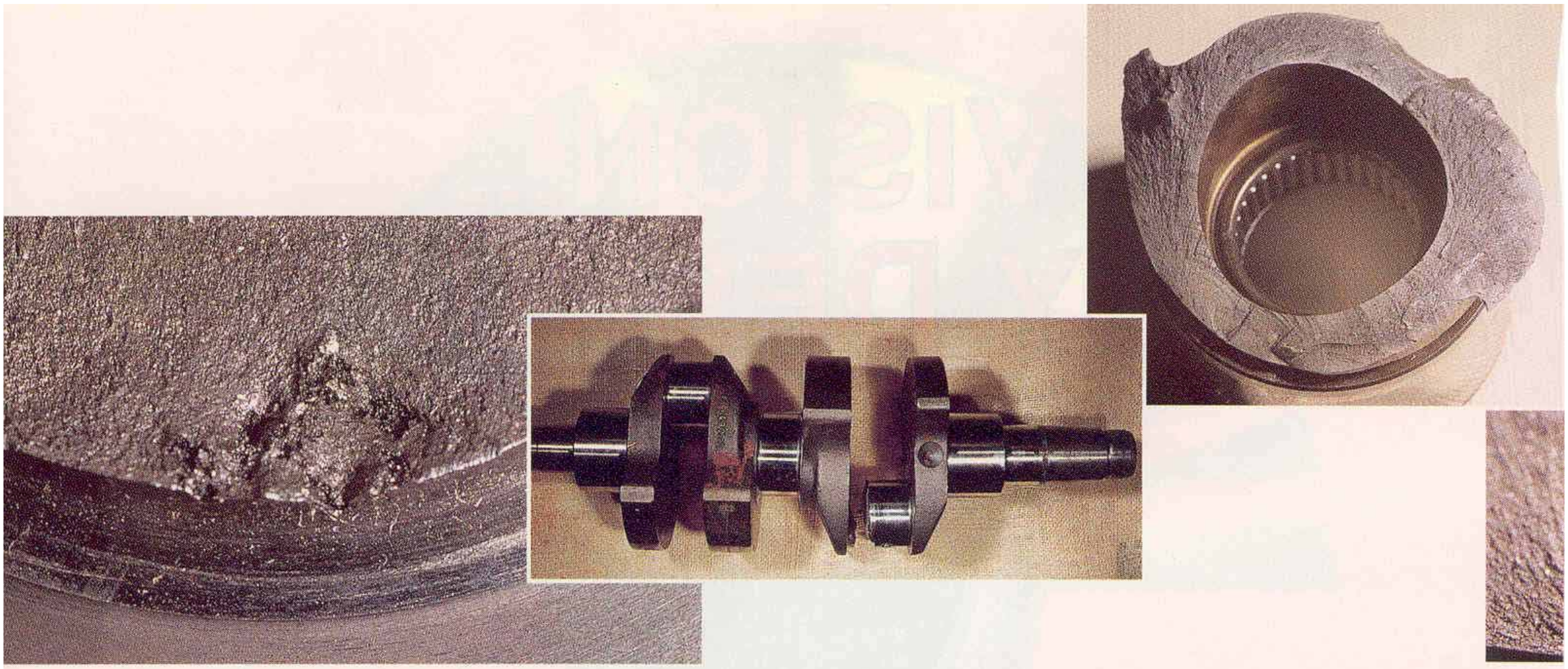


Analyzing Failed

It takes a trained eye to tell why rigging hardware, propulsion

Text and photos by Jonathan Klopman

I'll bet every professional in this industry has, at one time or another, been faced with the problem of deciphering why some critical metal component failed in service. As with most design considerations—and none more so than specifying equipment to survive the marine environment—proper material selection demands a balance of strength, weight, and corrosion resistance, all at a competitive cost. It's understandable that some parts simply wear out. What's more mysterious, though, are premature failures. Therefore, when pondering the early demise of, say, a "left-handed framis pin," many pros just throw their hands up in the air and leave the detective work to specialists.

The science of how and why parts fail has been extensively studied, but only since the end of the 19th century. Engineers working in heavy industry foresaw the need for this type of knowledge, as ever more powerful equipment began to exceed the material strength of component parts. A series of failures, for example, in steam locomotives spurred research that ultimately led to the development of high-strength steels.

Today, an array of advanced inspection techniques—including X-rays, ultraviolet radiation, and infrared spectroscopy—can be used to precisely identify constituent materials. Indeed, armed with scanning electron microscopes and electron microprobes, lab technicians can now photograph separate grains of a fracture surface and detect elements at the atomic level.

Most of us may never have the need for such in-depth services, but just a routine lab analysis can be valuable. Before you decide to get expert assistance, you ought to at least know how to conduct an initial inspection and write up an informal field report; this requires a basic understanding of why metals fail.

Much the same approach that goes into designing a device or structure is applied to figuring out why it failed. Fundamental engineering principles define materials and forces. In order to figure out why a part failed, the following questions must be answered:

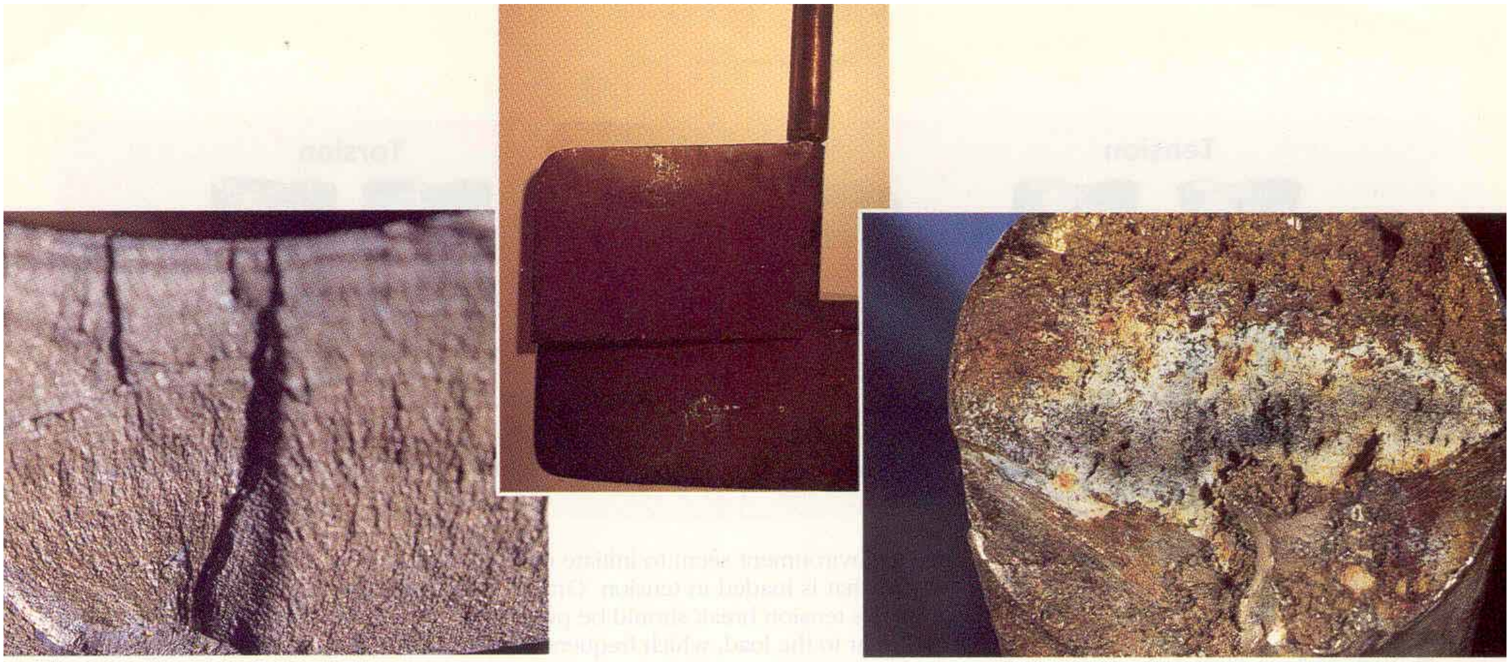
- What materials are in play and what are their properties?
- How was the part loaded?
- Where did the part fail, and does it show evidence of anomalies in construction, conditions, or use?

Material Properties

Ordinary metals can be classed as being either *ductile* or *brittle*. Softer, ductile metals would include aluminum, copper alloys, and mild steel. The principal brittle metals found in the marine industry are hardened steels used for machine parts. Some failure sites will show combined ductile and brittle qualities. This is typical in a case-hardened part, where a sharp, clean break through the protective case will turn rough as it tears through the softer steel core.

Ductile metals in severe overload will always show signs of *deformation*. As the part reaches its yield strength, it will buckle, twist, or "neck down" prior to ultimate failure. The shape and manner in which the part is bent often points to the precise way in which it was loaded at the instant of failure. The fracture surface of a ductile break frequently appears rough and woody. As the part yields and fails, the looser structure of the material tears between grain boundaries in a

Above, left*—This crankshaft from a 17-year-old 2-cyl diesel engine failed at the fillet of one of the journals. Close inspection reveals that the crack initiated at several small voids in the metal.* ***Middle two photos****—An aluminum outdrive upper-unit casting that failed just beneath a bearing carrier. The initiation site shows small "inclusions"— impurities—that lined up to create a catastrophic zipper effect in the part.* ***Facing page, right****—A failed bronze rudder and stock. Iron inclusions caused "segregation"—alloy elements separating out in the casting—which caused a weak spot in an area of high stress.*



Metal Parts

components, and underwater gear sometimes break in service

dynamic termed *microvoid coalescence.*

Brittle fractures, on the other hand, are far more difficult to read. By their nature, harder materials will not yield or deform prior to failure, which takes away some of the most obvious clues as to how the part was loaded. Instead, brittle metals tend to exhibit sharp transgranular breaks. Still, there are subtle indicators that show how a crack progresses or propagates. The key here is to identify these signs and trace them back to locate the initiation site.

Loads

After categorizing the material, the next step is to visualize the loads involved. Use what you know about how the part is designed to operate in order to deduce how tension, compression, and torsion were in effect at the time of failure. One, two, or all three forces may be involved. The fracture surface itself represents another stress—a shear plane—along which the part literally fails. As the diagram on page 58 illustrates, ductile and brittle materials behave differently when subjected to the same type of stress.

Tension—

Ductile metals in pure tension will neck down as the part passes its yield strength and deforms. Microscopic voids between the grain structure link up and enlarge as the metal begins to tear apart. Finally, the edges tear away at a 45° angle to the load. This sharp edge (*shear lip*) is a classic indicator of where the part ultimately failed. The pieces mate together in what is called a *cup and cone* failure.

By contrast, brittle metals under tension will break perpendicular to the applied load. There is no deformation, and the part leaves a clean, smooth break. A good example of brittle tensile failure in nature would be snapping an icicle in half. In the marine environment, Nitronic 50 stainless-steel rod rigging is designed as an ultra-high-strength (about 190,000 psi), relatively brittle alloy that is loaded in pure tension. When pull-tested to failure, the rod breaks in a clean line perpendicular to the load.

Compression—

Ductile metals overloaded in compression deform in a fairly predictable manner, depending on the shape of the part. A cylinder, for instance, will "barrel out" in compression, while a thin-walled tube will buckle. The important point to remember here is that a ductile metal does not crack in compression; it merely continues to deform.

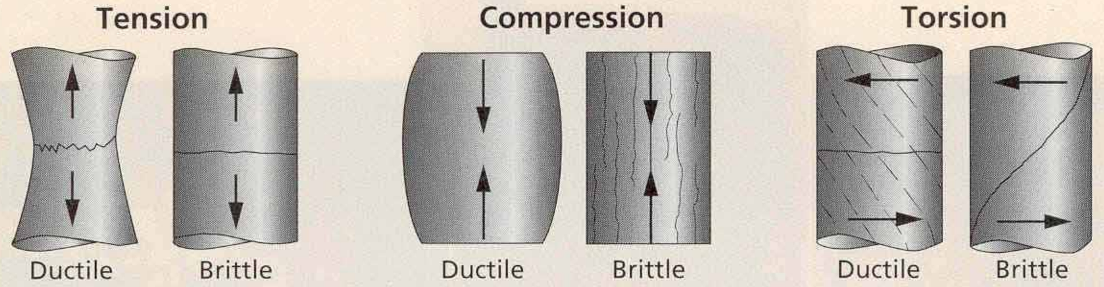
Brittle metals, on the other hand, fail in a pattern perpendicular to the load. Using the same example of the cylinder, a compression load creates force on the outside walls of the part. Since the material will not deform, it will bear the load up to failure, whereupon it splits along its length.

Torsion—

Ductile metals yield to severe twisting in the direction of force. The part continues to twist until it finally wrings off across the axis of torsion. Compared to the cup-and-cone fracture seen in tension, this torsional break will appear relatively flat.

Brittle metals in torsion exhibit the same resistance to deformation. The part will withstand the twisting energy until it finally fractures in a break that appears to be 45° to the axis of torsion. Actually, the material fails perpendicular to the load. Knowing this, note how the break twists in the direction opposite from which it was loaded.

In addition to the basic stresses discussed above, other forces may be at work within the part that can aid in describing a failure. Most notably, the part often fails due to shear stress tearing the grain boundaries of the material. Stress can even be engineered *into* a part. Some internal engine components, for instance, are pre-stressed by such processes as *shot-peening,* which induces a residual compressive stress on the outside of



Ductile and brittle materials behave differently under different loads. In pure tension, ductile metal will "neck down," and in compression, "barrel out." By contrast, brittle metals do not deform under load. Note the characteristic flat-break in torsion for a ductile part.

the part. The residual compression thereafter will make the part resistant to localized tension and fatigue failure in service.

Fracture

Time is an important question to answer in reconstructing a failure. Did the part fail from a sudden and massive shock load? A familiar example would be an outboard pinion gear that splits in two, rocketing through either side of the gearcase. On the other hand, did the crack initiate a year ago, and then gradually spread over a period of time? Determining overload vs. fatigue can be crucial in pinpointing the cause of failure.

Overload

If the damage was caused by a single massive overload, then the fracture site should reflect an uninterrupted occurrence. Initiation would be at the area of the part that receives the highest loading, or is structurally somewhat weaker. With the exception of pure torsion systems (like shafting), most failures in the marine environment seem to initiate on the face that is loaded in tension. Once again, this tension break should be perpendicular to the load, which frequently translates to a right-angle crack at the edge of the part.

Following initiation, the crack will widen and spread across the part toward final failure. As the metal shears, the front of the failure will fan out in a distinctive pattern across the part. The resulting *chevron marks* point back to the exact initiation site, and thus act as convenient indicators. These marks are quite common in ductile steel fractures.

Crack growth accelerates toward final failure. Naturally, since by this time the part has lost most of its strength, it will tear apart violently. Final failure is often accompanied by shear lips that ring the edge of the part at a 45° angle. Owing to the distinctive shape of shear lips and chevron marks, when you read the fracture surface of an overload, it is easier to identify the point of final failure and then work back to the initiation site.

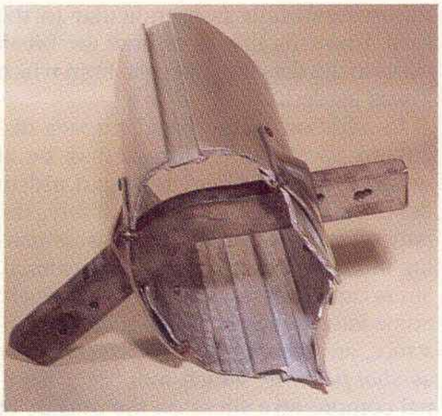
Fatigue

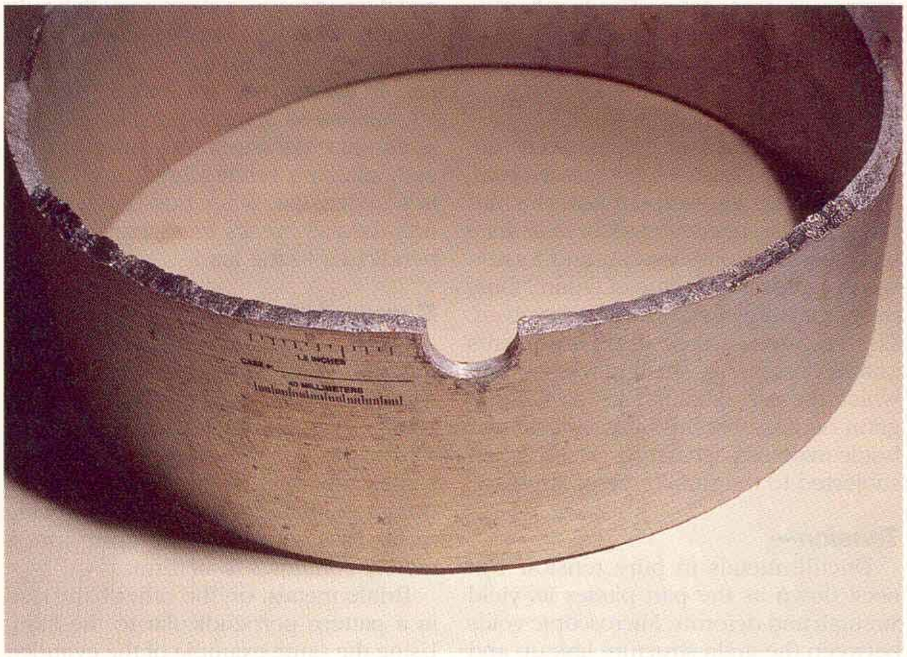
Metal can fail at levels far below its yield strength. This failure of the part over time and at normal working loads is usually referred to as *fatigue*. Fatigue is characterized by cyclic stress over time. The fatigue performance of a part can be studied and its ultimate failure predicted with an *S/N curve*, which plots stress against the number of cycles. Bending a paper clip back and forth 20 times would be an example of high-stress/low-amplitude fatigue. What is more frequently encountered, though, is low-stress/high-amplitude fatigue, where the number of cycles is expressed in the millions.

The design of a part and the presence of *stress risers* can greatly affect fatigue strength. This is not to say that any failure at a stress riser must mean fatigue was to blame. If you drill a hole into an aluminum tube, and then sharply bend the tube in a vise, the tube will overload and tear at the hole. But, if you stand the tube upright (as with a sailboat mast)

Continues on page 60

Below*—An aluminum mast that failed after a lower shroud let go. Deformation at the failure site is typical of a single-overload failure in ductile metal.*
Right*—This mast failed due to fatigue initiated by a hole drilled just below the partners. Note the black oxide and lack of deformation.*





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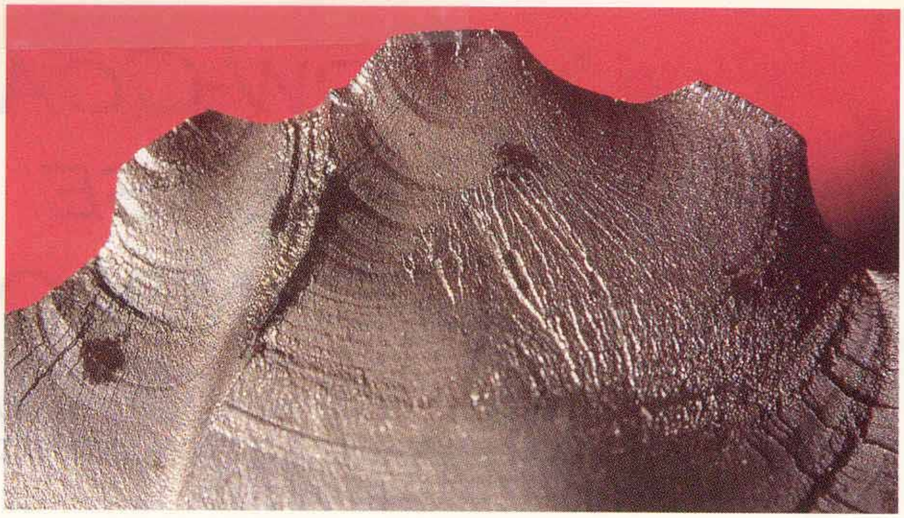


Above— *The splines on the lower end of this MerCruiser drive shaft tore off from impact. However, the "river marks" and ringed progression marks show that fatigue was involved as well: an old accident created a hairline crack that gradually led to the ultimate failure.*
Facing page— *In contrast to the above example, the upper splines of the same type of MerCruiser drive shaft tore off at the instant of impact. The close-up shows a smooth, uninterrupted torsion break across the surface of the stainless steel.*

and drill a hole in just the wrong spot, then the perfect dynamic for fatigue exists as the mast pumps back and forth.

The following are some unique identifying features that may be found in fatigue failure sites:

Ratchet marks are slight steps or notches, visible at the edge of the initiation site. These marks appear only at the surface, and blend into the fracture as the crack forms.

River lines are cleavage patterns of striations that resemble a river system, fanning out into a triangle of smaller tributaries. The light lines form at the initiation site, and then blend into a single larger line as the fracture gradually progresses. River marks are actually different stress planes in a brittle material, which combine as the crack becomes more severe.

Beach marks are smooth, semicircular bands that radiate away from an initiation site. The separate bands actually show the varying intervals at which the part was loaded and unloaded. These signs of crack progression leave a graphic "print" of how the part worked and fatigued prior to failure. Depending

on the forces involved, the beach marks may form either a single front, dual breaks (reversed, or back-and-forth bending), or concentric lines.

The importance of determining whether a broken chunk of metal failed from overload or fatigue should be clear. An outdrive manufacturer, for instance, cannot be expected to design for sudden overloads caused by striking large immovable objects like a granite ledge. On the other hand, if the same outdrive is mated to a more powerful engine, this may induce a fatigue failure at a stress riser in a part.

Evidence of fatigue failure might also prompt a more thorough examination of neighboring parts. Upon closer inspection, you might see that the entire unit had been involved in a prior accident (which may have initiated the crack, only to fail at a later date). Refer back to any statements made in a report regarding the conditions, sounds, and timing of the failure, and see if they support, or conflict with, the visible evidence.

Wear

Wear, especially in machine parts, can be studied to differentiate between normal and abnormal operation. Normal wear is termed *abrasive.* The abrasion can be caused by dissimilar metals or by debris. Wear occurs naturally, and can even be an intentional design factor. For example, the break-in period of an engine is a regime of controlled wear. Microscopic projections on the face of the cylinder (*asperities*) pierce the protective layer of lubricant and come into contact with the hard chrome piston rings. The rings shear

Above—*A broken aluminum propeller. "Microvoid coalescence"—a type of intergranular tearing—describes the fracture surface* ***(detail)*** *of a ductile material in single-overload condition.* ***Facing page***—*A bronze shaft strut that tore loose on impact. The fracture surface is similar to the rough tearing evident in the aluminum prop blade.*

off the tips of the asperities and displace them into a neighboring valley. This process effectively takes the freshly machined cylinder and smooths the surface to a perfect mate with the rings. The better the fit, the more consistent the layer of lubricant; hence, operating wear drops dramatically following the break-in period.

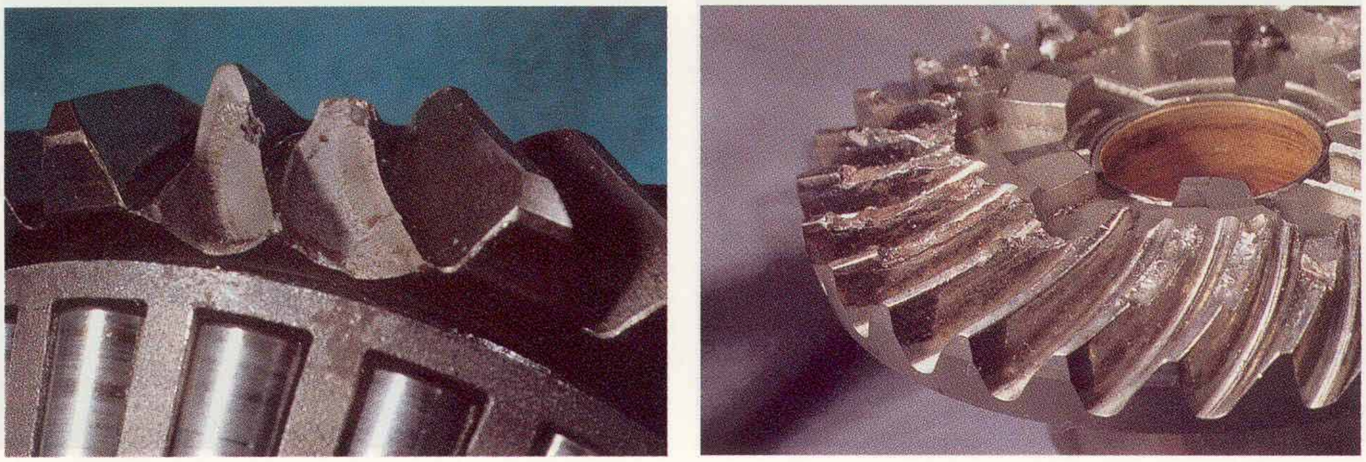
If there is a problem with the lubricant—such as incorrect viscosity, contaminatation, or prolonged overheating—then abrasive wear increases dramatically. The wear material will exceed the ability of the lubricant to wash it away, and debris begins to build up on both surfaces. In the example of an engine cylinder, the chrome rings will clog with aluminum (or iron, depending on the block casting), and so the contact will no longer be between dissimilar metals, one harder than the other. The debris heats up, and then "welds" onto the surface. This scuffing, scoring, or galling is more accurately termed *adhesive wear.*

Contact Stress Fatigue

Contact stress fatigue is a condition that describes several mechanisms that all create surface pitting. What is important here is that the pitting is associated with long-term wear or fatigue, as distinct from corrosion or impact-induced damage. *Surface pitting* can be found in machine parts that are subject to both rolling and sliding. In particular, the problem shows up on gear teeth just below the pitch line, and on cam followers. Marine transmissions and lower-unit gears would be good examples. The sliding component adds surface friction, which causes stress cracks to angle into the surface and eventually chip out a bit of metal. The pit enlarges in a distinctive arrowhead pattern, with the point facing the root of the tooth. The debris can cause the observed damage along with accelerated wear of other components, especially if the lubricant is not changed regularly.

Subsurface-origin pitting is present in rolling conditions, such as in bearings. The maximum stress on the part is actually just beneath the surface—no more than several thousandths of an inch. If there is a stress riser there, such as a nonmetallic inclusion (which we'll discuss in a moment), then a small crack will form. The chip of metal eventually flies out, leaving a pit. Since cost/benefit studies suggest that it is simply not economical to use microscopically pure metal for bearings, this particular condition is fairly common. What is debatable, though, is whether more damage will be caused by debris than by the minute loss of metal on the rolling surface.

Subsurface shear ("case crushing") is typical of prolonged overload. A gear that is improperly shimmed places an



Left— *The forward gear of an outboard motor that suffered a severe impact. The two teeth engaged at the instant of impact shattered and broke off—which is what properly loaded gear teeth are supposed to do.* ***Right***— *Gear-tooth failure on another forward gear, but here virtually all the teeth are damaged. In this case, the gears were improperly aligned, placing too much load on the tips of the teeth.*

imbalanced load on the teeth. The high loading will cause shear failure between the hardened case and the softer core. Unlike the relatively minor subsurface pitting mentioned above, subsurface shear causes large chunks of hardened case to tear off.

One clue to identifying this type of gear failure is a distinctive pattern on most of the teeth. In the case of impact failure, only the gear teeth that were engaged at the instant of failure were overloaded. A gear tooth that is properly shimmed will fail at the root, and the entire tooth tears out.

Fretting is a condition that induces fatigue in closely fitting parts. Unlike the types of metal failure mentioned above, fretting is not associated with moving parts. Instead, the fatigue cracking is initiated by vibration. One telltale sign that fretting occurred prior to failure is that an oxide film tends to form in the area of movement (black oxide on aluminum and light brown on steel).

Cavitation is often associated with corrosion, but this condition is more accurately associated with wear. Unlike the metal-to-metal contact previously described, the erosive element here is a liquid. The dynamic involves high-velocity impingement of the metal by a disturbed fluid flow. While cavitation is commonly associated with propellers, it can also be a problem inside pumps, cooling tubes, and water-injected elbows. Copper alloys and cast iron are particularly vulnerable to this type of erosion.

Defects

The term *defect* is misused regularly in the field. If an engine or assembly is torn down for repairs, and the cause of the problem points to a specific broken part, then the offending piece is often condemned out of hand as being "inherently defective." In fact, the incidence of failures that occur as the direct result of a defect is quite low. Defects are not a mysterious, invisible force; they're physical, and in most cases easily identified with the unaided eye.

Defects in Material—

Inclusions are nonmetallic compounds present in the casting or billet. The impurity creates a break in the grain structure that resembles a small plate. This discontinuity represents a weakness in the metal's otherwise tightly locked molecular structure. None of the metals employed in the marine industry are 100% pure, so inclusions can be expected in virtually any casting. The presence of a tiny inclusion deep within a part should not affect its strength. But, inclusions *can* become a problem if they are located close to a highly loaded area of the part. In extreme cases, the inclusion can act as a stress riser that initiates a fatigue crack.

The incidence of failures that occur as a direct result of defects is quite low.

Segregation can be a problem with alloy castings. Depending on the compounds used, an alloy casting may not be a perfectly homogeneous blend of the constituent metals. Some compounds tend to precipitate out, and this would create a weak spot in the material. Manganese bronze castings in particular, commonly used for underwater gear, can cause problems. Why? Because iron is often present in the alloy, added there for strength. The small rust stains seen on the surface of struts and rudders after they've been in service offer a graphic example of segregation. As with inclusions, if the deposits happen to line up with a stress riser on the part, they can act as a potential "zipper" for the formation of a crack.

Voids are another casting anomaly that must be expected in some parts. Trapped gases can result in significant mechanical weakness. As with a void in a fiber-reinforced plastic (FRP) laminate, a metal-casting void in a broken part, on close examination, appears to have radiused edges and a smooth finished surface (in contrast to the surrounding torn metal's grain structure).

Note, however, that the mere existence of any of the defects described above, anywhere on a fracture surface, does not necessarily mean they were the ultimate cause of the part's failure. The exact location of the defect should coincide with other evidence supporting a theory that the defect actually initiated a crack.

Defects in Workmanship—

Whenever you inspect a failure site, bear in mind how the piece was formed or fabricated. Mechanical failure that occurs coincidentally with a boating accident may be the result of unrelated damage. A closer look can reveal that poor workmanship was at fault.

Each fabrication process can produce latent stress concentrations in the part that could eventually lead to fatigue failure. Heat-treatment processes that are not controlled carefully can result in *quench cracking*. The same basic problem of improper cooling can cause cracked welds. On the other side of the equation, overheating can be just as damaging. In forging a part, portions of the billet may be heated close to the melting point. The localized effect is termed *burning*, and will result in a weaker grain structure. Yet another example: *forging laps* occur when folds are left inside the part during forming.

To actually pinpoint any of these discontinuities requires a solid understanding of the manufacturing processes involved—and additional testing. Still, the various defects cited here have one thing in common: they generally fail in fatigue. Once again, progression marks on the surface of a fatigue failure indicate a significant passage of time from initiation to final failure.

Defects in Design—

A *fatigue crack* that originated at the sharp corner of a cargo hatch of the tanker S.S. *Schenectady* "grew" until the deck suddenly gave away; the ship cracked in half and sank. All the metal parts on a boat—machine parts, spars, rigging, and shafting—are especially susceptible to stress risers. One of the most common occurrences would be fatigue cracking that initiates at the keyway on a shaft. In many cases, the point loading can be distributed, but not eliminated. Therefore, if a defect such as a void or inclusion happens to coincide with a highly loaded area of a part, that may be enough to initiate fatigue.

Surface discontinuities such as holes, grooves, or rings are stress risers. Still, given sound engineering to begin with, this should not ordinarily pose a problem. Original design specifications, however, may not allow for future modification. This is especially true of internal running gear in power plants. As an engine series is modified in the hope of producing higher power-to-weight ratios, the additional loading may exceed the safety factor of some internal parts.

An otherwise unexplained part failure may be due to *improper material specifications*. An older-model two-cycle diesel engine, for example, was originally rated at 150 bhp. The manufacturer offered a turbocharged version that bumped horsepower to 200. A third-party engine supplier took the same standard block, and by saddling it with oversized injectors and a big turbo, boosted the horsepower to 300.

Unfortunately, none of the internal gear was upgraded in the course of these modifications. Remember: this engine model was designed back when diesels were typically heavy and slow. Lab tests following the almost-inevitable engine failure revealed that the original design spec called for two-piece pistons of relatively low-strength steel. The additional loading brought about by hopping-up the engine caused one of the softer steel "ears" holding the pistons together to crack. The lower half of the piston promptly dropped into the crankcase; and the engine committed suicide with a connecting rod.

Successful failure analysis depends on gathering evidence and background information through careful field work. You can't reach reliable conclusions without properly preserving damaged parts, taking fluid samples, and noting operating conditions and history.

Protect the fracture surfaces (do not fit them together), oil them if necessary to prevent oxidation, and pack them in dry storage.

Another thing: *Take detailed photographs.* There is no better way to record "found" conditions and illustrate a technical report. But your photography has got to be good. Point-and-shoot cameras, Polaroids, and video cameras *cannot* produce quality images. Anyone who gets involved in this type of detective work should invest in a sophisticated 35mm SLR (single lens reflex) system, a close-up lens, and a book on *macro*-photography.

The objective in failure analysis is to reconstruct an event, to tell a story that has a beginning and an end. If you do your homework, make notes, and apply logic, and if you're reasonably able in the field, you can fit the pieces of the puzzle together. The greater goal here is to contribute to improving the overall reliability of marine-industry products. If future accidents are predictable, then they're preventable.

Clearly, this article is only an introduction to a broad and complex topic. Truly complicated metal failures deserve the attention of trained professionals.

The following sources have been helpful in advancing my own knowledge of this subject:

American Society of Metals International, Materials Engineering Institute, 9639 Kinsman Rd., Metals Park, OH 44073.

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Gordon, J.E., *The New Science of Strong Materials,* Princeton Science Library, Princeton University Press, Princeton, New Jersey.

Wulpi, Donald J., *Principles of Failure Analysis,* American Society of Metals International, 9639 Kinsman Rd., Metals Park, OH 44073.

About the Author: *Jonathan Klopman is a marine surveyor based in Marblehead, Massachusetts, and a contributing editor of* Professional BoatBuilder.

IMPORTANT TIPS:

- Don't jump to conclusions. Treat every situation as unique. Preconceptions may cause you to overlook important details.
- When there is conflicting information, the physical evidence itself will override any statements of condition and believed cause of failure that may have been provided to you.
- Do not become mired in the hypothetical.
- Look at *all* the parts for clues, not just the mangled ones.

—Jonathan Klopman