SHAFT FAILURE ANALYSIS

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Reference: Failure analysis of machine shafts @ Efficient Plant Magazine

SHAFT FAILURE ANALYSIS

There are only four basic failure mechanisms: corrosion, wear, **overload and fatigue.**

The first two—*corrosion and wear*—almost never cause machine-shaft failures and, on the rare occasions they do, leave clear evidence. Of the other two mechanisms, fatigue is more common than overload failure.
(NOTE: Keep in mind that many times corrosion will act in conjunction with fatigue loading to cause a shaft failure.)

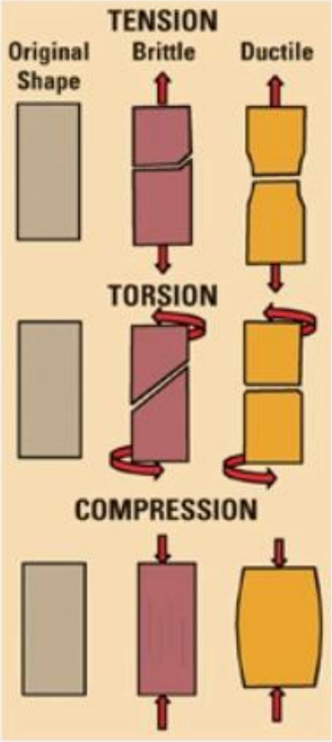


Fig. 1 The appearance of an overload failure depends on whether the shaft material is brittle or ductile.

SHAFT FAILURE ANALYSIS

Important Note: When Was the Failure Force Applied?

In diagnosing which mechanism caused the failure, a critical point to remember is that overload failures are generally caused by a single load application, while ***fatigue failures are always the result of a load applied repeatedly over many cycles.*** *This means if the shaft failed as a result of an overload, the force that caused the failure was applied the instant before the shaft broke. Conversely, if fatigue was the culprit, the initial force may have been applied millions of cycles before the final failure occurred.*

Photo 1. This shaft has been grossly overloaded by a torsional stress.

Photo 2. Occasionally, a ductile shaft will fail in a somewhat brittle manner, as this one did on a 200 hp, 3600 RPM motor that suddenly stopped running.

SHAFT FAILURE ANALYSIS

Overload failures

Overload failures are caused by forces that exceed the yield strength or the tensile strength of a material. As depicted in Fig. 1, the appearance of an overload failure depends on whether the shaft material is brittle or ductile. No shaft materials are absolutely brittle or absolutely ductile.

The shafts used on almost all motors, reducers and fans are low- or medium-carbon steels and relatively ductile. As a result, when an extreme overload is placed on these materials, they twist and distort. The bent shaft shown in Photo 1 has been grossly overloaded by a torsional stress.

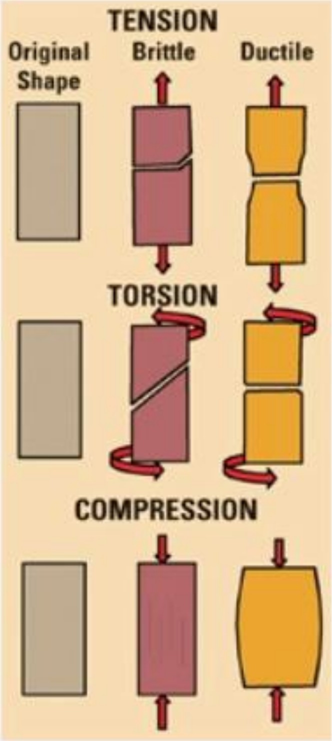


Fig. 1 The appearance of an overload failure depends on whether the shaft material is brittle or ductile.

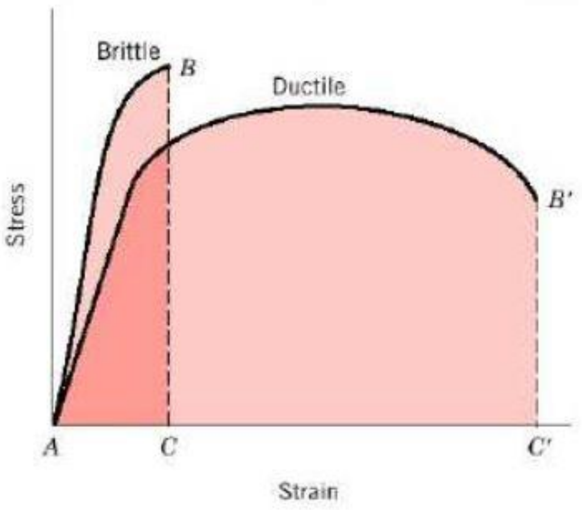
SHAFT FAILURE ANALYSIS

Overload failures

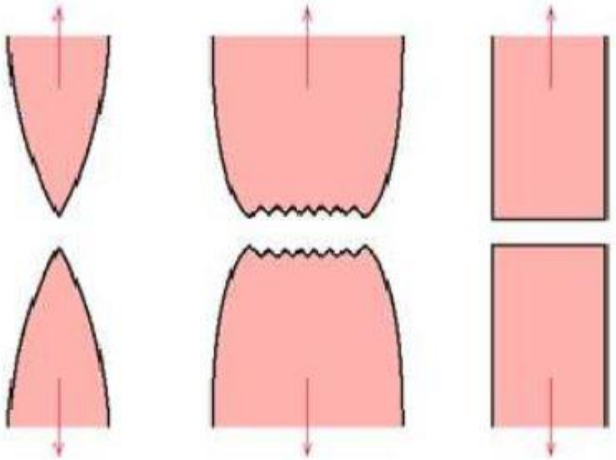
Ductile versus brittle failure

Ductile failure normally shows plastic deformation before failure while brittle failure can be quite abrupt without signs of materials deformation.

Ductile failure exhibits dull and fibrous surface with some signs of necking.



Comparison of stress strain curve of brittle and ductile material



pure ductile fracture

moderately ductile fracture

brittle fracture

SHAFT FAILURE ANALYSIS

Overload failures

There are occasional cases when a ductile shaft will fail in a somewhat brittle manner. Photo 2 shows an example of this situation—*i.e., what happened when a 200 hp, 3600 RPM motor suddenly stopped running*. The result was a huge torsional stress and a cracked shaft. But because the material is ductile, the angle of the crack it is not at the 45°position shown in Fig. 1, and there is obvious distortion of the keyway.

When ductile materials are grossly overloaded very rapidly, they tend to act in a brittle manner.

Photo 1. This shaft has been grossly overloaded by a torsional stress.

Photo 2. Occasionally, a ductile shaft will fail in a somewhat brittle manner, as this one did on a 200 hp, 3600 RPM motor that suddenly stopped running.

Overload failures

Brittle Fractures

Brittle fractures of machine shafts are extremely rare. Like all brittle fractures, they are characterized by a relatively **uniform surface roughness**—*the crack travels at a constant rate, and surface features called "chevron marks" are evident.*

Photo 3 shows the brittle fracture of the input shaft of a large reducer that was dropped. The "chevron marks" are the fine ripples on the surface that all point just to the left of the keyway.

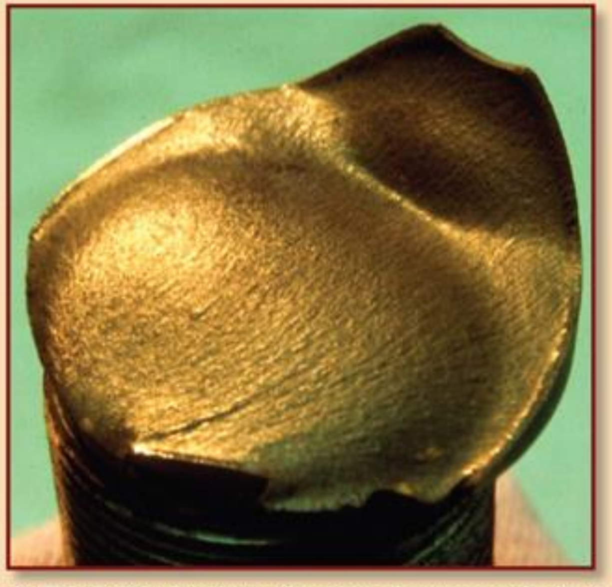


Photo 3. This brittle fracture, showing chevron marks just to the left of the keyway, occurred when the input shaft of a large reducer was dropped.

SHAFT FAILURE ANALYSIS

Overload failures

Brittle Fractures

Occasionally, a portion of a machine shaft will be case-hardened to reduce the wear rate. (NOTE: Case-hardening is usually done solely for wear-resistance purposes.)

Photo 4 shows the case-hardened splined section of a hydraulic pump shaft, including its hardened case, **the ring around the circumference with a very different texture than the majority of the shaft and “chevron marks” that point to the origin of the damage.**

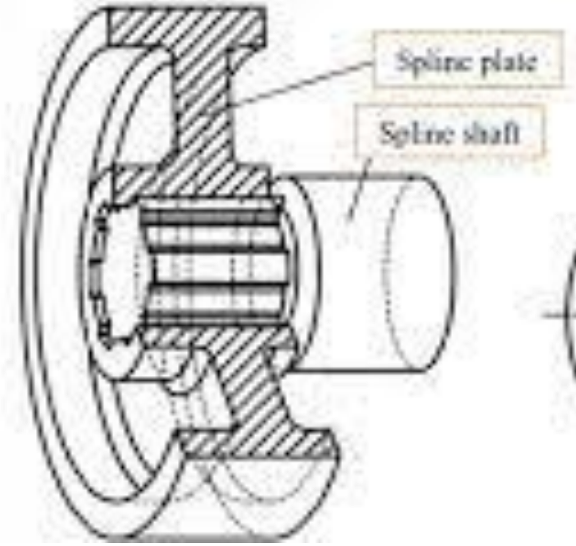
Based on how this fracture grew straight across the shaft, the cause could have been related to either bending or tension. Its relatively uniform surface, though, would indicate that this fracture is of a brittle nature—*which also means it was caused by a single force application*.

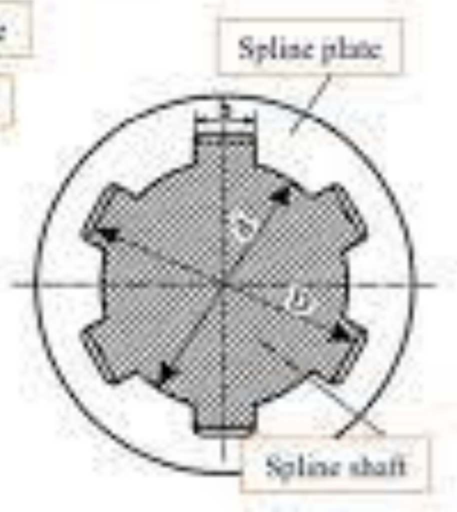
Furthermore, since it’s impossible to put significant tension on a spline, the analyst could safely say that a single bending force caused the failure.

Photo 4. This case-hardened splined section of a hydraulic pump shaft shows evidence of a brittle fracture caused by a single bending force.

Overload failures

Splines are grooves or teeth on a shaft that match up with grooves or teeth on another component to transmit torque.





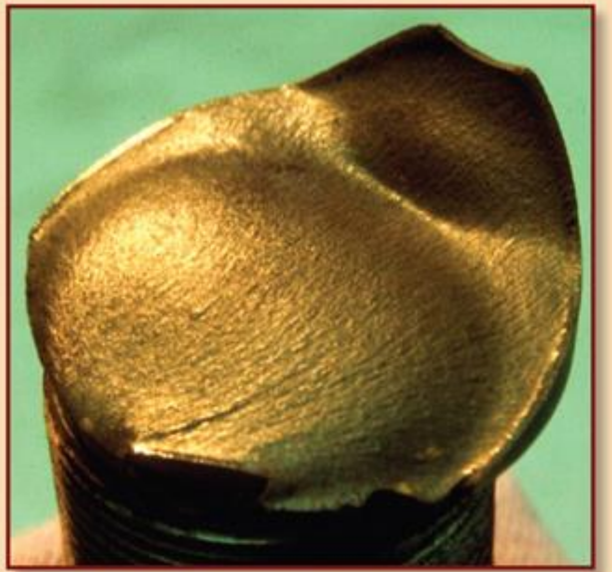


Photo 3. This brittle fracture, showing chevron marks just to the left of the keyway, occurred when the input shaft of a large reducer was dropped.

Photo 4. This case-hardened splined section of a hydraulic pump shaft shows evidence of a brittle fracture caused by a single bending force.

SHAFT FAILURE ANALYSIS

Fatigue failures

Fatigue is caused by cyclical stresses, and the forces that cause fatigue failures are substantially less than those that would cause plastic deformation.

Confusing the situation even further is the fact that corrosion will reduce the fatigue strength of a material. The amount of reduction is dependent on both the severity of the corrosion and the number of stress cycles.

Once they are visible to the naked eye, **cracks always grow perpendicular to the plane of maximum stress.** Figure 2 shows the fracture planes caused by four common fatigue forces.

Because the section properties will change as the crack grows, it's crucial for the analyst to look carefully at the point where the failure starts to determine the direction of the forces.

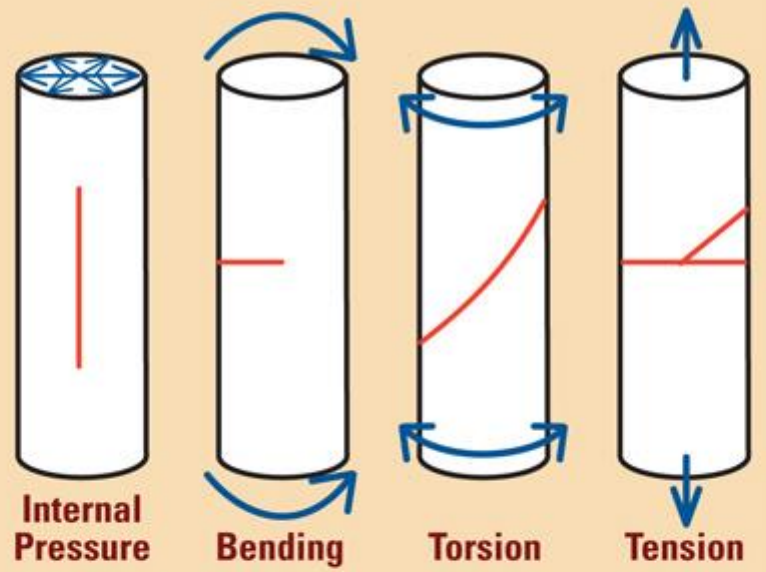


Fig. 2. Fracture planes caused by four common fatigue forces: Because the section properties will change as the crack grows, it's important to look carefully at the point where the failure starts to determine the direction of the forces.

SHAFT FAILURE ANALYSIS

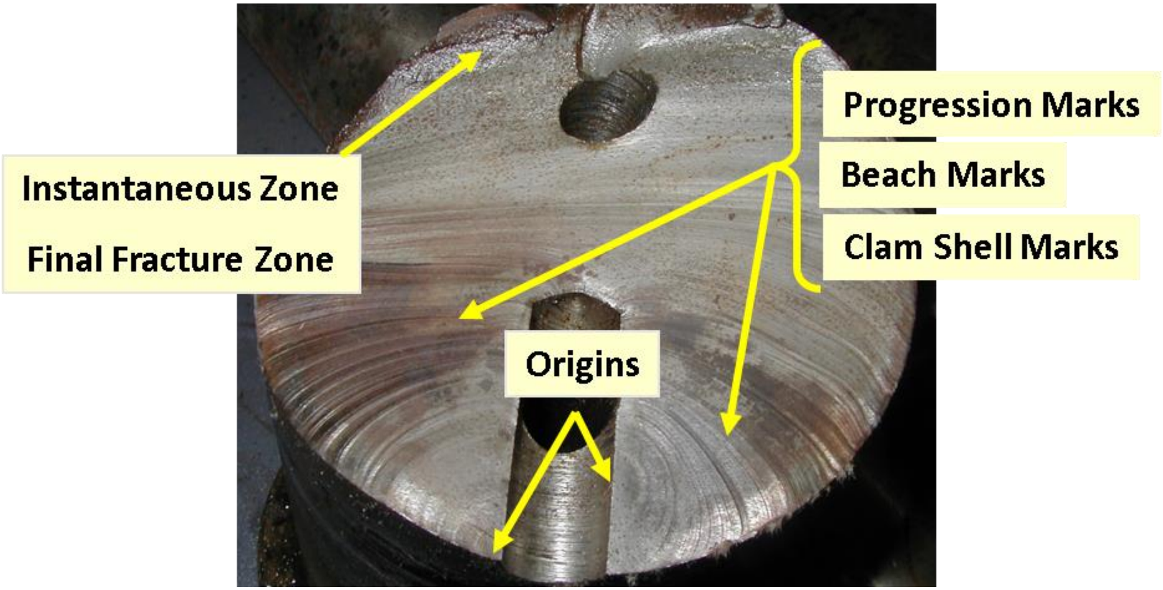
Fatigue failures

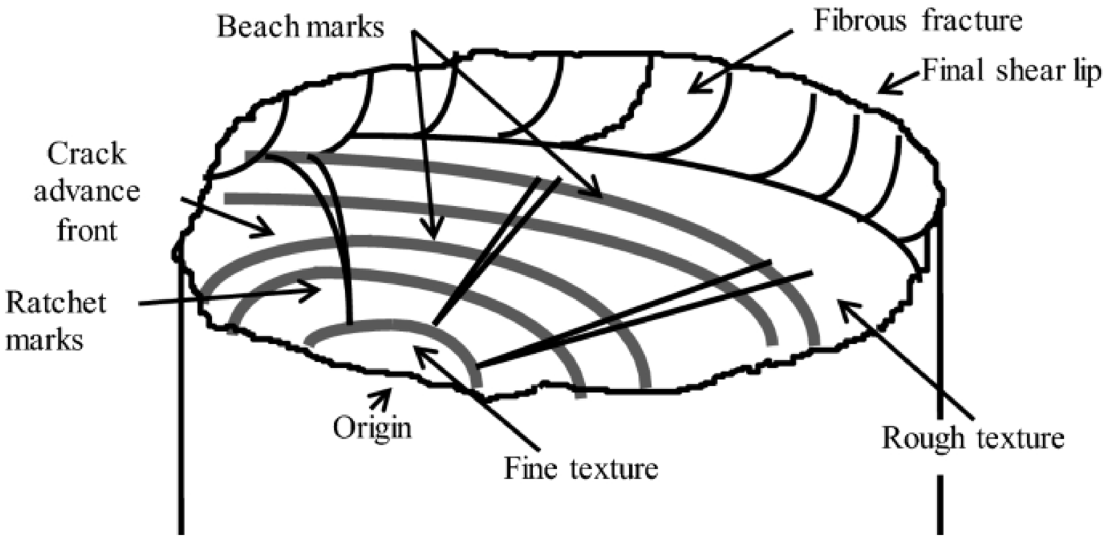
The condition or roughness of the fracture surface is one of the most important points to look at in analyzing a failure because of the difference between overload failures and fatigue failures.

With overload failures—*because the crack travels at a constant rate*—the surface is uniformly rough.

Fatigue-induced cracks, however, travel across the fracture face at ever-increasing speeds. **As a result, the typical fatigue fracture face is relatively smooth near the origin(s) and ends in a comparatively rough final fracture.**

Fatigue Failure





Fatigue failures

A typical plain **bending fatigue** failure is depicted in Fig. 3. The crack started at the origin and slowly grew across the Fatigue Zone (FZ).

When it reached the boundary of the Instantaneous Zone (IZ) the crack growth rate increased tremendously and the crack traveled across the IZ at approximately 8000 ft/sec.

During the period of growth across the FZ, there may be changes in the loading on the shaft, which result in changes in the surface that appear as progression marks.

A valuable feature of fatigue-failure interpretation is that the crack growth, i.e., the surface appearance, tells how the load was applied. **If the crack grows straight across the shaft (as shown in Fig. 3), the force that caused the failure must have been a bending load operating in a single plane.**

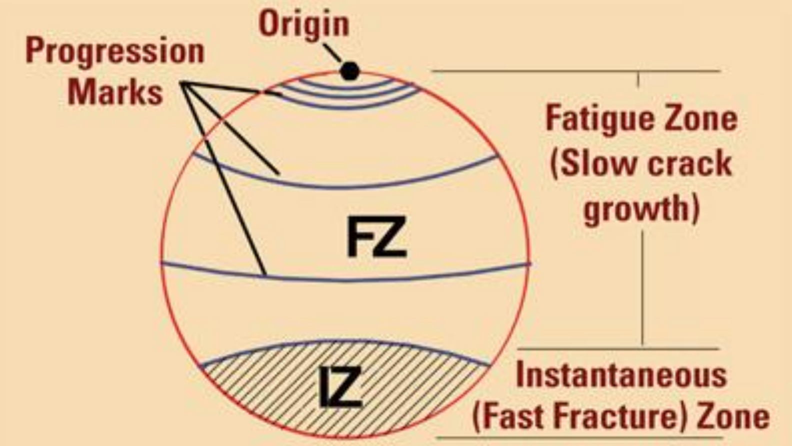


Fig. 3. This typical plane bending fatigue failure shows how a crack starts at the origin and slowly grows across the Fatigue Zone. When the crack reaches the boundary of the Instantaneous Zone, its growth rate increases significantly.

Fatigue failures

Figures 4 and 5, however, show examples of **rotating bending.** The difference between these two failures is that the shaft in Fig. 4 has a single origin, while the fracture in Fig. 5 has multiple origins.

Looking at the two sketches, we see the IZ of Fig. 4 is the larger of the two—*which indicates that* ***the load on the shaft when it failed was greater than that on Fig. 5.***

The analysis also shows that, even though Fig. 5 was less heavily loaded, it had many more fracture origins, an indication of a high stress concentration, such as a shaft step with a very small radius. The ratchet marks are the planes between adjacent crack origins and grow perpendicular to the crack propagation.

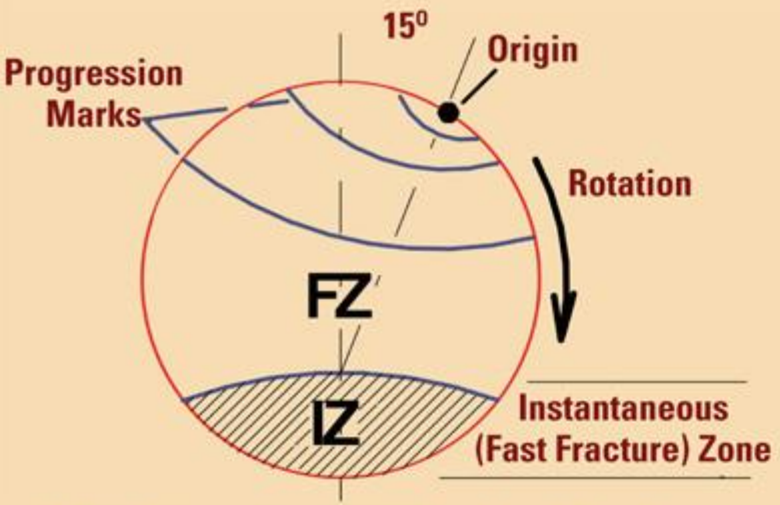


Fig. 4. In this example of rotating bending failure, the fracture has a single origin (and the load on the shaft when it failed was greater than that on the shaft in Fig. 5 when it failed).

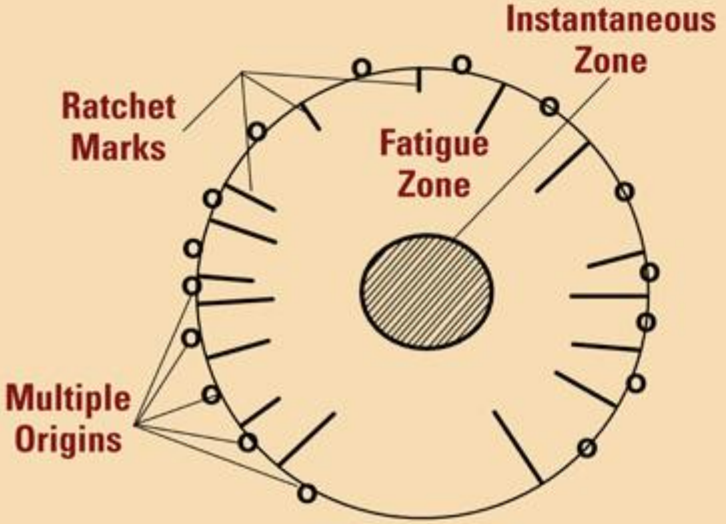


Fig. 5. Analysis of this rotating-bending failure (with its multiple fracture origins) showed that the shaft was less heavily loaded than that in Fig. 4 when it failed.

Fatigue failures

Photo 5 shows a 200 hp, 1180 RPM motor shaft that failed in less than a day. **No progression marks means the fatigue load was constant.**

The instantaneous zone is relatively large, indicating the shaft was heavily loaded. **Cracking started at numerous locations around the shaft, pointing to rotating bending as the cause.**

So many ratchet marks concentrated on the top and bottom of the photo make us suspect the shaft may not have been straight.

Inspection, though, would indicate the root cause was associated with the belt drive. In fact, the sheaves were worn so badly that the belts were riding in the bottom of the grooves. This situation approximately doubled the shaft bending stress.

Photo 5. The shaft on this 200 hp, 1180 RPM motor failed in less than a day as a result of badly worn sheaves on the belt drive.

Fatigue failures

The drive shaft in Photo 6 was on a steel-mill elevator. The surface is smoothest near the root of the keyway and became progressively rougher as the crack grew across the shaft.

Numerous progression marks surrounding the tiny IZ and the change in surface condition about 40% of the way across the shaft from the IZ suggest something changed during the crack growth or that the elevator was not used for an extended period.

These features are indicative of a slow-growing failure—*and the fact that fretting corrosion may have substantially reduced the fatigue strength.*

Photo 6. This slow-growing failure on a steel-mill elevator drive was initiated by fretting corrosion that substantially reduced the fatigue strength on the shaft.

Fatigue failures

Torsional fatigue failures

Until the advent of variable speed drives (VSDs), torsional fatigue failures were rare. Equipment designers could anticipate operating speeds and excitation frequencies and engineer around them.

The purpose of a VSD is to allow operation at a wide range of speeds.

That, unfortunately, has led to many motor and driven-shaft failures due to torsional-fatigue factors. While the most common torsional fatigue cracks start at the sharp corner (stress concentration) at the bottom of the keyway when couplings are poorly fitted, another common appearance is the diagonal shaft crack (like that shown in Fig. 2).

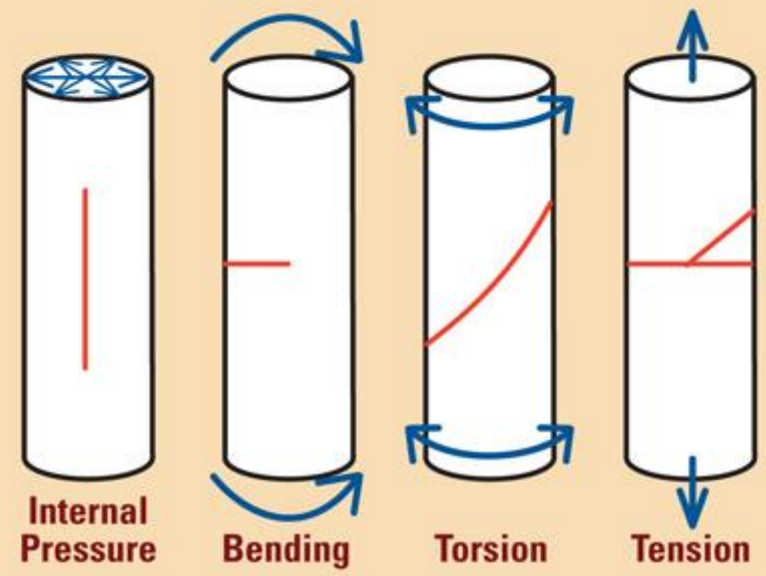


Fig. 2. Fracture planes caused by four common fatigue forces: Because the section properties will change as the crack grows, it's important to look carefully at the point where the failure starts to determine the direction of the forces.

Fatigue failures

Torsional fatigue failures

Photo 7 reflects the battered end of a motor shaft with a terrible (loose) coupling fit that let the hub repeatedly drive the key against the side of the keyway until a fatigue crack developed.

Photo 8 shows both halves of the torsional-fatigue failure of a fan shaft in a plant that had recently changed to a VSD. The 45° angle to the central axis is a sure sign of torsional stresses, and the change in surface roughness across the shaft indicates the cause was fatigue forces.

Photo 7. The terrible (loose) coupling fit on this motor shaft allowed the hub to repeatedly drive the key against the side of the keyway until a fatigue crack developed.

Photo 8. The torsional fatigue failure of this fan shaft occurred shortly after the installation of a variable speed drive.

Fatigue failures

Torsional fatigue failures

For example, both of the pump shafts shown in Photo 9 failed due to torsional fatigue aggravated by a reduction in strength caused by corrosion. Some might look at the fracture face of the shaft on the right and think it was caused by rotating bending. Closer examination of the many ratchet marks shows they are at a 45° angle to the centerline of the shaft—*a positive indication of torsional fatigue stresses with numerous origins*. (Note that the ratchet marks seen in Photo 5 have straight sides, an indication that they were caused by bending forces.)

Photo 9. These pump shafts failed due to torsional fatigue aggravated by the reduction in strength caused by corrosion, not because of rotating bending.

Photo 5. The shaft on this 200 hp, 1180 RPM motor failed in less than a day as a result of badly worn sheaves on the belt drive.