

# Understanding Factors That Cause Shaft Failures

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Shaft failures do not happen everyday, but when they do, it can be a challenge to determine the cause of failure. Here's a technical explanation of what happens when the shaft bends or breaks.

To understand shafts and why they fail, you need to understand the relationship between stress and strain for steel.

*Stress* is the force carried by a material per unit area, measured in *psi* (pounds per square inch) or *Mpa* (Megapascals or Mega Newtons per square meter). If a material is under tension, the stress is acting to pull apart the molecules that make it up, making it longer; if the material is under com-

pression, the stress is pushing the molecules together, causing the material to get shorter (and fatter as the compressed material "bulges" outward) if enough stress is applied (see Figure 1).

*Strain* is the change in the length, or elongation per unit length, of a material under a tensile stress.

Most shafts are made of hot-rolled carbon steel, but for more specialized loads or environments, you may see shafts that are made of alloyed or stainless steel. When a tensile stress is added to a material, the material begins to deform at a certain level of stress. This applies to steel, wood,

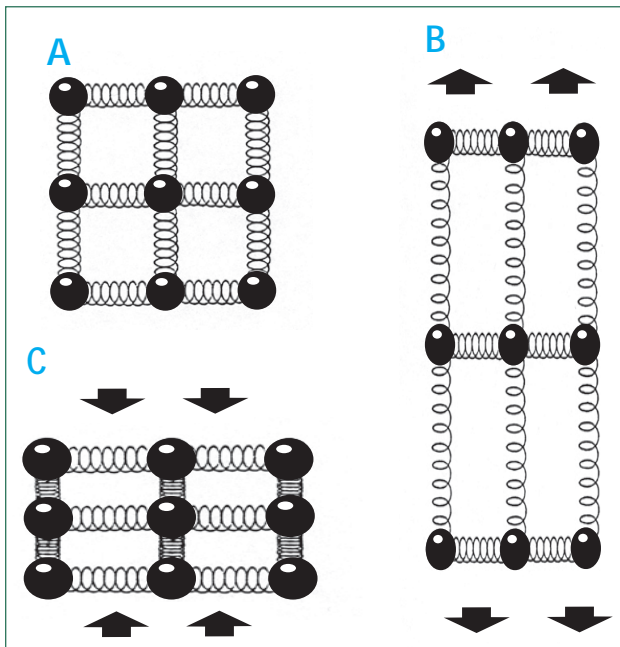


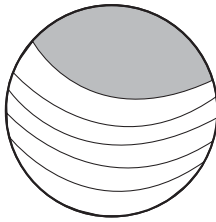
Figure 1. Simplified model of the distortion of molecules under stress: (A) Material in neutral state. (B) Material under tension. (C) Material under compression.

## Glossary of Terms

- Stress** – The force carried by a material per unit area normal to the force direction.
- Strain** – The elongation per unit length of a material.  $CE = \Delta L/L$  where CE is the strain and L is the original length of the material.
- Tension** – A stress that produces an elongation of an elastic physical body.
- Compression** – A force that attempts to push molecules of a material closer together.
- Elastic Material** – An object behaves elastically if it returns to its original shape after a force is applied and then removed. (If an applied force causes a permanent deformation, the behavior is termed *plastic*.)
- Plastic Deformation** – Deformation that remains after the load causing it is removed. It is the permanent part of the deformation beyond the elastic limit of a material.
- Maximum Tensile Strength** – The maximum stress that a material can withstand. In tensile testing, the ratio of maximum load to original cross sectional area. Also called **Ultimate Tensile Strength**.

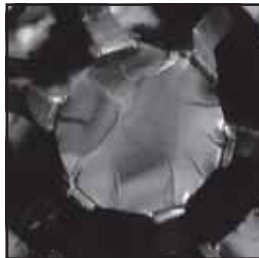
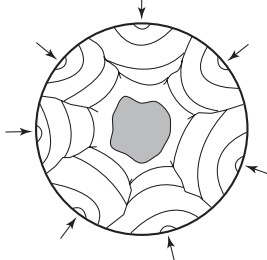
## Appearance of the Most Common Shaft Failures

### BEACH MARKS (CLAMSHELL, CONCHOIDAL)



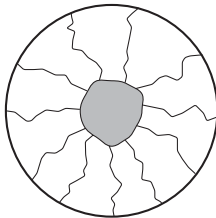
Beach marks indicate successive positions of the advancing crack front. The texture of the marks is usually smooth near the origin and becomes rougher as the crack grows.

### RATCHET MARKS (RADIAL STEPS)



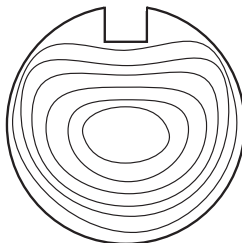
Ratchet marks are the telltale sign of several individual cracks that ultimately merge to form a single crack. Ratchet marks are present between the crack origins.

### CHEVRON MARKS



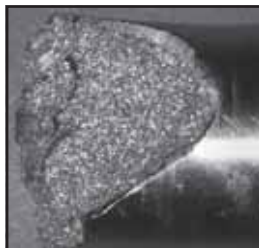
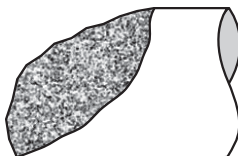
Chevrons, or arrows, point to the origin of the crack. Rotational bending fatigue failures occur when each part of the shaft is subject to alternating compression and tension under load. A crack can start at any point on the surface where there is a stress raiser.

### HELICAL (TORSIONAL)



Torsional failures have a "twisted" appearance. Their appearance will depend on the amount of torsional loading and whether the material is ductile or brittle. This particular shaft shows some twisting before failure. If the shaft material is ductile, it will twist more before failing. If the shaft is more brittle, or subject to extreme torsion, the fracture will have a rougher appearance.

### BRITTLE FRACTURE (TORSIONAL)



A brittle failure due to a sudden torsional load results in a diagonal break with a rough surface. Possible causes include an equipment jam, high-impact loading or a voltage transient.

concrete or any other “engineering” material. In the case of a motor shaft, the material is steel.

The deformation due to the tensile stress is elastic until the stress reaches its yield strength point for the steel (typical carbon steel = 73000-psi or 503-Mpa). The yield strength will vary with the material. For example, a 416 stainless steel shaft, while offering corrosion resistance, will actually have slightly lower yield strength than a typical 1045 hot-rolled carbon steel.

## Effects of Deformation

If the stress applied to a shaft is below the yield strength, when the stress is removed there is no permanent change in the molecules of steel. *Elastic deformation* simply means that the steel shaft will return to its original shape and dimensions when the force is removed. In other words, if you apply enough force to deflect the shaft, and release the force, it will spring back to the original position.

Strain is measured by the percent of deformation, and the yield strength is the point where the strain is equal to 0.2 percent deformation. If the applied stress is greater than the yield strength, then the deformation becomes plastic and the steel will not return to its original shape. That is, if you bend it past the yield strength, it remains bent.

Even if the shaft is straightened, it will still be weaker than before it was bent. This is why we should always consider the application before deciding whether to straighten a shaft or replace it. The *maximum* (or *ultimate*) *tensile strength* is the point at which the material is just about to fracture.

## Tensile vs. Brittle Strength

Materials can be classified as ductile or brittle. A material that undergoes extensive plastic deformation before fracture is called *ductile*. This simply means that it can bend (as opposed to it “snapping”) before it finally breaks.

Figure 2 shows a stress-strain diagram for an elastic material. Point A is the yield strength, Point B is the maximum tensile strength, and Point C is the point at which the material breaks. Even if the stress between points A and B remains stable, the strain will continue to cause deformation, where the molecules are changing position and forming new bonds within the material.

A *brittle* material can undergo only a small amount of plastic deformation before breaking. A glass rod is a good example of a brittle material. You cannot bend it, but if enough force is applied, it snaps. A perfectly brittle material will break exactly at the yield stress point, as shown in Figure 3.

Carbon steels used to make shafts are relatively ductile materials. However, shafts are manufactured with steps of different diameters along the length. These steps are stress raisers where a failure is more likely to occur. Even though the material is ductile, in the presence of a sharp radius at the step, the steel will act more like a brittle material and may fail before it reaches the maximum tensile strength point. If you’ve ever broken a bolt, you realize that they usually break at the bolt head or the

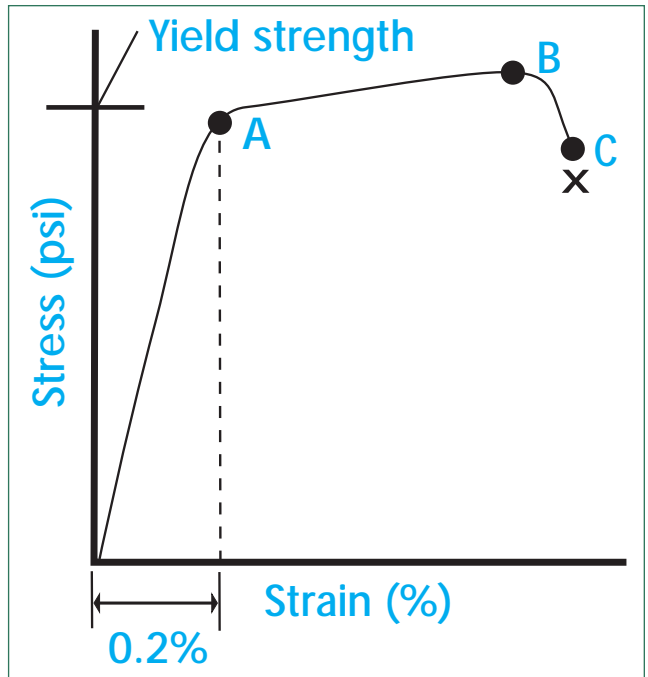


Figure 2. Stress-strain diagram for an elastic material.

first thread. Those are both stress raisers.

As the stress on the shaft increases, the elastic behavior stops and the material enters the plastic deformation range, where irrevocably internal changes take place within the steel. If the stress is removed, then the shaft will not return to its original dimensions. If the stress continues or increases, the shaft may bend or break, resulting in a catastrophic failure.

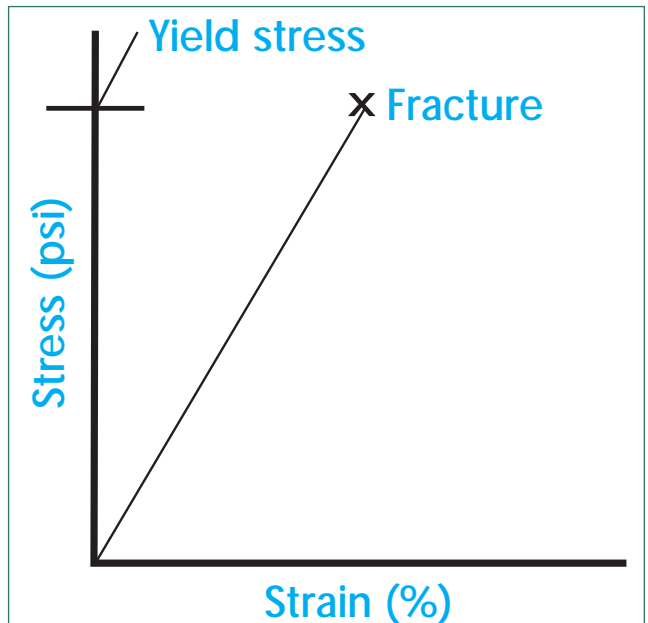


Figure 3. Stress-strain diagram for a perfectly brittle material.

## Ductile vs. Brittle Failures.

### Fracture in a Shaft

A break or fracture in a shaft is almost always initiated at some imperfection on the surface, such as a microscopic crack, and accompanied by a stress concentration (or stress raiser) at the tip of the crack.

With the applied stress (rotational bending, overhung load, cyclical loading, etc.) on the crack, the bonds between the molecules of the steel break and the crack spreads across the shaft. Depending on the amount of stress, the process of crack propagation may be very slow or very fast. The higher the stress, the more brittle a shaft failure will appear. Over time, there may be different rates of growth of the crack, depending on loading conditions.

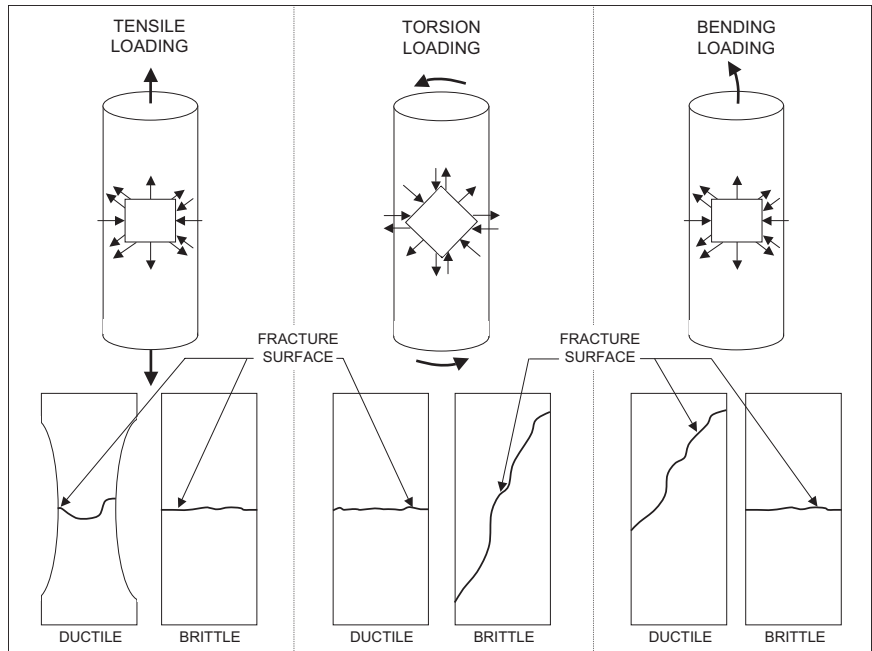
We can tell whether the fracture was slow or sudden by looking at the break. The rougher the texture, the faster the break. If several regions of different texture are visible, we know the crack grew slowly, and "sped up" as the crack became larger.

Compare the starting region to 220-grit sandpaper, and the final region may look more like 60-grit. Shaft failures due to bending are the result of a combination of tension and compression. The appearance of the shaft makes sense: if we bent the shaft to breaking, the pattern would indicate the direction it was bent. A rotational bending failure looks sort of similar to this in each direction.

There are three different kinds of ductile and brittle failures for shafts, depending on the type of loading – tensile, torsional, and bending. The surface of the fracture will normally reveal a clue to the magnitude of the load. This means if the appearance is very brittle, then the failure occurred very quickly. If the failure is very ductile or smooth, then the crack propagated for some time.

The full-page chart featured earlier in this article shows the appearance of the most common shaft failures. The majority of shaft failures are fatigue related, due to excessive rotary bending. Almost all shaft failures occur at the point of a stress raiser, typically at the bearing shoulder or the keyway.

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