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Understanding the Surface Features of Fatigue Fractures: How They Describe the Failure Cause and the Failure History

Most of us have been exposed to fatigue failures since we first started looking at broken pieces. In many cases, the first explanation of a failure began with a well-intentioned person explaining that a component had "crystallized" because it was a piece of defective steel. However, as we know, virtually all structural metals are crystalline, and after working with fatigue analysis for a while, it becomes apparent that defective materials are not common failure causes. Additionally we learn that the fracture face can provide a wealth of information about the causes. It can show the type and direction of the forces acting on the part, the magnitude and fluctuations of these forces, and can give a general indication of the length of time from initiation to final fracture. This paper is a review of a selection of fracture faces and the descriptions of how to interpret some of the details on these faces.

Figure 1 shows the major surface features seen on almost every fatigue face. The *origin* is where the crack actually started. The crack then grew slowly across the *fatigue zone,* with a typical growth rate averaging approximately 10^{-6} in./stress cycle. During this slow crack growth, there were variations in the load that resulted in corresponding variations in the crack growth rate that appear as *progression marks.* Eventually, the crack reached the point where the remaining material was overstressed, and the overload zone resulted. In the *overload zone,* most cracks grow as macroscopically brittle fractures, and the crack growth rate is approximately ½× the speed of sound in the piece. However, the overload zone may develop by either ductile or brittle fracture mechanisms.

Each of these features deserves more of an explanation:

- A single origin *usually* indicates a failure with low overstress, while the presence of multiple origins may be the result of either high stress or high stress concentrations.
- The *fatigue zone* is the area of slow crack growth. There are low-cycle fatigue failures where the crack growth occurs over relatively few cycles, frequently less than a hundred. However, in most of the machinery failures analyzed by the author, the crack has taken between 400,000 and 20,000,000 cycles to grow across the fracture face. The plane of this fatigue zone is very important, because it develops perpendicular to the plane of maximum stress in the part, thus helping the investigator to understand the source of the stress.
- The *progression marks* show how the crack has grown and are only present in fractures where there have been substantial variations in the component stress as the crack grew across the piece. (The traditional name for these indicators has been *beach marks,* because they frequently look like the lines that waves leave on a sandy beach. However, *progression marks* is a much more descriptive term, because these lines tell us exactly how the crack face has progressed across the piece.) There are actually two mechanisms that generate progression marks. Most commonly, they are seen in the older portion of a failure, where they show gross changes in load, such as startup and shutdown forces. However, in the latter stages of a fracture life, they show the individual stress cycles.

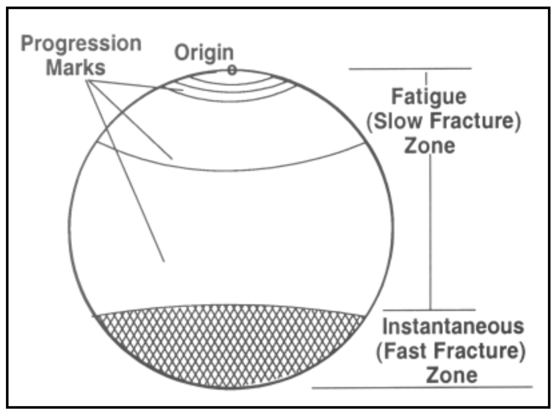


Fig. 1 Macroscopic surface features

One frequently hears of confusion between progression marks and *fatigue striations.* Fatigue striations show each stress cycle experienced by the part and are generally visible only under extremely high magnification, while progression marks are visible to the naked eye (Fig. 2). Also, in many alloys, such as austenitic stainless steels, fatigue striations are very difficult to detect, while in others, for example most of the aluminum alloys, striations are relatively easy to find.

- The *overload zone,* or fast fracture zone, is the portion of the piece where the final catastrophic failure occurs. This zone is usually macroscopically brittle, although in a small percentage of the pieces, ductility is present. In this area, the crack propagates at approximately ½ the speed of sound in the material. The size of the overload zone indicates the magnitude of the load when the final fracture occurs; that is, a large overload zone indicates the part was heavily stressed at the time of final fracture. Note, however, that if there are large changes in the load over time and many progression marks, this final fracture load could differ greatly from the load at the time of crack initiation.

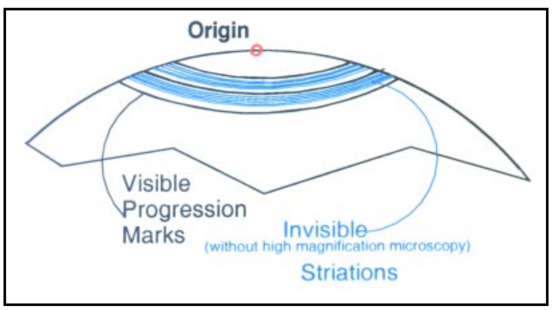


Fig. 2 *Progression marks*

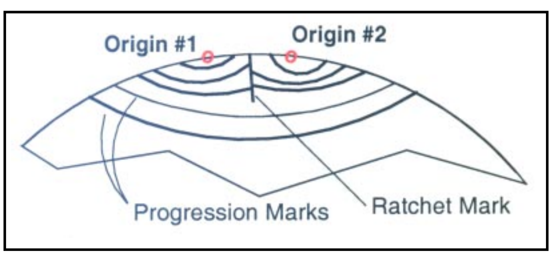


Fig. 3 *Ratchet mark added*

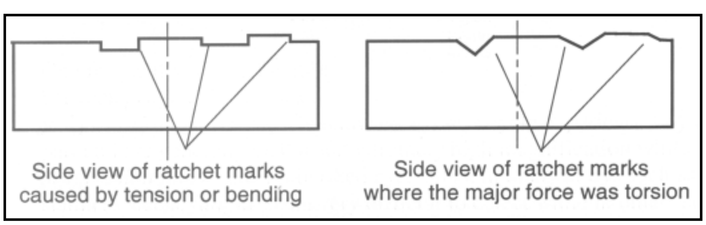


Fig. 4 *Two similar appearing sections of shaft failures resulting from different causes*

There are two other important surface features of fatigue failures that have not been mentioned. The first of these is the *ratchet mark.* In Fig. 3, a ratchet mark indicating the boundary between two adjacent failure planes has been added to Fig. 2. One can see that there are two crack origins, and the ratchet mark is between them. The presence of ratchet marks indicates multiple origins and relatively high total stresses. Ratchet marks can result from either high stress on the part or from high stress concentrations. However, by looking at both the ratchet marks and the size of the instantaneous zone, one can generally understand whether the load or the stress concentration was the major cause of the fracture. For example, the combination of many ratchet marks and a small overload zone indicates that the load was light, but there were high stress concentrations.

In addition, by looking at the edges of the ratchet marks, one can tell whether torsional forces were involved with the failure. Two examples of this are shown in Fig. 4. If plane bending or tension has caused the failure, the sides of the ratchet marks will be essentially perpendicular to the fracture face. If the primary load causing the failure was torsional, the sides will be tapered.

With fractures that have multiple origins, analysis of the angles of the ratchet marks in the fracture plane can usually be used to determine which of the origins was actually the primary one. In situations such as that shown in Fig. 5, it can be seen that the center two ratchet marks are slightly closer at the surface, indicating the failure began between them.

The second important feature is the shape of the fracture as viewed from the side. If the stress concentration is relatively insignificant, the fracture face will essentially be a flat plane. But if the stress concentration played an important part in causing the failure, such as a sharp corner on a step in a shaft, the fracture face will be curved in that area affected by the stress concentration. The sketch in Fig. 6 shows a side view of a shaft, and the concave fracture face indicates that there was a serious stress concentration. (If there had been an adequate radius on the shaft and a low stress concentration factor, the fracture face would have been essentially flat, or the failure may not have happened at all.)

The last of the common surface features that are important to show

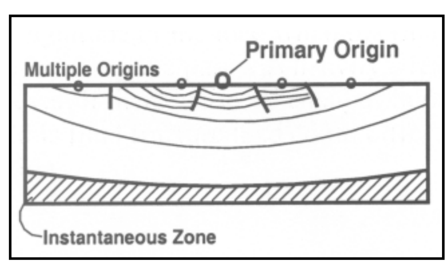


Fig. 5 *Origin of failure shown*

are called *river marks,* because they look like a river as shown on a physical map. They show the direction of progression of the fatigue crack. Figure 7 shows an example of some river marks copied from the fracture face of a failed pump shaft. River marks show up most frequently in the relatively fast-growing sections of the fatigue zone, and, other than indicating the direction of crack growth, they supply little information that can be used to diagnose the cause of the failure.

The following sketches show a series of typical fatigue failures and their surface interpretations. In most cases, diagnosing the direction and magnitude of the applied forces is relatively straightforward and is a great asset in determining the physical causes of the failure.

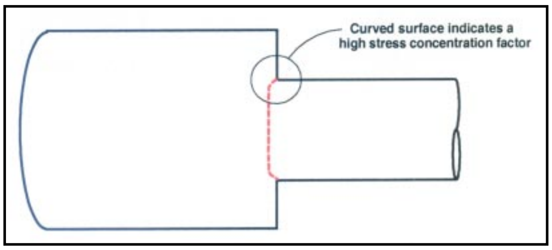


Fig. 6 *Concave fracture surface*

However, one should be cautious in analyzing the surface. As a part fails and a smaller cross section is available to support the load, the physical characteristics of the system, such as resonant frequencies and the center of mass, tend to change. In turn, these changes affect the appearance of the fracture face. In conducting a failure analysis and determining the physical causes, it is imperative to determine and understand the conditions at the time of crack inception, not those later in the failure life.

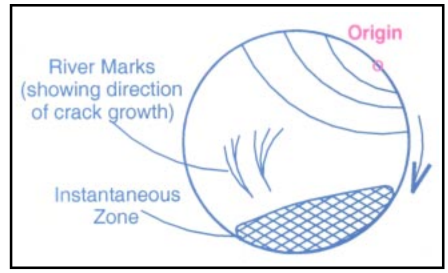
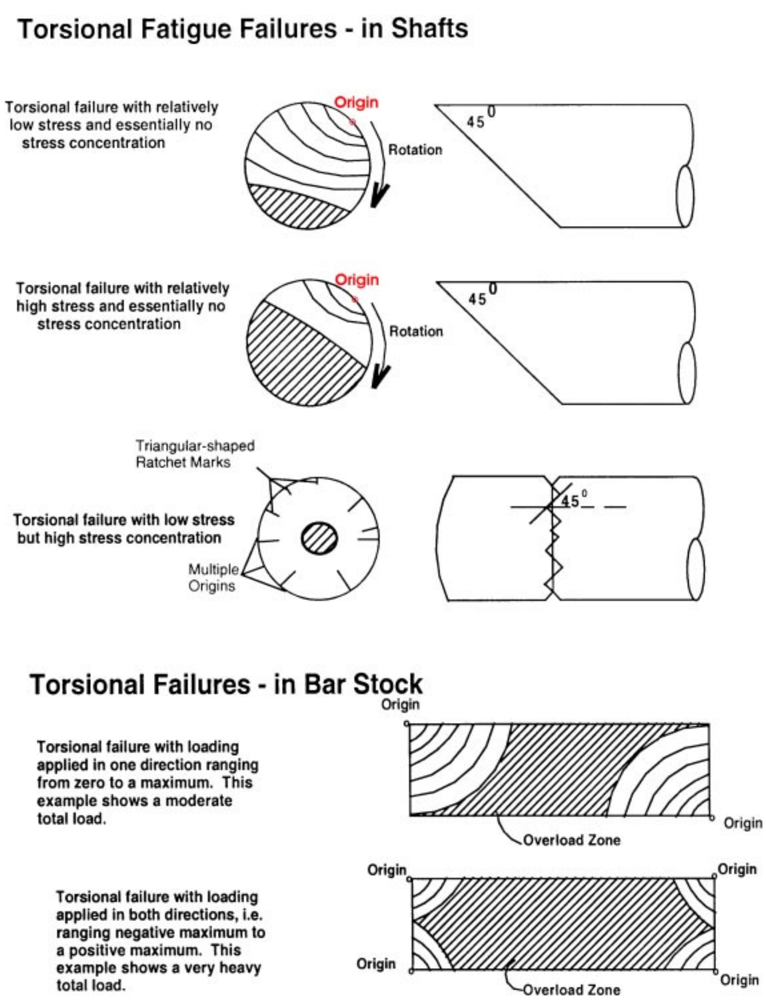
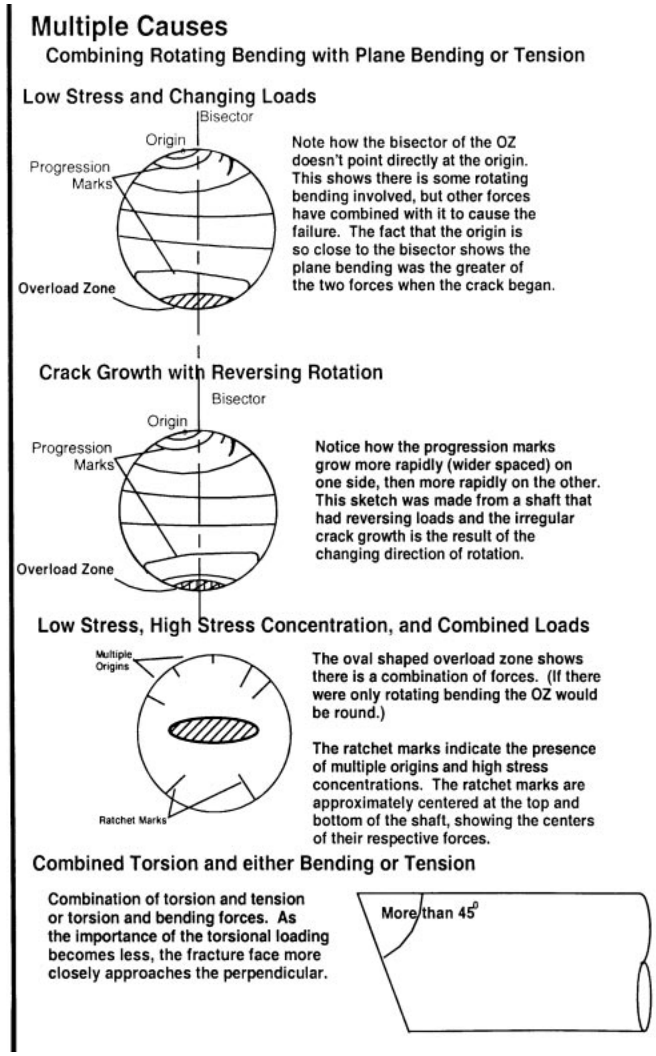
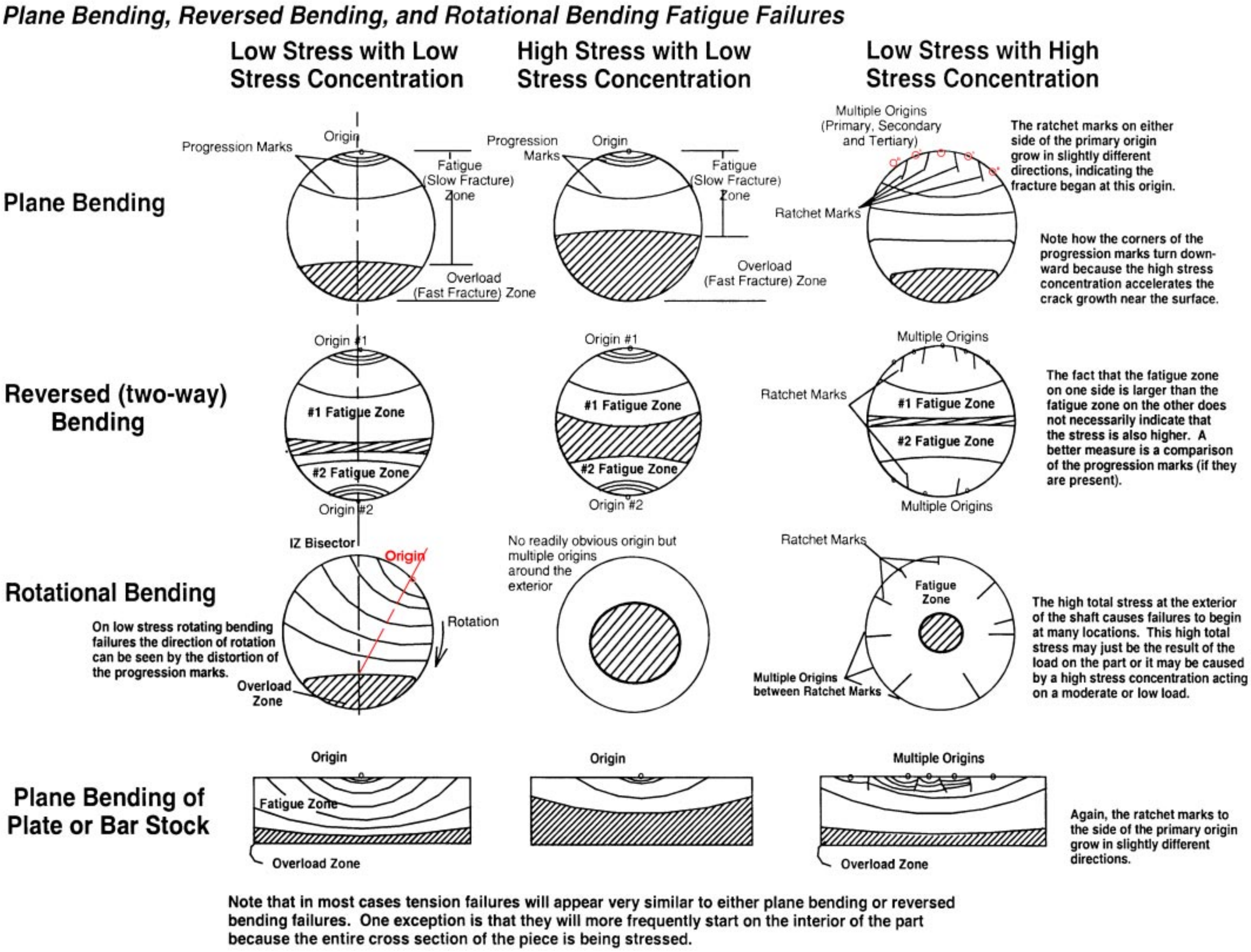


Fig. 7 *River marks shown*







Fatigue Fracture Face Examples

This series of photographs highlights some of the points in this article.

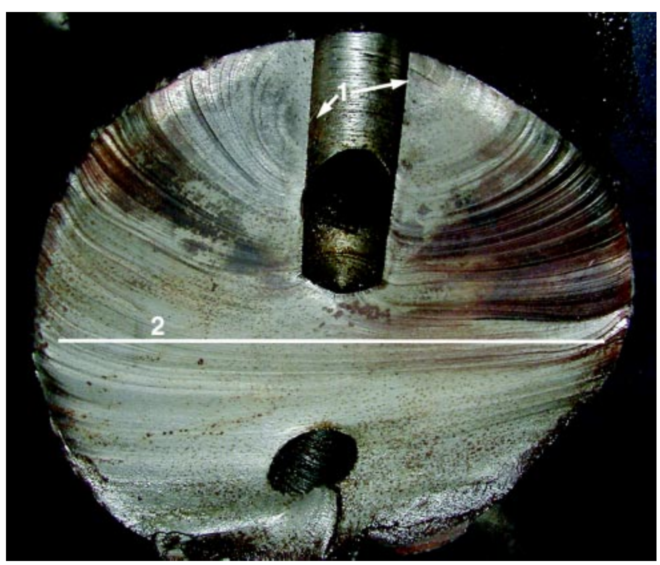


Photo 1 *A basic fatigue failure complicated by several holes. Two origins are seen at (1). The progression marks work across the fracture face. At (2) the growth of the fracture face is essentially straight across the face. (With high magnification, fatigue striations may be seen between the progression marks.)*

Photo 2 *A view of an agitator shaft showing two ratchet marks separating the three failure origins. Note that the origins are not on the same plane and that the ratchet marks are in effect boundaries between the fracture planes. (There is yet another origin on the other side of the failure face.)*

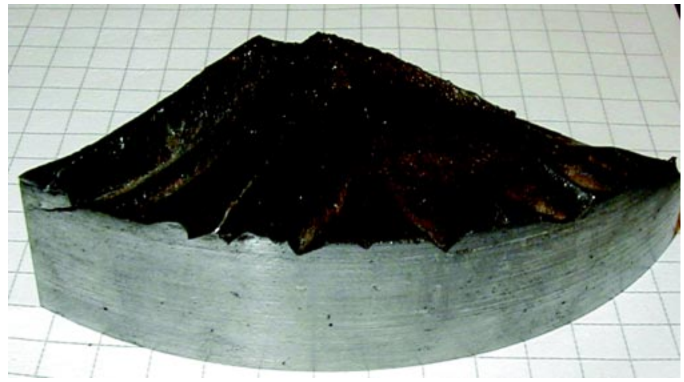


Photo 3 *This section of a crankshaft shows the ratchet marks that result when a torsional fatigue failure has multiple origins. Note that the sides are at approximately a 45° angle, whereas the sides of the ratchet marks shown in Photo 2 are essentially axial.*

Photo 4 *A view of a low-cycle fatigue failure of a gear tooth from a large compressor. Note that both the coarse ratchet marks on the left and the fine ones to the right point away from the origin, which is on the bottom edge of the tooth, just to the right of the center.*

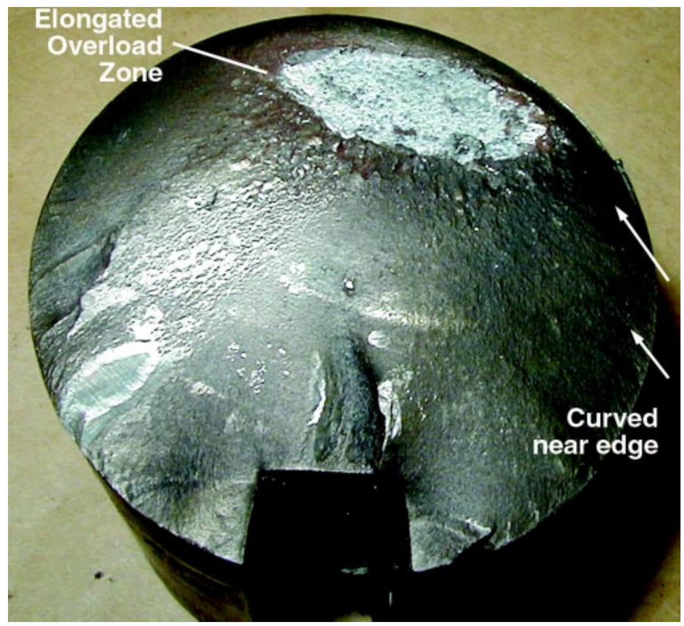


Photo 5 *A cross-sectional view of this classic fatigue failure shows that the piece is domed with the smallest radius near the outer edge. This small radius testifies to a high stress concentration that, when multiplied by the stress concentration of the keyway, caused the failure. Also of interest is the shape of the overload zone. The fact that it is elongated indicates some plane bending loads were present.*

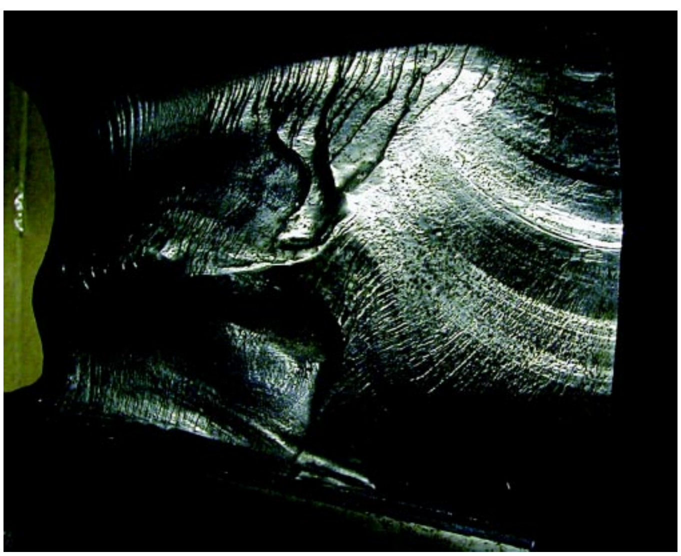


Photo 6 *These are "river marks" in a case hardened gear used in a 3500 hp pump drive. Like rivers flowing downstream, they indicate the direction in which the crack progressed and show the crack grew from top to bottom. However, the pressure side of the teeth is toward the bottom, that is, the gear is being driven in an upward direction, indicating a serious torsional problem.*

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