly, as does the corresponding fatigue strength with or without reinforcements. These unfused interfaces between filler metal and base metal or between different layers of the filler material—characterized as fusion defects, or LOP and LOF—are difficult to detect with non-destructive
testing such as dye penetrant.

Poor fit-up affects alignment as well as gap filling. Misalignment can cause localized stress concentrations because the resulting weld is oversized, and also cause localized secondary bending stresses because of discontinuity between butted plates. The combination of these localized effects exposes the weld toe to higher-than-expected stress (see Fig. 15).

The increase in secondary stresses is related to the geometric relationship of plate thickness and distance of misalignment. We can calculate the increase of stress at the weld toes in the plate by the simple relationship:

\[ s_N + s_M = s_N \cdot (1 + 3.e/t) \]

Where:
- \( s_N \) is axial stress
- \( t \) is plate thickness
- \( e \) is eccentricity

The term in parentheses is the stress-magnification factor, \( K_m \). So if, for example, you have an axial misalignment of just 10% of the plate thickness \( (e/t = 0.1) \), \( K_m = 1.3 \). A similar increase in stress results from a 1° angular misalignment, which means that if the plate is off by 10% and the angle of the joint is also rotated by just 1°, these slight imperfections combine for \( K_m = 1 + 0.3 + 0.3 = 1.6 \). That’s a 60% increase of stress at the weld toe.

Fig. 16 shows the result of attempting to overcome the gap where a frame rider butts into another rider running transversely. To fill the excessive gap, the welder “buttered” each edge with two passes, which cooled and locked in stress. The weld was finished by filling the middle with additional weld beads achieving no real penetration. Aluminum has approximately five times the thermal conductivity, and twice the rate of thermal expansion, of steel, so the heat from welding travels farther and faster than in steel. The crack is shown by the circles on either side of the rider, and the arrows indicate the hairline crack that has surfaced across the weld. It cracked because the oversized volume of weld could not cool evenly across the whole joint, which caused internal thermal stress gradients. Thus, it cracked as it cooled.

Fig. 17 illustrates several bracket-
installation errors. The crack circled in red is the most obvious one. It was caused by the lack of a proper weld return, which led to too much heat at the ends as the welder stopped, which in turn pulled the joint as it cooled. To the left of the crack, the welder gap-filled to overcome bad fit-up. You also can just see a hard saw cut, indicated by the arrow, in the bracket material. This hard edge will also crack.

Gaps and misalignment aside, oversized or misshapen welds on their own are sources of local discontinuity. The stress in a typical weld varies from the nominal stress—what you expect the weld to carry—to a much higher peak at the weld toe. How this affects the fatigue life is shown in Fig. 18. Within a window of likely weld profiles, the lower the toe angle (meaning the more rollover), the lower the load the weld can carry. As the allowable stress is lower, so too is the fatigue life.

If we look at the profile of a butt weld as a discontinuity, it shortens the fatigue life of a structure. Fabricators can minimize the effect by dressing the weld bead, which reshapes the weld toe to eliminate rollover. The curves shown in Fig. 19 clearly illustrate that an as-welded joint, which shows the weld bead profile untouched, has a much lower load-carrying capacity, and thus a shorter fatigue life, than a dressed weld or the virgin plate.

Welding over a weld, and rewelding existing welds owing to mistakes and/or replacing plate, are far-too-common poor practices. When subjected to a typical UTS bend test, these joints show undesirable effects on the grain size. Fig. 20 shows an increase in grain size of 33% by the fourth repair. Hardness is proportional to yield strength, so as grain size increases, hardness decreases, which in turn reduces strength.

The effect of multiple welding repairs on mechanical strength is quantified in Fig. 21. As weld repairs increase, UTS consistently falls below accepted standards.

Weld temperatures in the heat-affected zone typically range from 932°F to 1,112°F (500°C to 600°C). At these temperatures, fine particles called intermetallics—such as Al6(MnFe) or Al6Mn and Al3Fe—precipitate from the alloy, and are no longer soluble once the weld cools.
The increase in grain growth shown in Fig. 20 is consistent with the increase in intermetallics and porosity—sites of crack initiation—caused by repeated exposure to welding temperatures. Welding over a weld increases the grain size and the number of intermetallics inside the alloy with each thermal cycle. This has the effect of greatly reducing strength and the fatigue life of the welded joint, and expanding the weakened area around a weld. The specific influence on fatigue life owing to the increase of intermetallics can be as much as a 30% reduction, and porosity alone can reduce the fatigue life by as much as 200 times, with increasing flaw size (Fig. 22). In repairs, the welder should always cut out the heat-affected zone to avoid the cumulative degradation of the metal from repeated welding.

Solutions

In repairing the original failure in our waterjet-powered vessel, we identified the fabrication faults that initiated fatigue-related failures in its complex stern structure. With FEA we found the locations of the load paths that the original design and fabrication had failed to identify as sources of potential failures that could result in cracking (Fig. 23). By applying best practices in aluminum to the next generation of waterjet-powered vessels, we have avoided those faults in fabrication.

We introduced more transverse frames in the detail design, so we could then reduce or completely eliminate longitudinals in the affected region. This provided easy access, so the welder could make one continuous weld, thereby limiting the start-stops that introduce so much potential for cracking. With no longitudinals or need for cutouts through structural members, all the connections were smoothed, minimizing welding discontinuities.

During fabrication, builders now roll the plate with more care and attention, and along the grain rather than across the grain. Where feasible, we introduced post-weld treatment to dress welds, reducing the stress concentrations at the weld toes (Fig. 24), which has been shown to improve the fatigue life.

The application of the new waterjet structure design and fabrication philosophies were fully adopted on a class of...
147.6' (45m), 200-metric-ton, 45-knot vessels. Twenty-three metric tons of water per second pass through the waterjet duct shown in Fig. 25. To the best of my knowledge, the boats have not experienced a single structural failure of the transom around the waterjets in their 17 years of service of 12–16 hour days, seven days a week. The same is true of the smaller repaired waterjet structure highlighted at the beginning of the article.

This evidence justifies the close attention to detail that took place during design and fabrication to ensure that a structure will be trouble-free for its lifetime. In all the waterjet-powered vessels I have designed during the past 17 years, I
have found that establishing correct procedures and sticking to them are the keys to a long-lived and warranty-free vessel.

**About the Author:** John Kecsmar formed the marine consultancy company Ad Hoc Marine Designs Ltd with Nigel Warren in 2005, after spending nearly 20 years together at FBM Babcock Marine, in Newport, United Kingdom. John is on Lloyd’s Register Technical Committee, RINA’s High Speed technical committee, MCA’s High Speed Advisory Group, and SNAME’s O-50 Maritime Quality Culture Group. He has designed high-speed aluminum vessels such as patrol boats, fast ferries, SWATHs, and crew boats for more than 20 years and is the author of many technical papers on high-speed design, structural design, and fatigue. He lives in Japan. John dedicates this article to his friend and mentor, Nigel Warren, who died during its preparation. John writes that Nigel was very generous with his encyclopedic knowledge of boats, and is sadly missed.

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**Further Reading**

For in-depth study of fatigue failures and aluminum boat construction, we include a list of the author’s technical papers and other sources he credits for this article.


