The following are recommended “highlights” from Volume 12 of ASM Handbook (available online through UP library).

Fractography – Principles and Practices
- Scanning Electron Microscope
  - SEM Fracture

Atlas of Fractographs
- Pure Irons
  - Figs: 16, 20, 28
- Low Carbon Steel
  - Figs: 141-145, 152, 158-159, 163
- Medium Carbon Steel
  - Figs: 167, 191-192, 199, 208, 211-212, 221
- High Carbon Steel
  - Figs: 274-277, 281-282, 286-288, 306-307
- Cast Aluminum Alloys
  - Figs: 922-928 (esp 924, 927), 938, 952
- Wrought Aluminum Alloys
  - Figs: 1008, 1016, 1046, 1095

Understanding How Components Fail

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in others. For example, certain processing equipment may operate continually at elevated temperatures. In this case brittle fracture may not be a consideration unless there is a damaging environmental factor, such as absorption of hydrogen or hydrogen sulfide.

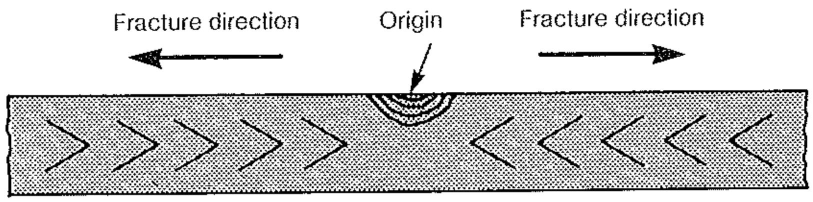
In many other applications, exposure to relatively low temperature for the steel involved may be a real possibility and thus a real problem if the other contributing factors are likely to exist. The steel itself thus may be the only factor that can be controlled in order to prevent brittle fracture of normally ductile steel. The metallurgical trends that tend to decrease the likelihood of brittle fracture of steel are: low carbon content, moderate manganese content, high manganese/carbon ratio, inclusion of certain alloying elements, fine grain size, deoxidation of steel, and heat treatment to produce tempered martensitic or lower bainitic microstructures. This subject is covered in more detail in Ref 7. Prevention of brittle fracture is entirely possible if advantage is taken of the recent technology that has led to the development of steels specifically for increased notch toughness.

CHARACTERISTICS OF BRITTLE FRACTURE

Brittle fractures have certain characteristics that permit them to be properly identified:

1. There is no gross permanent or plastic deformation of the metal in the region of brittle fracture, although there may be permanent deformation in other locations where relatively ductile fracture has occurred.
2. The surface of a brittle fracture is perpendicular to the principal tensile stress. Thus the direction of the tensile stress that caused the fracture to occur can be readily identified.
3. Characteristic markings on the fracture surface frequently, but not always, point back to the location from which the fracture originated.

   In the case of flat steel, such as sheet, plate, or flat bars, and also case-hardened regions, there are characteristic V-shaped "chevron" or "herringbone" marks that point toward the origin of the fracture. In many instances, these marks are extremely fine and very difficult to recognize unless a strong light is po-



Note the classic chevron or herringbone marks that point toward the origin of the fracture, where there usually is some type of stress concentration, such as a welding defect, fatigue crack, or stress-corrosion crack. The plane of the fracture is always perpendicular to the principal tensile stress that caused the fracture at that location.

Fig. 2. Sketch of pattern of brittle fracture of a normally ductile steel plate, sheet, or flat bar.

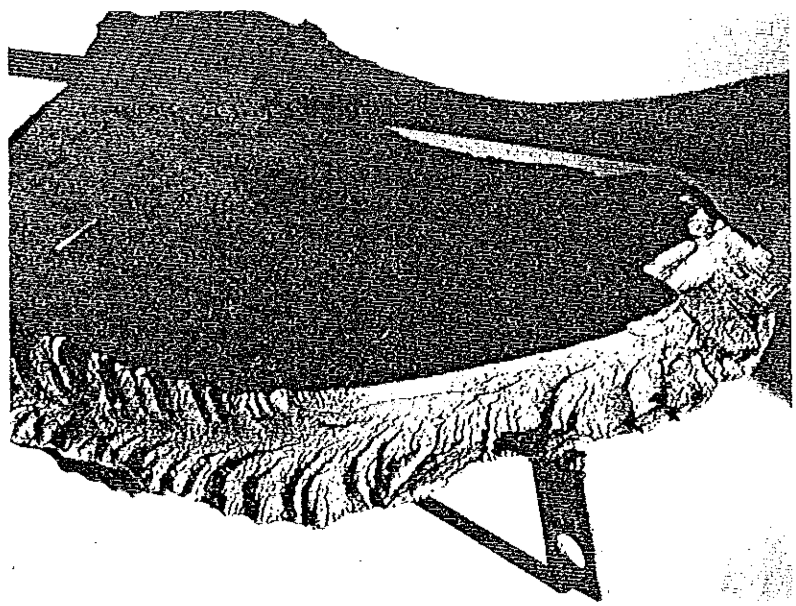
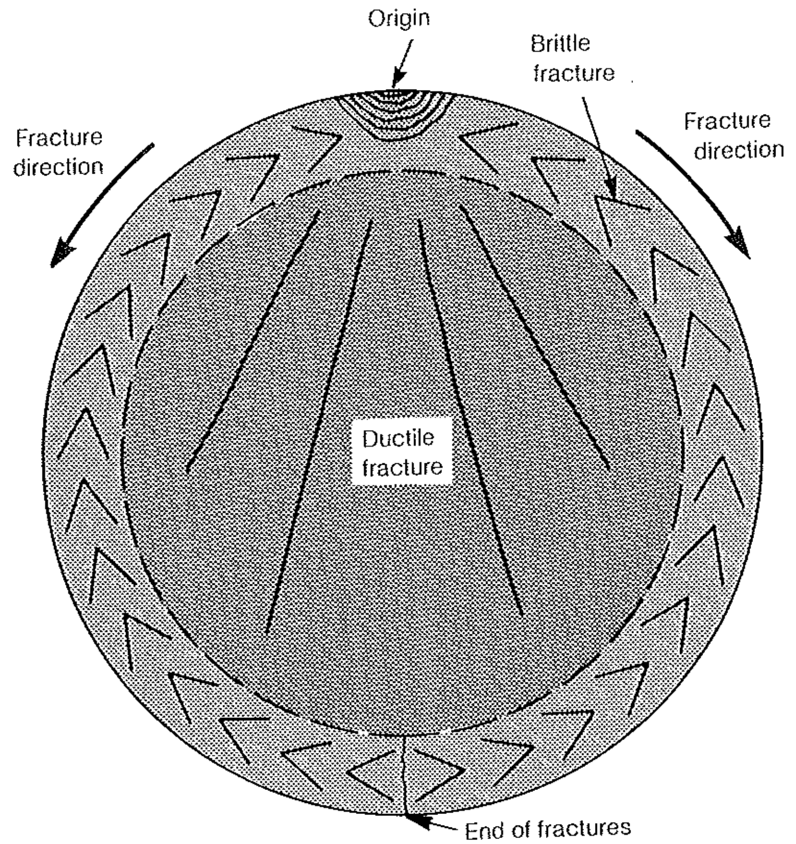


Fig. 3. Fragment of a thick-walled fractured drum. The fracture, which started at the right side of the photo, ran rapidly to the left, resulting in a well-defined chevron pattern. (Ref 10)

sitioned so that it just grazes the projections of the surface texture. See Fig. 2 through 8 for illustrations of these marks.

Brittle fractures of some parts may have a pattern of radial lines, or ridges, emanating from the origin in a fan-like pattern. Again, it may be difficult to perceive the texture of the fracture surface unless the light is carefully controlled. See Fig. 9 through 11.

Brittle fractures of extremely hard, fine-grain metals usually



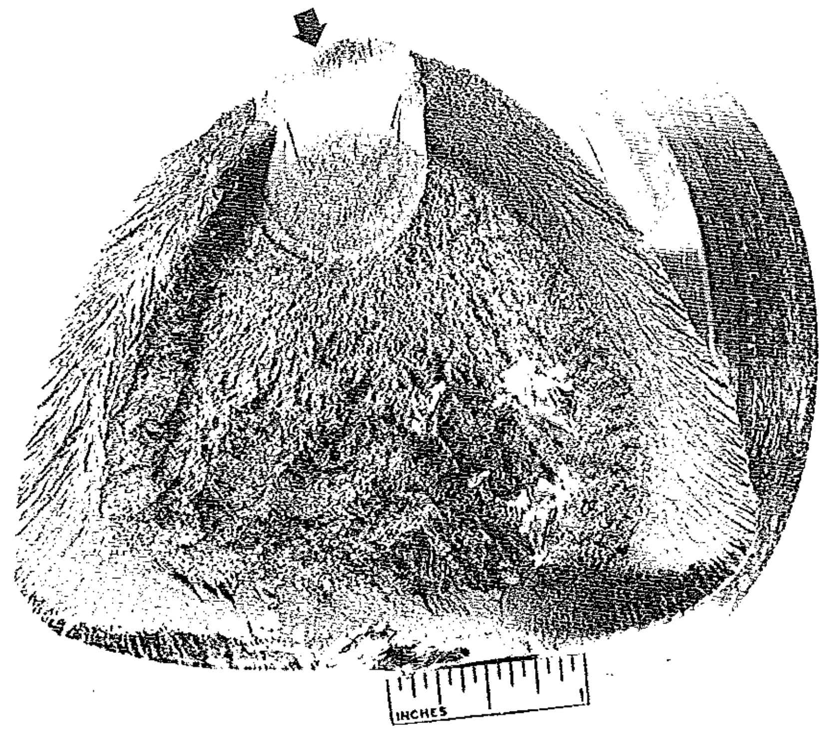
If brittle fracture continues completely around the part, the two separate fractures may form a step where they overlap opposite the origin. The interior, or core, is likely to have a ductile fracture, with dimpled rupture on a microscale.

Fig. 4. Sketch of a fractured case-hardened shaft showing chevron marks pointing back toward the fracture origin.

have little or no visible fracture pattern. In these cases, it may be very difficult to locate the origin with certainty.

NOTE: The preceding discussion of the ductile/brittle transition primarily concerns carbon and alloy steels as well as certain nonaustenitic stainless steels. Other metals with body-centered cubic crystal structures behave similarly but are less common. Most nonferrous metals, such as alloys of aluminum and copper, and austenitic stainless steels have crystal structures that are not susceptible to the ductile/brittle transition characteristic of body-centered cubic metals.

See Chapter 3 on Basic Single-Load Fracture Modes for other discussion on ductile/brittle fracture.



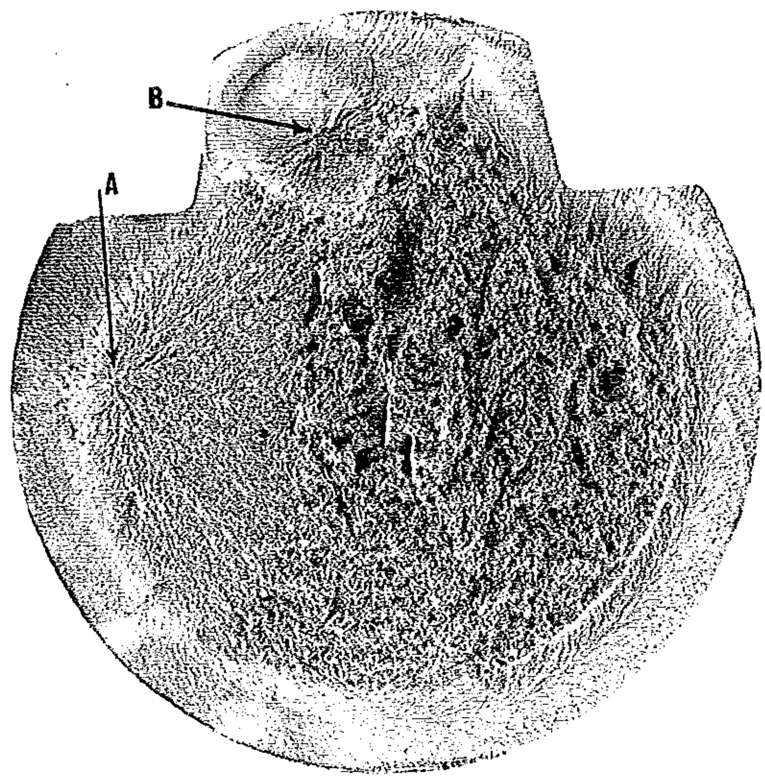
The fatigue crack originated (arrow) at a fillet (with a radius smaller than specified) at a change in shaft diameter near a keyway runout. Case hardness was about HRC 46 at the surface. Note the well-defined chevron marks in the two brittle fractures pointing toward the roughly circular fatigue portion of the fracture. Note also that this fracture is at a 45° angle to the shaft axis, as is typical of fatigue and brittle fracture of shafts in torsion.

Fig. 5. Surface of a torsional fatigue fracture that caused brittle fracture of the case of an induction-hardened axle of 1541 steel.

MICROSTRUCTURAL ASPECTS OF BRITTLE FRACTURE

Brittle fractures usually propagate by either or both of two fracture modes: cleavage and intergranular. In most cases it is necessary to study the fracture surface with an electron microscope. Since very high magnifications are usually not necessary, a scanning electron microscope is usually preferred to a transmission electron microscope.

Cleavage fractures are characterized by splitting of the crystals, or grains, along specific crystallographic planes without respect to the grain boundaries, as shown in Fig. 12. Since the fracture goes through the grains, this type of fracture is frequently referred to as transgranular, or transcrystalline. Cleavage fractures are the most common type



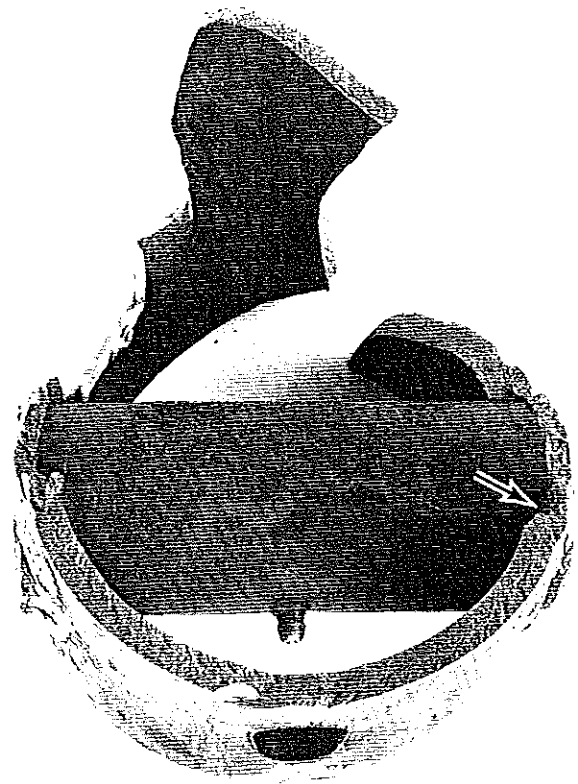
Fatigue fracture origins A and B were subsurface because of the steep induction-hardened gradient and lack of an external stress concentration. (See Fig. 9 in Chapter 6.) Fatigue crack A, the larger of the two, propagated through the core and case regions on the left side; then the shaft suddenly fractured in a brittle manner around the right side of the case. Note the chevron marks on the lower right pointing in a clockwise direction toward fracture origin A.

Fig. 6. Fatigue fracture of a $3^1/_4$-in.-diam induction-hardened shaft of 1541 steel after fatigue testing in rotary bending.

of brittle fracture and are the normal mode of fracture unless the grain boundaries have been weakened by a specific environment or process.

A typical cleavage fracture viewed by the scanning electron microscope is shown in Fig. 13. It will be noted that the pattern is characterized by the joining together of microscopic ridges, much like the joining of tributaries of a river system to form the main stream of the river. This pattern reveals the direction that the fracture ran; the fracture propagated in the same direction that the water in a river flows: downstream.

Intergranular fractures are those that follow grain boundaries weakened for any of several reasons. An analogy may be made to a brick wall, which fractures through the mortar rather than through the bricks themselves. The mortar is analogous to the grain boundaries,



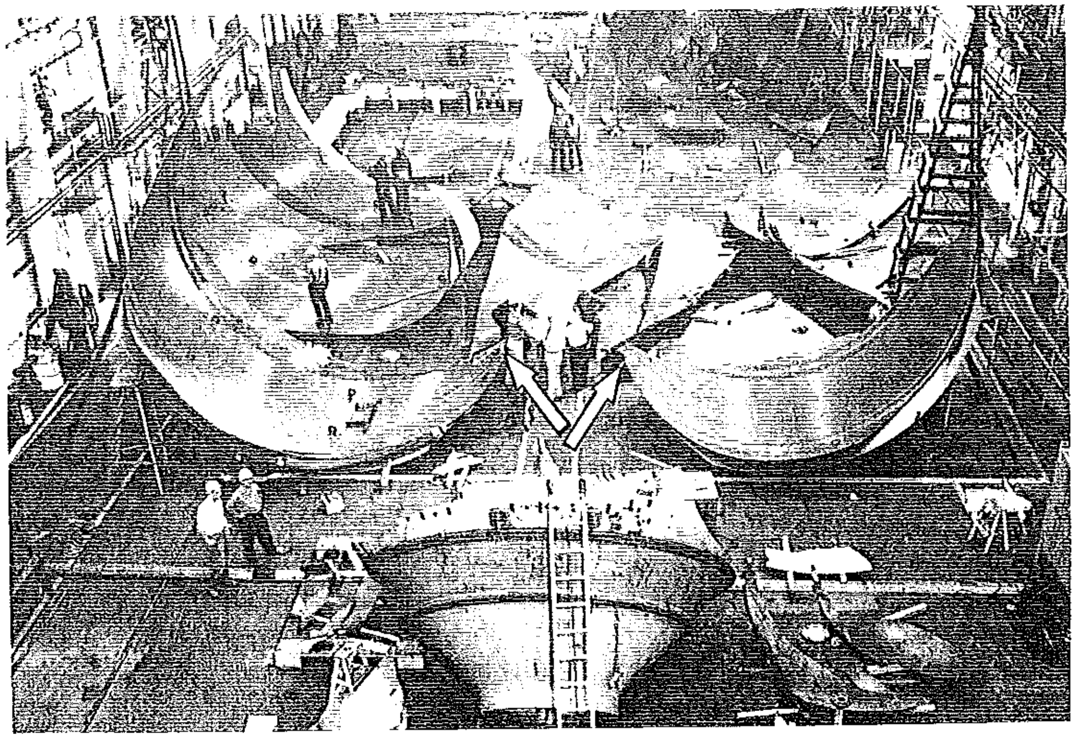
Fracture originated at a weld defect (arrow) during testing in very cold weather. Note well-defined chevron marks clockwise from the arrow pointing back toward the origin. Note also that the steel around the access hole in the grease fitting is actually necked down along the tube axis. The upper side of the tube is deformed and torn in a ductile manner.

Fig. 7. Surface of a brittle fracture in a cold drawn, stress-relieved 1035 steel axle tube.

while the bricks are analogous to the metal grains. A typical intergranular fracture is shown in Fig. 14.

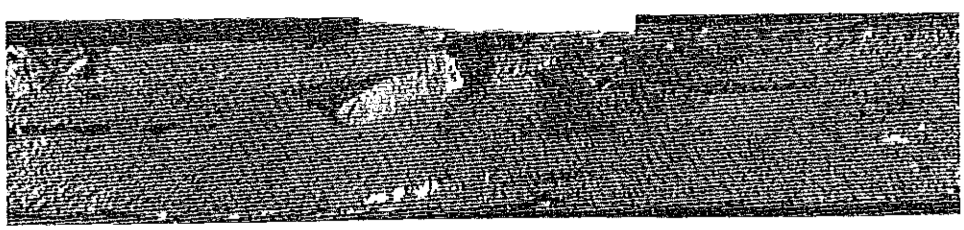
The reasons for weakened grain boundaries are frequently very subtle and poorly understood. Under certain conditions some metals are subject to migration or diffusion of embrittling elements or compounds to the grain boundaries. The major forms of embrittlement of steel will be discussed briefly here, but are covered in considerably more detail in various articles in Ref 7 and 8, as well as in other sources.

Strain-age embrittlement. Most susceptible to the phenomenon of strain-age embrittlement are low-carbon rimmed or capped steels that are severely cold worked during forming processes. Subsequent moderate heating during manufacture (as in galvanizing, enameling, or



The case fractured at a repaired weld imperfection during a hydrostatic pressure test. Fracture occurred at about 57% of the intended proof stress. All welds of the case had been carefully inspected by X-ray and ultrasonic inspection. Arrows indicate origin of fracture.

Fig. 8(a). Catastrophic brittle fracture of a 260-in.-diam solid-propellant rocket motor case made of 18% Ni, grade 250, maraging steel.



A crack was found beneath a gas tungsten-arc repair weld on the inner surface of the case (surface at top in this fractograph) in the heat-affected zone of a longitudinal submerged-arc assembly weld. The crack was about 1.4 in. long, parallel to and 0.47 in. beneath the outer surface of the case (surface at bottom). Radial marks are visible that confirm that fracture proceeded to the left and to the right. (Ref 11)

Fig. 8(b). Light fractograph of crack origin in the weld-related catastrophic fracture of the motor case shown in Fig. 8(a). $1^1/_3\times$.

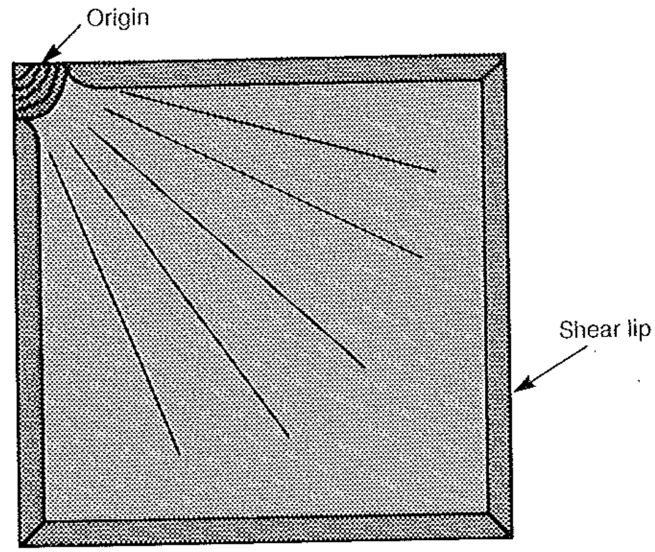
This bar, which supports the front end of a large crawler tractor, was in service for about 200 h and was then returned to the laboratory, where it was flexed in high-stress, low-cycle fatigue, fracturing at 60,000 cycles. Note that the fatigue-crack zone at upper left has a very fine texture, the result of continual testing. Note also the radial, fan-like ridges emanating from the fracture origin and the very small shear lips around the periphery of the brittle fracture. This fracture of a very large, high-strength part released a large amount of energy in a very short time.

Fig. 9(a). Fracture surface of a large (approx $5^3/_4 \times 6$ in.) equalizer bar made from D6B steel heat treated to a hardness of HRC 45 to 47.

paint baking) or aging at ambient temperature during service may cause embrittlement.

Quench-age embrittlement. Rapid cooling, or quenching of low-carbon steels (0.04 to 0.12% carbon) from subcritical temperatures above about 560 °C (1040 °F) can precipitate carbides within the structure and also precipitation harden the metal. An aging period of several weeks at room temperature is required for maximum embrittlement.

Blue brittleness. Bright steel surfaces oxidize to a blue-purple color when plain carbon and some alloy steels are heated between 230 and 370 °C (450 and 700 °F). After cooling, there is an increase in tensile



Fracture originated at a sharp stress concentration that grew to the critical flaw size for that metal. The sharp stress concentration is frequently, though not always, a fatigue crack or a stress-corrosion crack. Note the fan-shaped pattern radiating from the origin region in the upper left corner. When viewed under the electron microscope, this type of fracture is likely to reveal a cleavage or quasi-cleavage fracture mode.

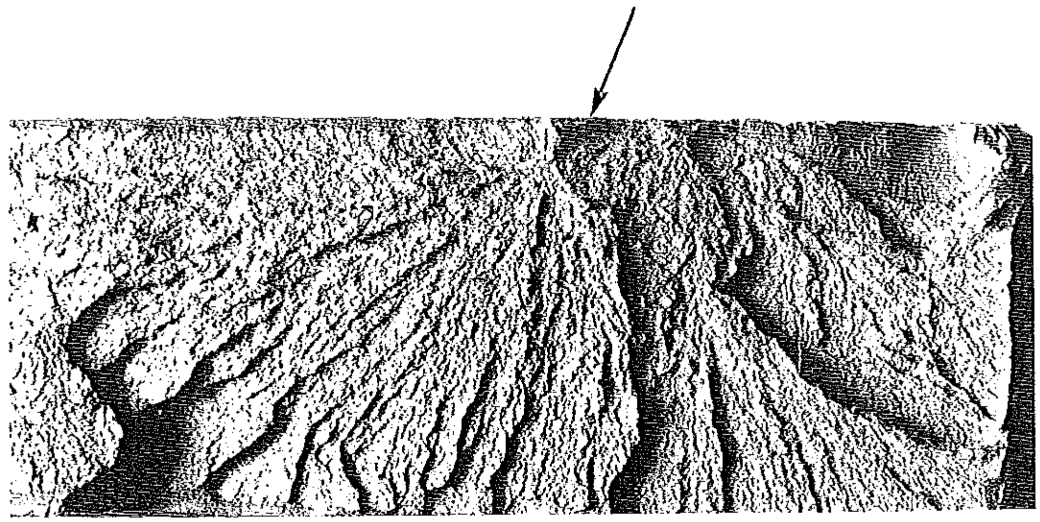
Fig. 9(b). Sketch of pattern of brittle fracture in a moderately hard, strong metal.

strength and a marked decrease in ductility and impact strength caused by precipitation hardening within the critical temperature range.

Temper embrittlement. Quenched steels containing appreciable amounts of manganese, silicon, nickel, or chromium are susceptible to temper embrittlement if they also contain one or more of the impurities antimony, tin, and arsenic. Embrittlement of susceptible steels can occur after heating in the range 370 to 575 °C (700 to 1070 °F) but occurs most rapidly around 450 to 475 °C (840 to 885 °F).

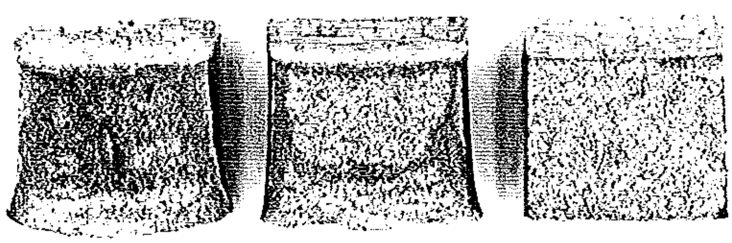
500 °F embrittlement. High-strength low-alloy steels containing substantial amounts of chromium or manganese are susceptible to embrittlement if tempered in the range of 400 to 700 °F (200 to 370 °C) after hardening, resulting in tempered martensite. Steels with microstructures of tempered lower bainite also are subject to 500 °F embrittlement, but steels with pearlitic microstructures and other bainitic steels are not susceptible.

400 to 500 °C embrittlement. Fine-grained, high-chromium ferritic stainless steels, normally ductile, will become embrittled if kept at 400 to 500 °C (750 to 930 °F) for long periods of time. Soaking at higher temperatures for several hours should restore normal ductility.



Radial ridges emanate from the origin in a fan-shaped pattern. The brittle part of the fracture is bright and sparkling, in contrast to the dull appearance of the fatigue zone and the thin shear lips at top and bottom surfaces.

Fig. 10. Origin (at arrow) of a single-load brittle fracture which initiated at a small weld defect. Note also a fatigue fracture in the upper right corner.



At the highest temperature (left), the fracture is virtually all shear. At intermediate temperature (center), the fracture is combined shear and cleavage. At the lowest temperature (right), the fracture is virtually complete cleavage. Note increased deformation with increased temperature.

Fig. 11. Three Charpy V-notch impact test specimens of the same metallurgical conditions tested at three different temperatures.

Sigma-phase embrittlement. Prolonged service at 560 to 980 °C (1050 to 1800 °F) can cause formation of the hard, brittle sigma phase in both ferritic and austenitic stainless steels and similar alloys. Impact strength is greatly reduced, particularly when the metal has been cooled to about 260 °C (500 °F) or less.

Graphitization. Formation of graphite may occur in a narrow heat-affected zone of a weld in carbon and carbon-molybdenum steels held

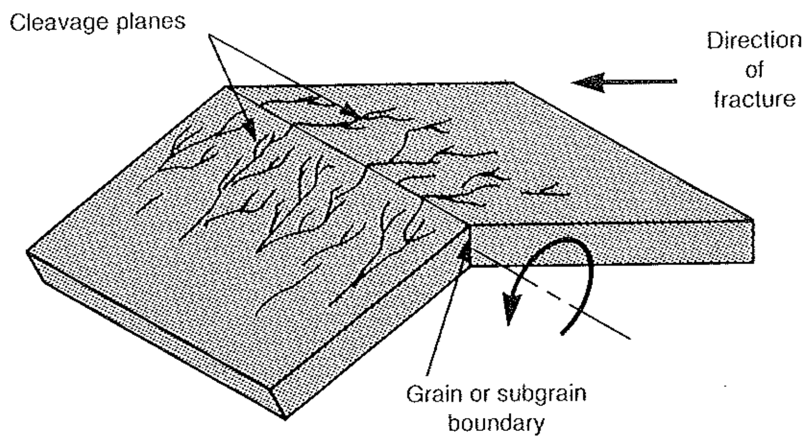


Fig. 12. Cleavage-fracture model showing fracture direction, cleavage planes, and low-angle grain or subgrain boundary. (Ref 8)

at temperatures over 425 °C (800 °F) for prolonged periods. The degree of embrittlement depends on the distribution, size, and shape of the graphite formed in the heat-affected zone.

Intermetallic-compound embrittlement. Long exposure of galvanized steel to temperatures slightly below the melting point of zinc (420 °C or 787 °F) causes zinc diffusion into the steel. This results

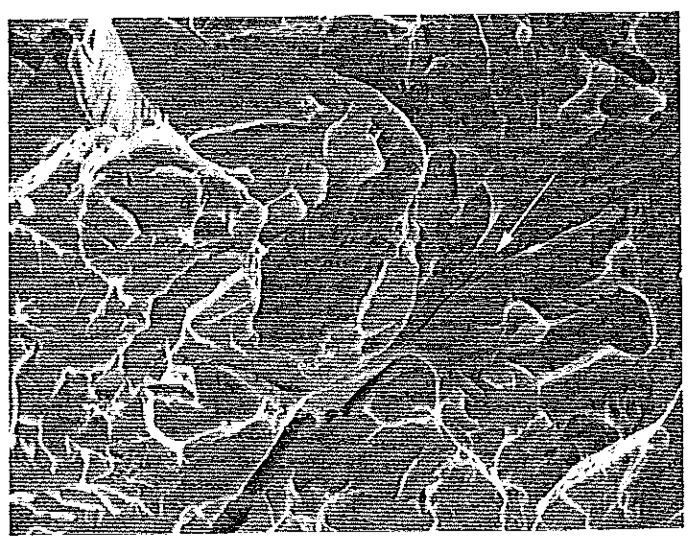


Fig. 13. Cleavage fracture in hardened steel, viewed under the scanning electron microscope. Note progression of "river" marks in the direction of arrow. Grain boundaries were crossed without apparent effect. 2000×; shown here at 75%.

Fig. 14. Intergranular fracture in hardened steel, viewed under the scanning electron microscope. Note that fracture takes place between the grains; thus the fracture surface has a "rock candy" appearance that reveals the shapes of part of the individual grains. 2000×; shown here at 75%.

in the formation of a brittle iron-zinc intermetallic compound in the grain boundaries.

Other types of embrittlement leading primarily to intergranular fracture are caused by environmental factors. These include the following:

Neutron embrittlement. Neutron irradiation of steel parts in nuclear reactors usually results in a significant rise in the ductile/brittle transition temperature of the steel. Metallurgical factors such as heat treat practice, microstructure, vacuum degassing, impurity control, and steel composition greatly affect susceptibility to this type of grain-boundary weakening.

Hydrogen embrittlement. Hydrogen atoms diffuse readily into steel during processes such as acid pickling, electroplating, arc welding with moist or wet electrodes, and exposure to hydrogen sulfide. After stressing, delayed brittle fracture may occur, particularly in higher-strength steels.

Stress-corrosion cracking. Simultaneous exposure to a tensile stress (applied or residual) and to a relatively mild corrosive environment may cause brittle fracture in metal parts that may be either intergranular or transgranular, depending on conditions. If either factor is eliminated, stress-corrosion cracking cannot occur.

Liquid-metal embrittlement. Certain liquid metals can embrittle the solid metals with which they are in contact. A tensile stress is also required for brittle fracture to occur.

Each of the above types of embrittlement is the result of exposure to one or several environmental factors during manufacture, storage, or service. Each type is extremely complex and must be considered during any failure-analysis investigation.

COMBINED FRACTURE MODES

It must not be assumed that brittle fracture always occurs solely by the cleavage or the intergranular fracture mode as described above. In most cases one mode predominates but is not necessarily the only mode. For example, in a predominantly intergranular fracture, there probably will be regions, large or small, in the fracture surface that contain cleavage fracture as well. The reverse also is true. In other words, the mode of fracture that occurs at a particular location depends on the local composition, stress, environment, imperfections, and crystalline orientation of the grains. There may also be regions of tough, fibrous, dimpled-rupture fracture, particularly away from the origin of the major fracture.

It should be noted that cast metals generally tend to be less ductile (or more brittle) than wrought metals of the same composition under the same conditions. The reason is that various types of casting imperfections—particularly shrinkage porosity, gas porosity, and certain types of inclusions—act as internal stress concentrations in castings. In wrought metals the hot working process closes the porosity and changes the shape of many inclusions to long, thin stringers, which are usually less harmful.

SUMMARY

As can be seen from the study of the preceding sections, the subject of brittle fracture is exceedingly vast and complex, with many interrelated factors of material, design, manufacture, quality control, and environment, both thermal and chemical. Study of the references cited is urged as well as those in the more recent literature.

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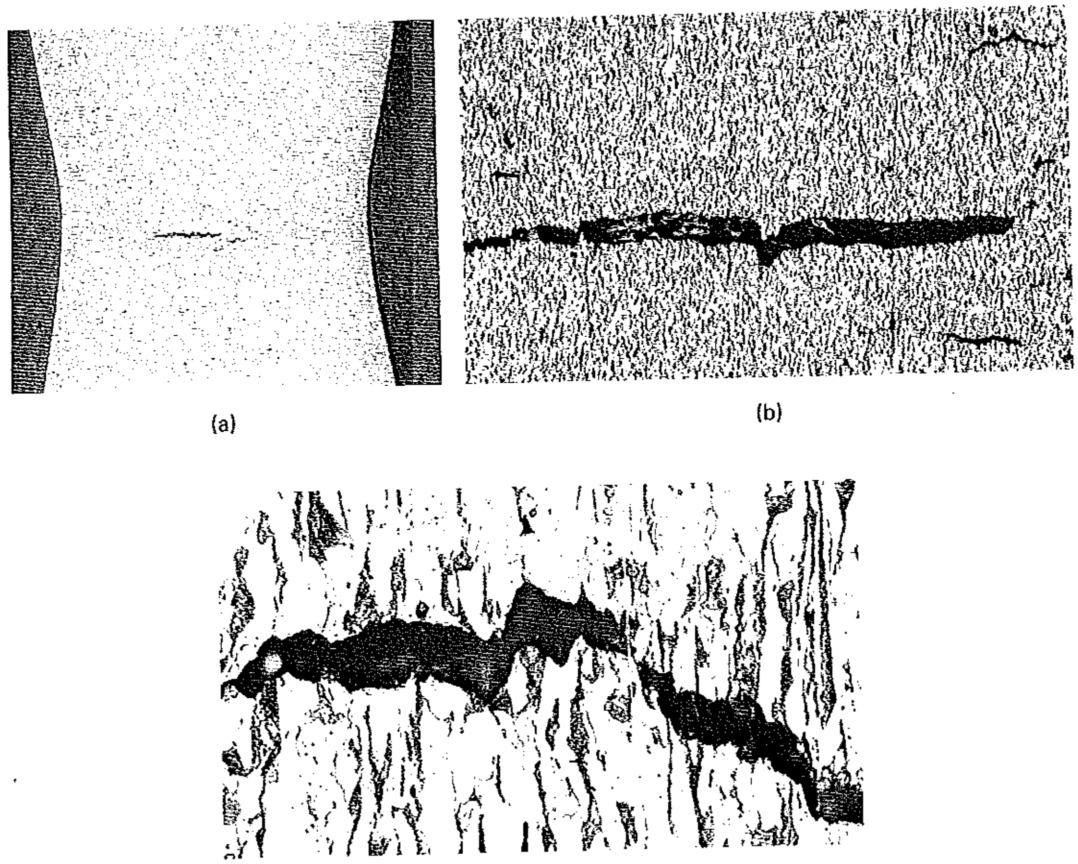

(a) (b) (c)

(a) At 6× magnification, shows internal cracking, reduced section, and severely deformed grain structure.
(b) At 50× magnification, shows one large crack and several smaller cracks and elongated grains.
(c) At 250× magnification, shows lack of fit due to distortion; also elongated ferrite (light) and pearlite (dark) areas. See text.

Fig. 5. Photographs at three different magnifications (shown here at 75%) of longitudinal section of tensile test specimen of hot rolled 1020 steel. Test was stopped immediately prior to fracture (region c of Fig. 4).

Figure 5 shows the behavior that occurs within a typical ductile metal immediately prior to fracture due to a tensile force. Detailed study of these three photographs is instructive.[6]

Figure 5(a) is a photograph at low magnification (6×) of the necked-down portion of a tensile specimen made from hot rolled 1020 steel immediately prior to fracture. In order to make this study, it was necessary to stop the test after the maximum load had been attained, in the region of the stress-strain curve just prior to the fracture at "X" in Fig. 4. The specimen was sectioned longitudinally and metallo-

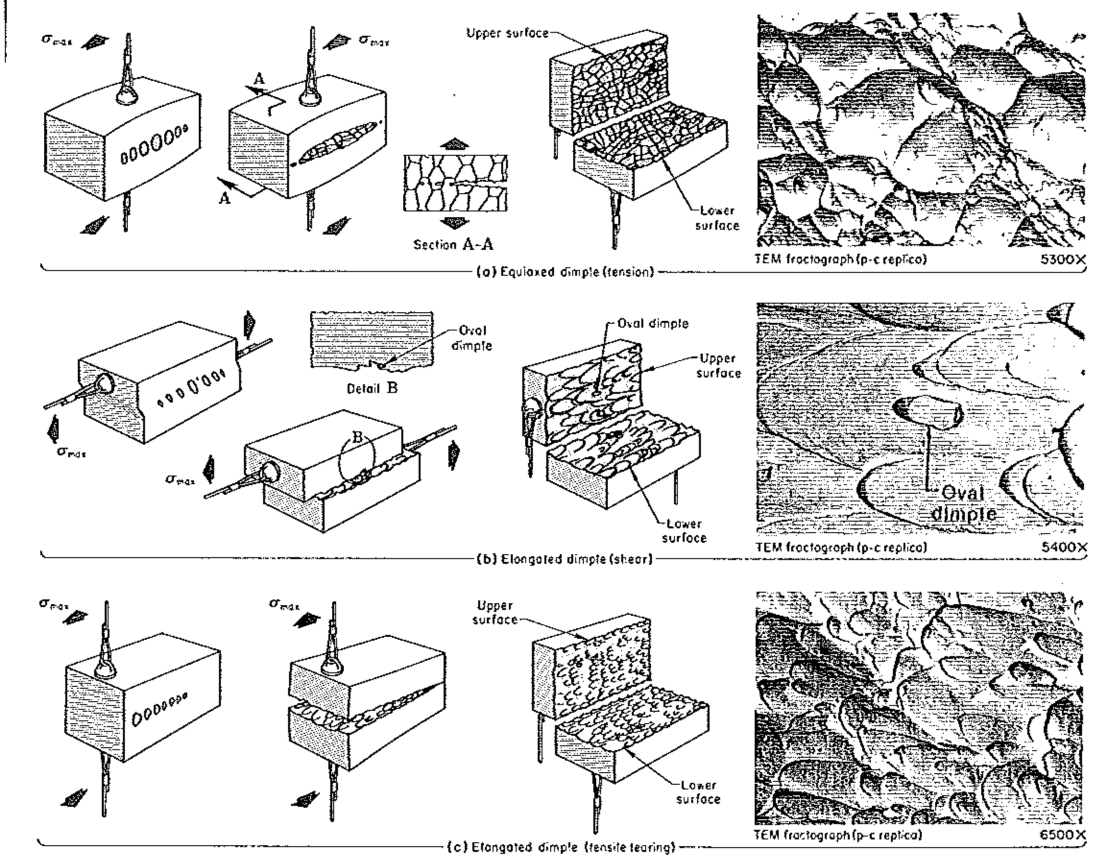

Fig. 7. Influence of direction of principal normal stress on the shape of dimples formed by microvoid coalescence. See text for discussion. (Ref 7)

han at the center. This is due to a bending force on the part which causes tensile fracture with equiaxed dimples at the region close to he origin, while the actual tensile tearing causes the C-shaped dimples to form near the end of the fracture, opposite the origin.

In addition to these three basic modes of microvoid coalescence and fracture, there are several others described in Ref 6 and shown n Fig. 8. The three modes just discussed appear at the upper left of he figure.

CAUTIONS IN INTERPRETATION

At this point, it is prudent to insert some cautions about interpretation of the evidence visible with this type of microscopic examination. The

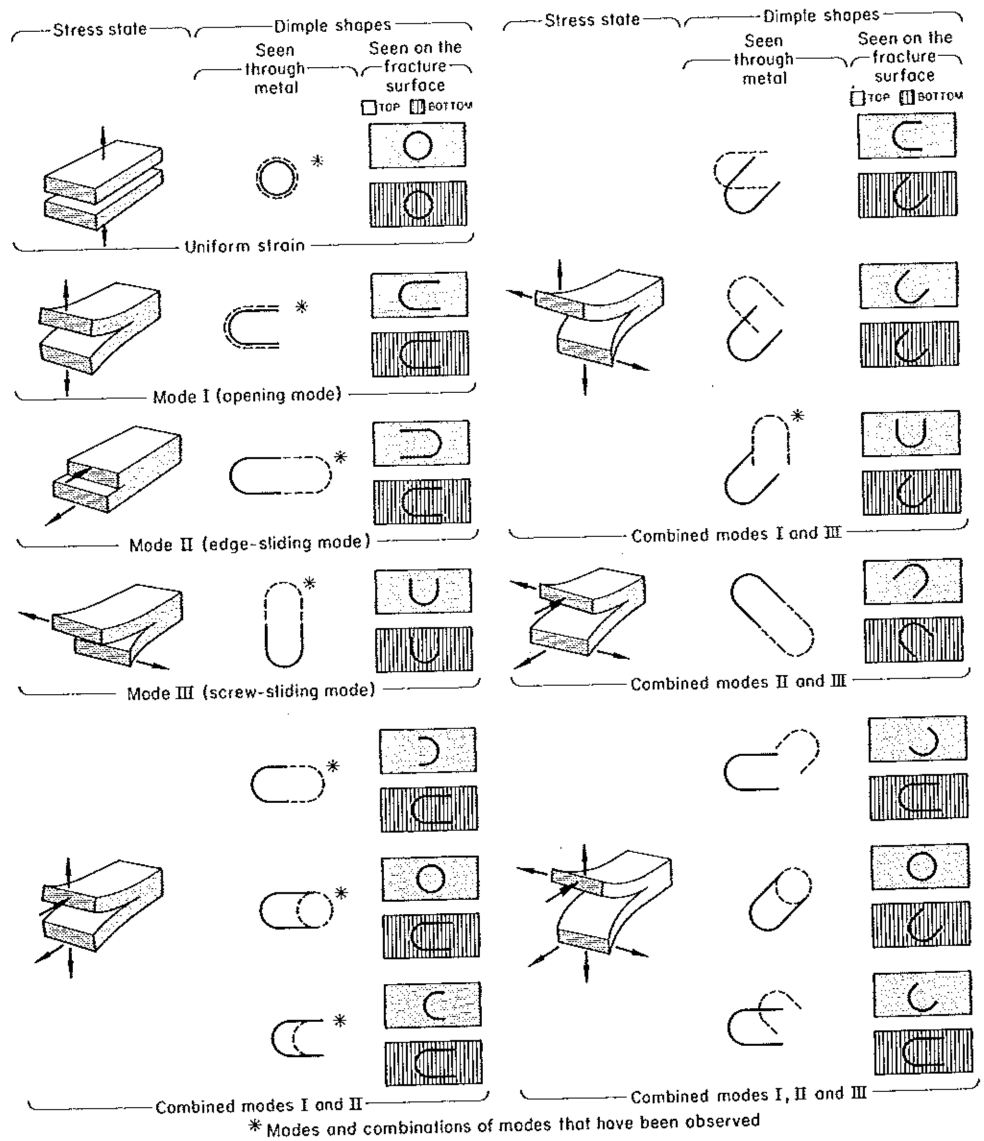

Fig. 8. Fourteen probable combinations of mating dimple shapes, resulting from different stress states that caused metal at the crack tip to deform by various modes. (Ref 7)

analyst must be aware of complicating factors extraneous to the fracture itself:

1. *Mechanical Damage*. The fracture of a metal part is always a violent event because of the sudden release of energy. Fracture surfaces frequently are rubbed or pounded against each other, causing rub marks, abrasion, dents, smearing or other scars of postfracture damage. It is not unusual for much of the fracture

surfaces to be obliterated so that microscopic examination as discussed above is difficult or impossible. The microscopic features on fracture surfaces are fragile and are easily damaged; when this occurs, one must rely on the macrofeatures of the part or parts for useful evidence in analyzing the fracture.

2. *Chemical Damage*. Surface pits resembling the dimples of ductile fracture may instead be the result of severe etching with corrosive acids (or bases, in some metals) or of cleaning techniques used to remove atmospheric corrosion. In other cases, a corrosive film, or layer, may have formed on the fracture surface and completely obliterated the underlying character of the surface.
3. *Cavities May Not Be Dimples*. In certain metals, cup-like cavities may be present on a fracture surface, but the cavities may not be the dimples characteristic of ductile fracture. In cast metals and weldments, particularly, this type of rounded cavity may actually be evidence of gas porosity. Gas porosity occurs because the inevitable gases in castings and weldments (which are actually localized castings) cannot escape to the atmosphere before the metal solidifies and traps the gas in tiny, smooth-walled bubbles within the metal. This is particularly true in welds in metals such as aluminum, which has a high rate of thermal conductivity. In effect, large, cold members having high thermal conductivity act as heat sinks, causing rapid solidification of the weld metal and entrapping gas bubbles before they can escape. In ductile fractures of metals with extensive gas porosity, it may be quite difficult to determine which cavities are true dimples and which are evidence of gas porosity.
4. *Mixed Fracture Modes*. During study of a fracture surface, one should not be surprised to find different fracture modes. A predominantly ductile fracture surface may have certain locations with cleavage or intergranular fracture because of differences within the metal. These differences may result from crystalline orientation with respect to the fracture stress, or from differences in the microstructure of the metal. A steel with a partly pearlitic, partly ferritic microstructure, for example, may fracture with dimpled rupture in the ferrite regions but fracture by cleavage in the pearlite regions. A notched-bar impact test specimen may fracture by cleavage in some areas and with dimpled rupture in others. A hydrogen-embrittlement fracture may have certain areas with intergranular fracture and others with dimpled rupture. No true fatigue striations are possible in a single-overload fracture; however, there may be somewhat similar-appearing parallel ridges resulting from fracture through pearlite or other lamellar structures, or resulting from mechanical rub-

bing either during or after the fracture. These spurious marks may resemble striations that may confuse the analyst, who has a difficult task even without these complications. Of course, if cyclic loading has in fact occurred, true fatigue striations may also be present in addition to any or all of the other fracture modes. See Chapter 10 on Fatigue Fracture for more information.

SUMMARY

Ductile fracture occurs when the shear strength is the limiting factor. Permanent (plastic) deformation is inherent in ductile fracture and is usually obvious. The micromechanism of dimple formation and distortion must be understood in order to study electron microscope views of ductile-fracture surfaces.

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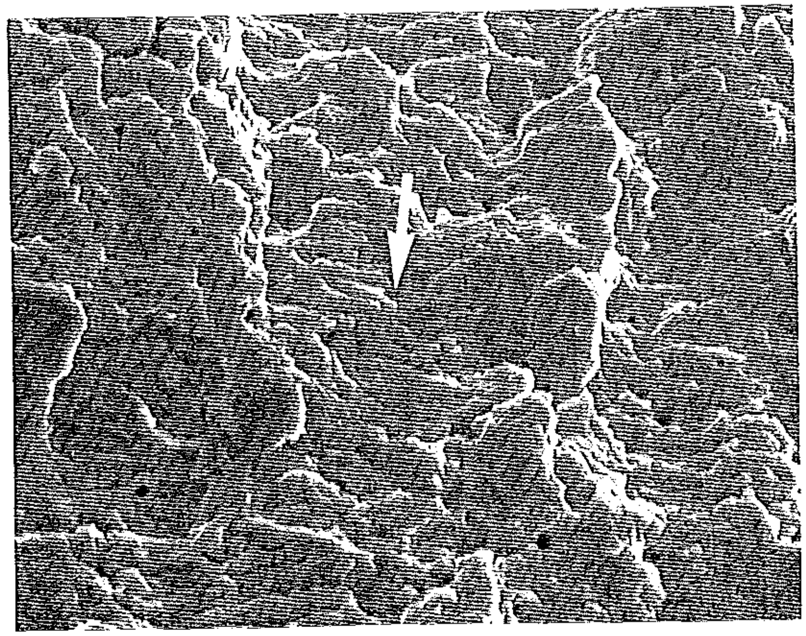
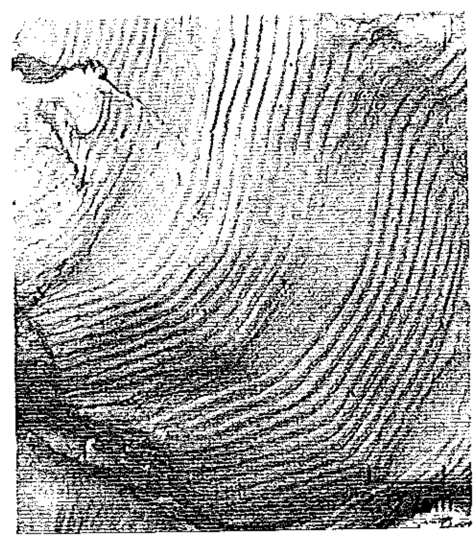


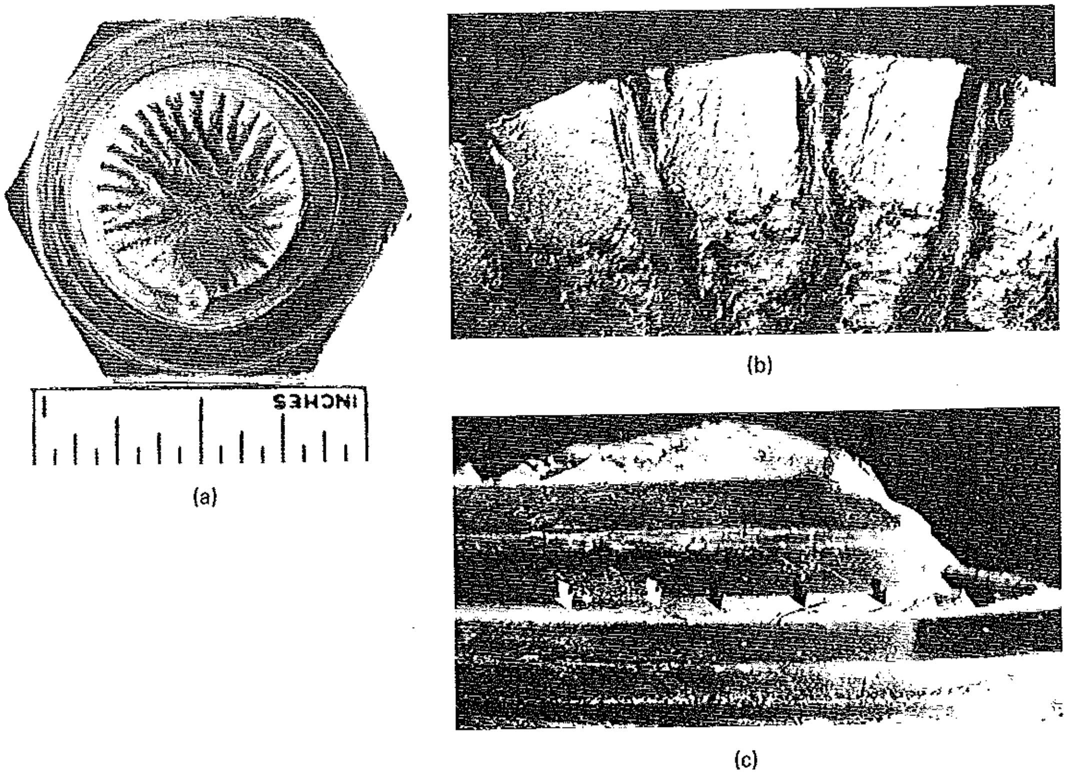
This scanning electron microscope fractograph shows the roughly horizontal ridges which are the advance of the crack front with each load application. The crack progressed in the direction of the arrow. 2000×; shown here at 90%.

Fig. 3(a). Fatigue striations in low-carbon alloy steel (8620).



In this test, the specimen was loaded 10 cycles at a high stress, then 10 at a lower stress, and alternated with these stresses as the fatigue crack continued to propagate. This produced 10 large striations, then 10 small striations, alternately, across the fracture surface. 4900×. (Ref 5)

Fig. 3(b). Fatigue striations showing the result of spectrum loading in a laboratory test of aluminum alloy 7075-T6.



(a) Numerous fatigue origins separated by radial ratchet marks.
(b) Close-up of several fatigue origins separated by ratchet marks. Since this bolt was in a continuously operated test machine, there is no evidence of beachmarks on the fatigue areas. These areas are at a slight angle to the axis of the bolt, as seen in (c).
(c) Fatigue cracks in root of thread (arrows) that have not yet grown large enough to come close to the neighboring cracks to form ratchet marks between them. Note slight angle of fatigue cracks that form ratchet-like appearance upon fracture.

Fig. 7. Multiple-origin fatigue fracture of a short, stubby $^5/_8$-in. bolt that fractured under tensile fatigue.

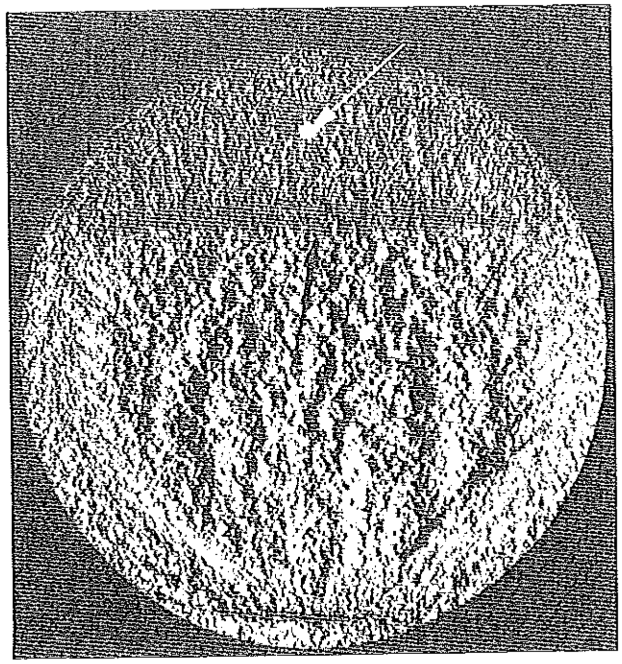
each ring shows the size of the trunk at a given time. By counting rings, it is possible to determine the age of the tree. Striation counting is usually not practical because of the very large number, but it could indicate the number of load applications that made the stage 2 crack enlarge. However, this would provide no clue about the total number of load applications, since those of stage 1 would not be recorded.

• Both striations and beachmarks expand from the fatigue origin or origins, often in a circular or semicircular fashion. This is analogous to circular ripples expanding from the location where a stone is thrown into still water. Obviously, the ripples in the water rapidly disappear, whereas striations and beachmarks leave a record, unless they are

Presence of numerous ratchet marks (small shiny areas at surface) indicates that fatigue cracks were initiated at many locations along a sharp snap-ring groove. The eccentric pattern of oval beachmarks indicates that the load on the shaft was not balanced; note final rupture area (stage 3) near left side.

Fig. 10. Surface of a fatigue fracture in a 1050 steel shaft, with hardness of about HRC 35, that was subjected to rotating bending.

least two means: increasing the hardness (strength) level by more effective heat treatment or using a higher-quality metal with fewer internal discontinuities, such as a vacuum-treated steel. The resultant stress level can be decreased by redesigning to permit a more generous radius in the fillet, or, if that is impracticable, by putting an undercut radius into the shoulder; or by mechanically prestressing the fillet with shot peening or surface rolling. See Chapter 7 on Residual Stresses for more information. Either shot peening or surface rolling, when properly performed, induces compressive residual surface stresses to neutralize the cyclic tensile applied stresses which cause fatigue cracks to form and propagate. This mechanical prestressing can be considered either as increasing the general strength level or as decreasing the maximum cyclic tensile applied stress level. In either case, the result is the same: improved fatigue performance.



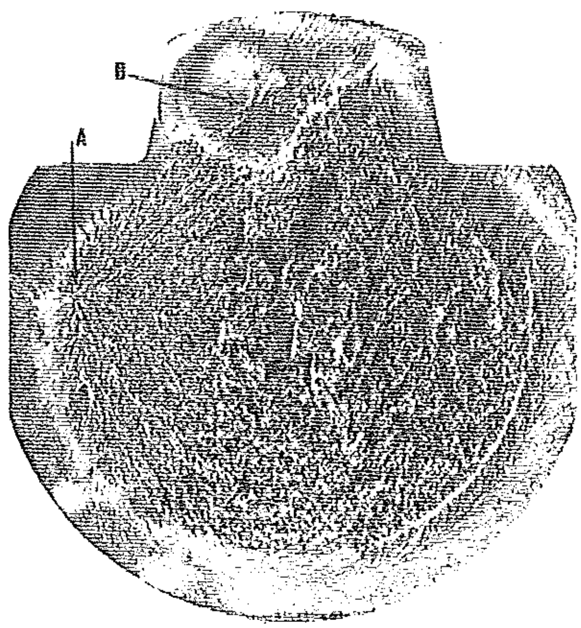
Test was stopped because fatigue crack went about one third of the way around the 0.250-in.-diam test specimen, after being continuously tested at a maximum bending stress of 150,000 psi for 9,300,000 cycles. Crack penetrated partway through the core (black arrow) but was left for many months until the specimen was deliberately broken open (light-colored area). The dark color of the original fatigue fracture area was the result of corrosion from the atmosphere in the laboratory. 12×.

Fig. 12(a). Subsurface fatigue origin (white arrow) on a reversed bending fatigue specimen of carburized low-carbon alloy steel.

Fatigue Under Compression Forces

A seemingly puzzling type of fatigue crack is one that grows in a part, or a region of a part, that is stressed in compression when the part is under load. However, it is not really difficult to analyze this phenomenon if one understands the mechanical formation of residual stresses. Review of Chapter 7 on Residual Stresses is recommended, particularly the section on mechanical residual stresses.

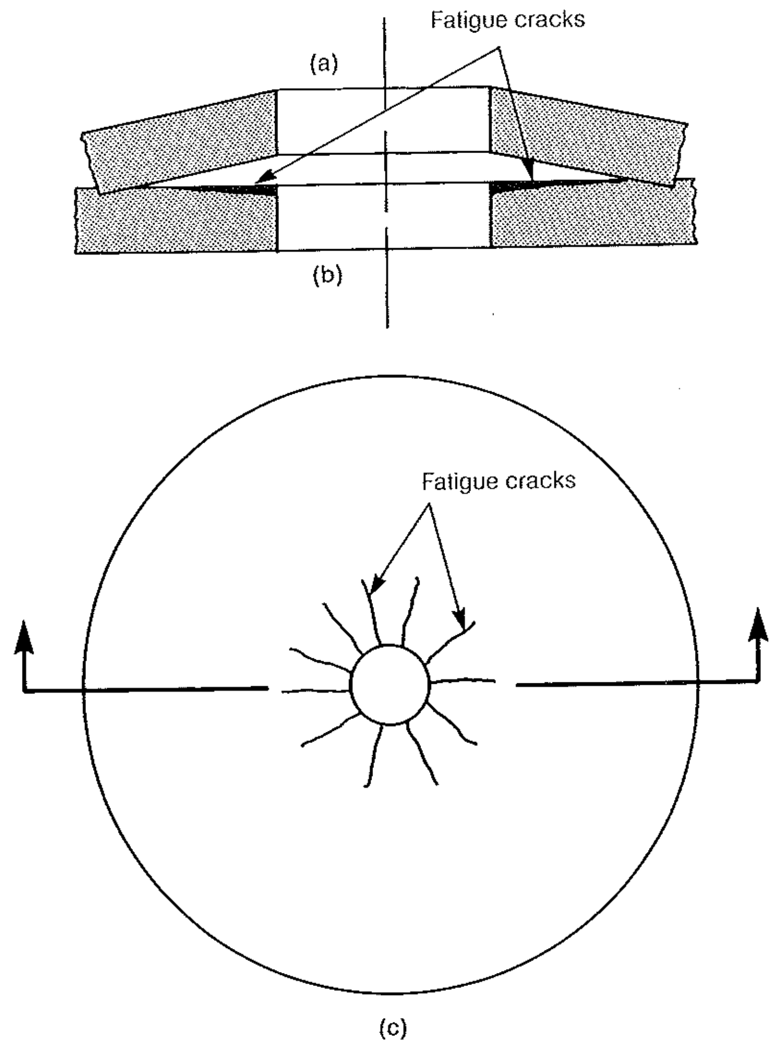
It may be recalled that the general principle of mechanically induced residual stresses is that "*tensile* yielding under an applied load results in *compressive* residual stresses when the load is released, and vice versa." Fatigue under nominal compressive loads is explained by the "vice versa" part of the above statement — that is, "*compressive* yielding under an applied load results in *tensile* residual stresses when the load is released." This type of fatigue fracture can be illustrated with the example of the Belleville spring washer, a hardened spring steel washer that is cone-shaped in order to give high spring rates in limited space, as shown in Fig. 13.



The primary fatigue fracture originated at A, while a smaller crack was progressing at B. Note that no beachmarks are visible because of the continuous testing and that both origins are near the inner edge of the induction-hardened zone. The larger fatigue crack (from A) was in the left third of the fracture before it triggered a brittle fracture in the case (notice the chevron marks at lower right) and ductile fracture in the core. (Ref. 5)

Fig. 12(b). Subsurface-origin fatigue fracture in an induction-hardened 3.25-in.-diam 1541 steel axle which was continuously tested in rotating bending fatigue in the laboratory.

When this type of spring washer is pressed flat, the upper surface and corner of the hole are heavily compressed in a triangular pattern around the hole, as shown by the shaded area in Fig. 13(b). The compressive stress may be so high that the metal yields compressively around the hole. That is, the circumferential compressive stress on the upper side of the plate at the hole forces the metal to yield compressively when the spring washer is pressed flat. When the fatigue load is released, the washer springs back to its original position and the upper surface now is stressed in residual tension as a result of compressive yielding when the load was applied. This is in accordance with the "vice versa" part of the mechanical residual stress principle quoted above. Consequently, the fatigue action causes the necessary tensile stress at this location when the load is released, not when it is applied. With continued operation, radial fatigue cracks will form at the upper corner, as shown in Fig. 13(b) and (c). These cracks are innocuous and do not affect operation because they will not progress to cause fracture. In time, however, normal fatigue cracks



The spring, actually a cone-shaped spring steel washer, is shown in the free condition in (a), and in the flattened condition in (b). When flat, the corner of the hole on the convex (upper) side becomes compressively yielded, causing tensile residual stresses when the load is released. Repetitive loading to the flat condition causes radial fatigue cracks to form on the convex side (b and c), but the cracks do not cause fracture. Eventually, independent fatigue cracks will form on the lower (concave) surface that will lead to complete fracture. See text.

Fig. 13. Sketch of a Belleville spring washer showing how fatigue cracks can form in a nominally compressive stress area.

form at the lower corner of the hole that may eventually cause complete fracture, for this location is stressed in tension when the load is applied.

The solution for this "compression" type of cracking often lies in the field of design, as well as in heat treatment to increase yield strength. In the case of Belleville spring washers, they are frequently made with

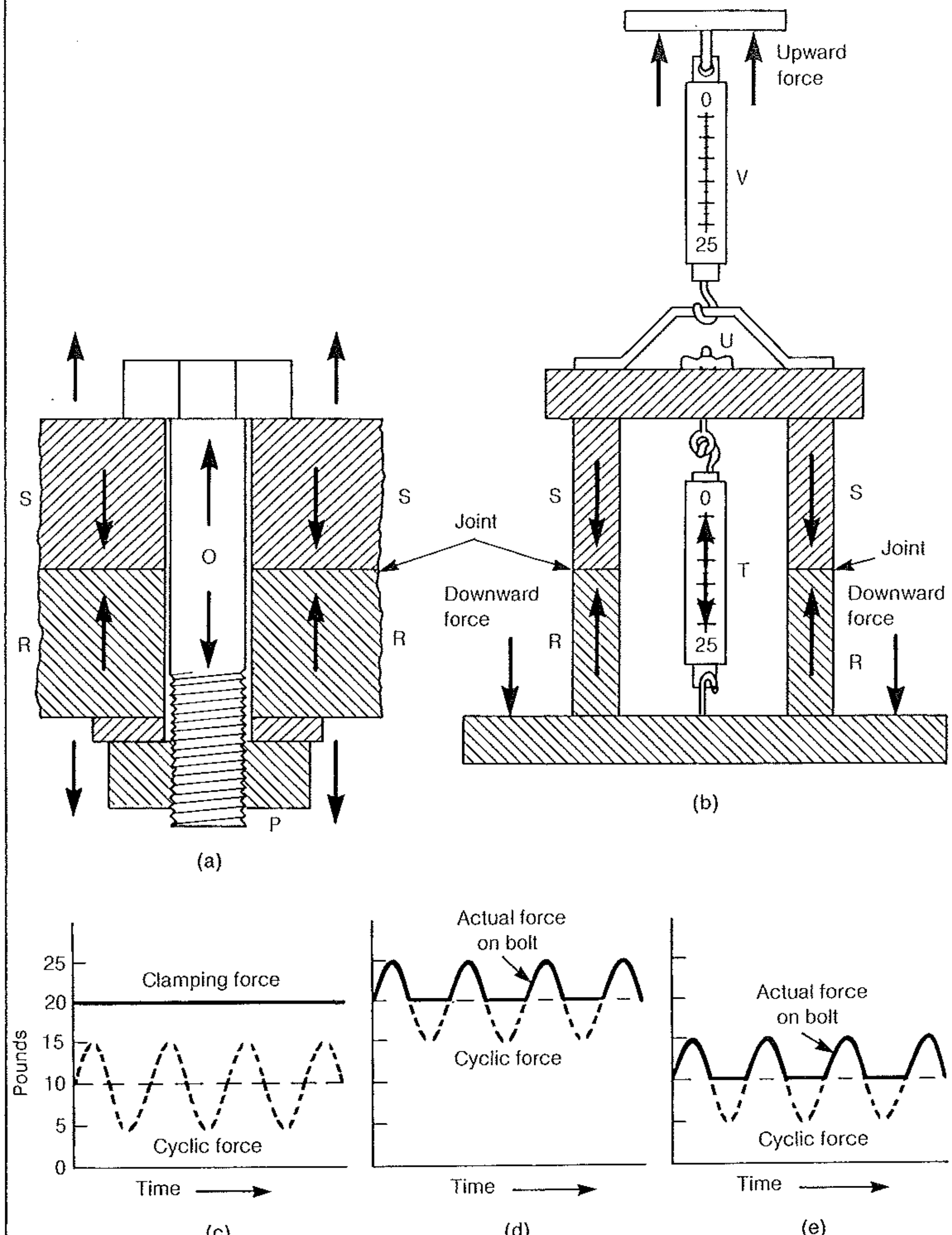
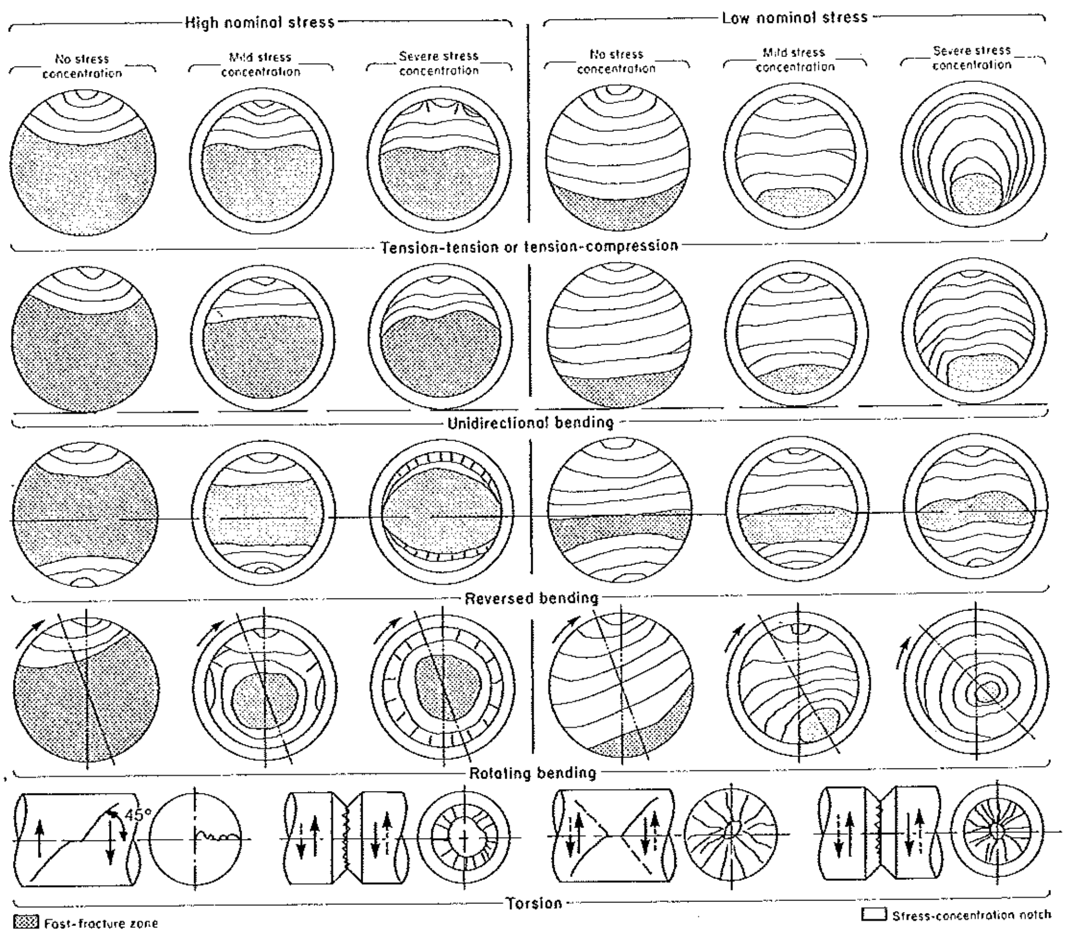


Fig. 14. Demonstration of fatigue of a bolted joint. See text for discussion.

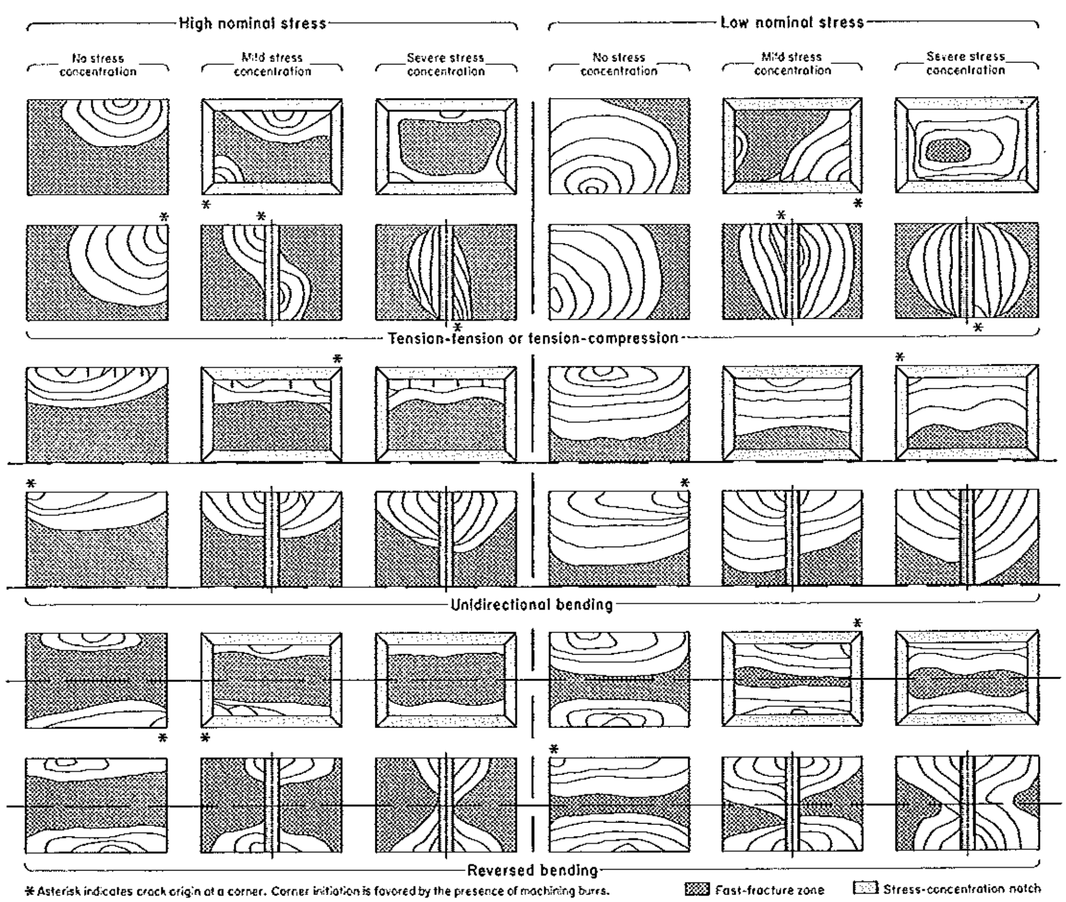


Note that the final rupture zones (fast-fracture zones) on the left half of the figure, which had a high nominal stress, are considerably larger than the corresponding final rupture zones on the right half, which had low nominal stresses. The individual lines in the sketches represent the general configuration of the progression of the fatigue crack, as recorded by possible submicroscopic striations and macroscopic beachmarks. The long dashed lines in reverse and unidirectional bending indicate the bending axes. Also note the radial ratchet marks between origins of the high nominal stress fractures.

In the torsional fatigue fractures (bottom row) note that unidirectional fatigue (left) is at an approximate 45° angle to the shaft axis, while reversed torsional fatigue of a cylindrical shaft (second from right) has an X-shaped pattern with the origin in either the longitudinal or the transverse direction. Torsional fatigue cracks in stress concentrations tend to be very rough and jagged because of the many 45° cracks.

Fig. 15. Schematic representation of fatigue-fracture surface marks produced in smooth and notched cylindrical components under various loading conditions. (Modified from Ref 6)

radial slots from the hole outward, so that a series of "fingers" are the springs that carry the axial compressive force. The slots interrupt the continuity of the circular hole and prevent circumferential compressive and tensile yielding. Shot peening is commonly used on these and many other springs to prevent fatigue fractures.



Note that the final rupture zones (fast-fracture zones) on the left half of the figure, which had a high nominal stress, are considerably larger than the corresponding final rupture zones on the right half, which had low nominal stresses. The individual lines in the sketches represent the general configuration of the progression of the fatigue crack, as recorded by possible submicroscopic striations and macroscopic beachmarks. The long dashed lines in reverse and unidirectional bending indicate the bending axes.

Note that fatigue origins at corners of rectangular shapes or at ends of drilled holes are quite common in this type of part. Also, multiple fatigue origins are quite common with parts under high nominal stress; ratchet marks perpendicular to the surface separate adjacent fatigue areas.

Fig. 16. Schematic representation of fatigue-fracture surface marks produced in components with square and rectangular cross sections and in thick plates under various loading conditions. (Modified from Ref 6)

Other parts that develop fatigue cracks under nominal "compressive" loads should be studied with an eye to reducing the possibility of yielding when the compressive load is applied. The point to remember is that compressive yielding can result in tensile residual stresses that can cause fatigue cracking when the load is released. The cracks

Note smooth origin region (arrow) and gradually coarsening fracture surface as the fatigue crack progressed. Note that there was a thread groove running around the periphery and that the fracture origin is in the root of the thread. However, the nominal stress was quite low because the part was still intact and operating even though the fatigue crack had gone nearly all the way through the section. This indicates that only a slight improvement in the thread groove would be necessary to prevent this type of long-term fracture.

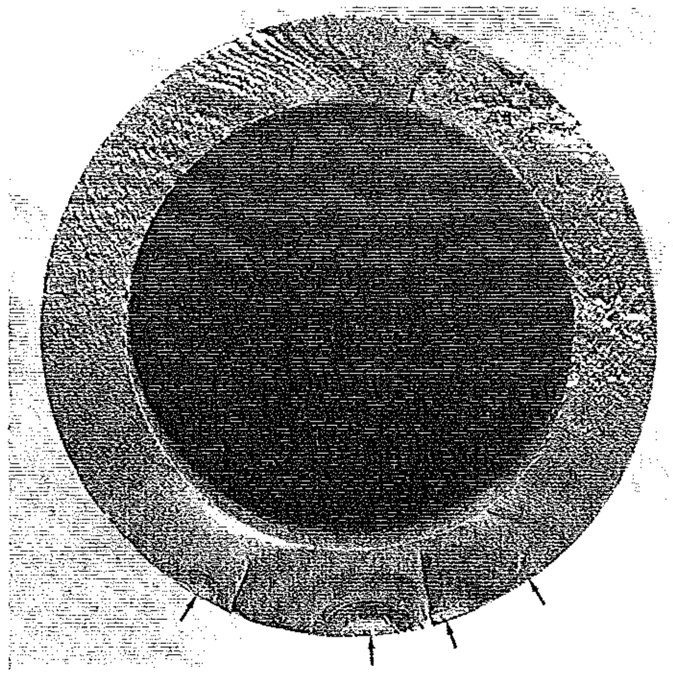
Fig. 17. Large axle shaft of medium-carbon steel with fatigue fracture across most of the cross section before final rupture.

may be harmless to service operation, but they certainly are not desirable and should be prevented.

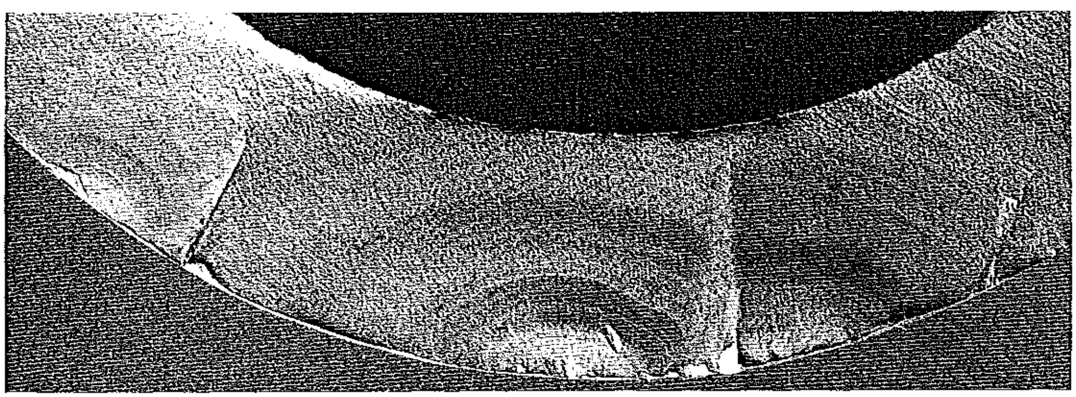
Thermal Fatigue

A somewhat similar type of fatigue fracture is caused not by repetitive mechanical stresses but by cyclic thermal stresses. Review of the section on thermal residual stresses in Chapter 7 will help the analyst understand how thermal residual stresses are formed.

The basic principle to recall is that the metal that cools last will have tensile residual stresses; also, for thermal residual stress to oc-



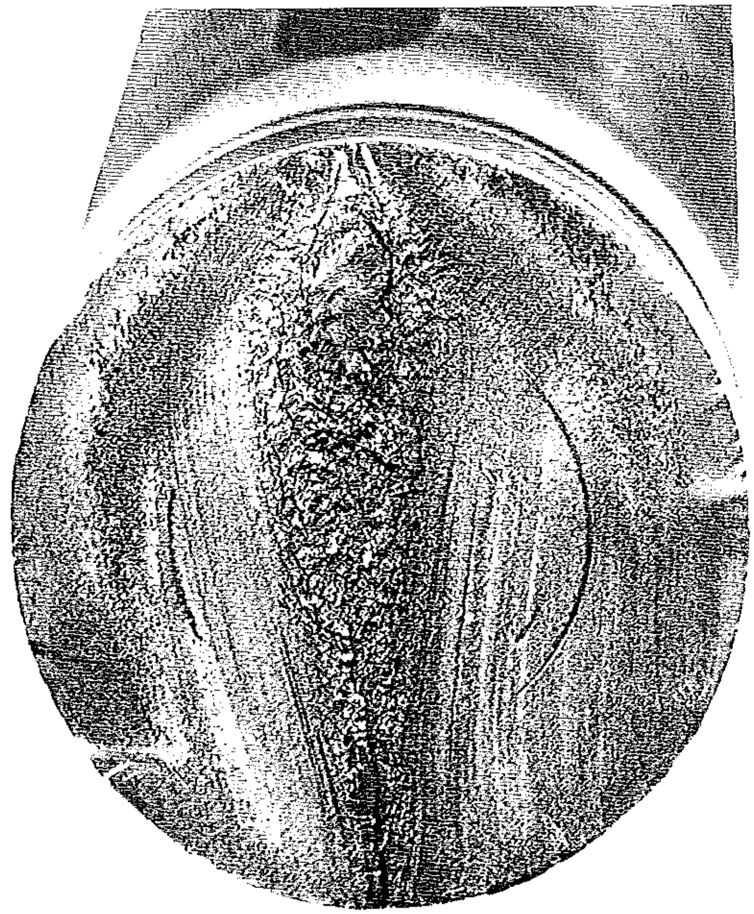
(a)



(b)

This part was subjected to unidirectional bending stresses normal for the operation. The metal was a medium-carbon steel with a hardness of HB 217 to 229. From the origin areas at the bottom, the fatigue cracks progressed up both sides of the tube and joined at the small final rupture area at the top. Note the increasing coarseness of the fracture surfaces as the cracks grew from bottom to top.

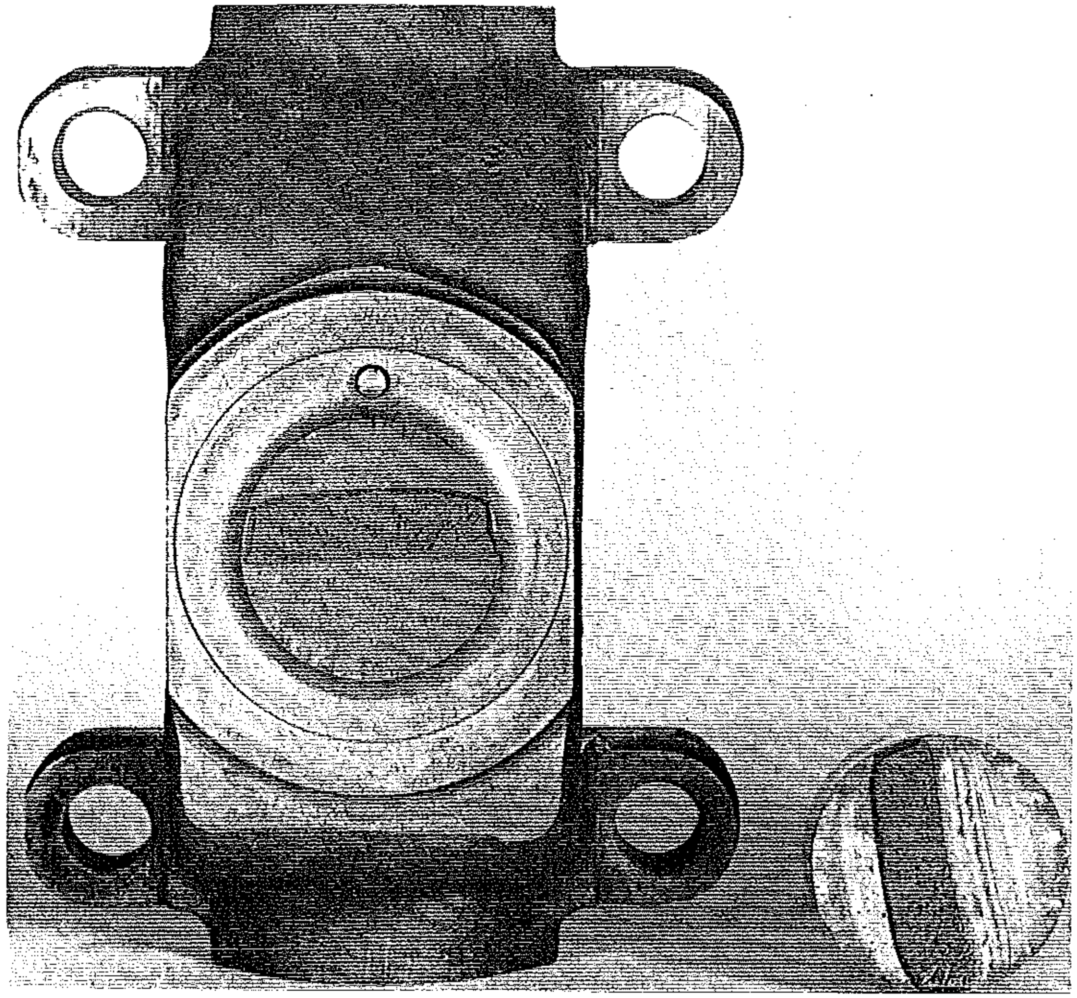
Fig. 18. (a) Fracture surface of a 3.6-in.-diam axle housing tube showing four major fatigue-fracture origins (arrows) at the bottom. (b) Origin areas at higher magnification. Beachmarks are clearly seen. Small areas of postfracture damage are present, but in general the fracture is in excellent condition after careful cleaning.



Note the symmetrical fatigue pattern of beachmarks on each side, with the final rupture on the diameter. This indicates that each side of the shaft was subjected to the same maximum stress and to the same number of load applications.

Fig. 19. Reversed bending fatigue of a 1.6-in.-diam shaft of 1046 steel with a hardness of approximately HRC 30.

cur, it is necessary to have both heat and restraint. If, for example, a sharp edge of a part is repetitively heated and cooled while the restraining bulk of the part remains relatively cool, the sharp edge will expand when heated and contract when cooled. That is, the sharp edge will develop compressive forces and yield compressively when hot because of the lower strength and lower modulus of elasticity at the elevated temperature. When the edge is cooled, tensile residual stresses will form; if this action is repeated many times, thermal fatigue cracks will develop and will tend to grow each time the metal is cooled from the elevated temperature, for it is at that time that the tensile residual stress is again applied. When the metal is hot, the cracks will tend to close, although this will probably be resisted by

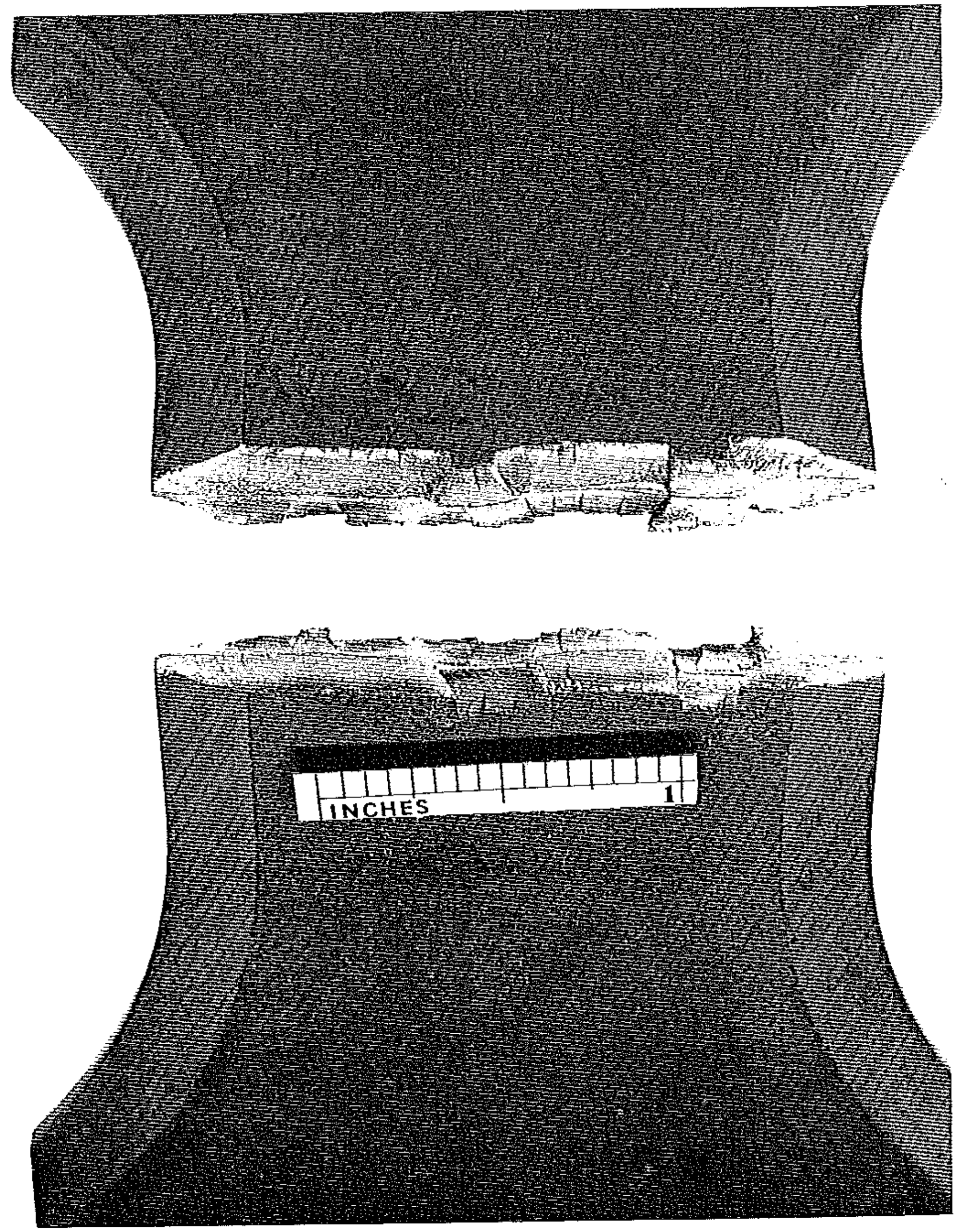


The multiple-origin fatigue at the bottom was caused by the tendency of normal wheel loading to bend the spindle (lower right) of the knuckle upward. The fatigue on the upper side (smaller area) of the fracture was caused by turning maneuvers in which the wheel acts as a lever to bend the spindle downward. Note the many radial ratchet marks on the fatigue surfaces. The part had been overloaded during service.

Fig. 20. Reversed bending fatigue of an alloy-steel steering knuckle at a hardness level of HRC 30 with nonuniform application of stresses.

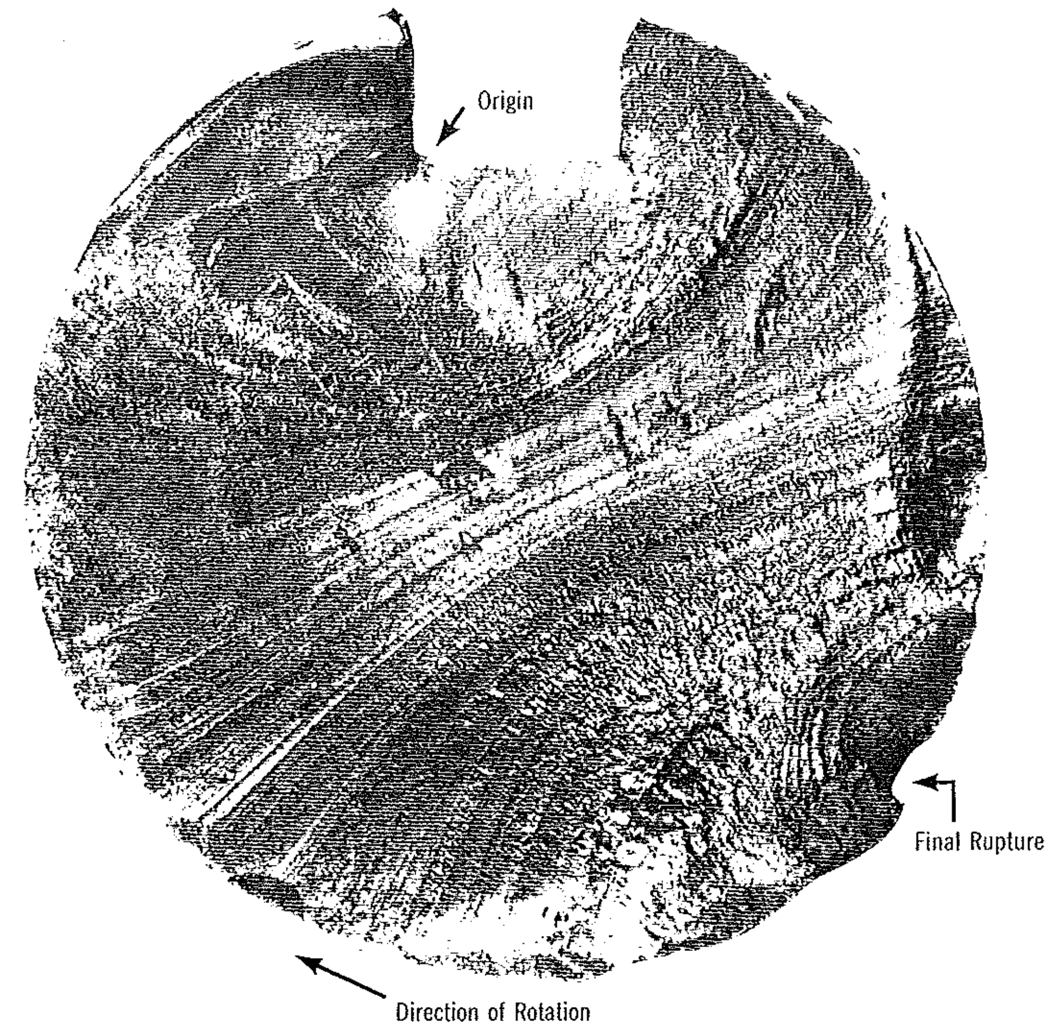
an accumulation of oxide scale or other products of combustion from the high-temperature atmosphere. In fact, these products in the crack can act as a wedge and increase the compressive yielding when hot, so that the tensile residual stress that forms on cooling is increased.

Since both heat and restraint are necessary for thermal residual stresses to occur and repetitive thermal cycling is necessary for thermal fatigue, the methods to prevent such fracture should become obvious. If restraint is internal within the part, as described above with the



Note the many separate origins on each side and the very thin final rupture region separating the two fatigue areas on each half. Many other fatigue cracks were present in the reduced section, for this was designed to have a relatively uniform stress in the reduced section.

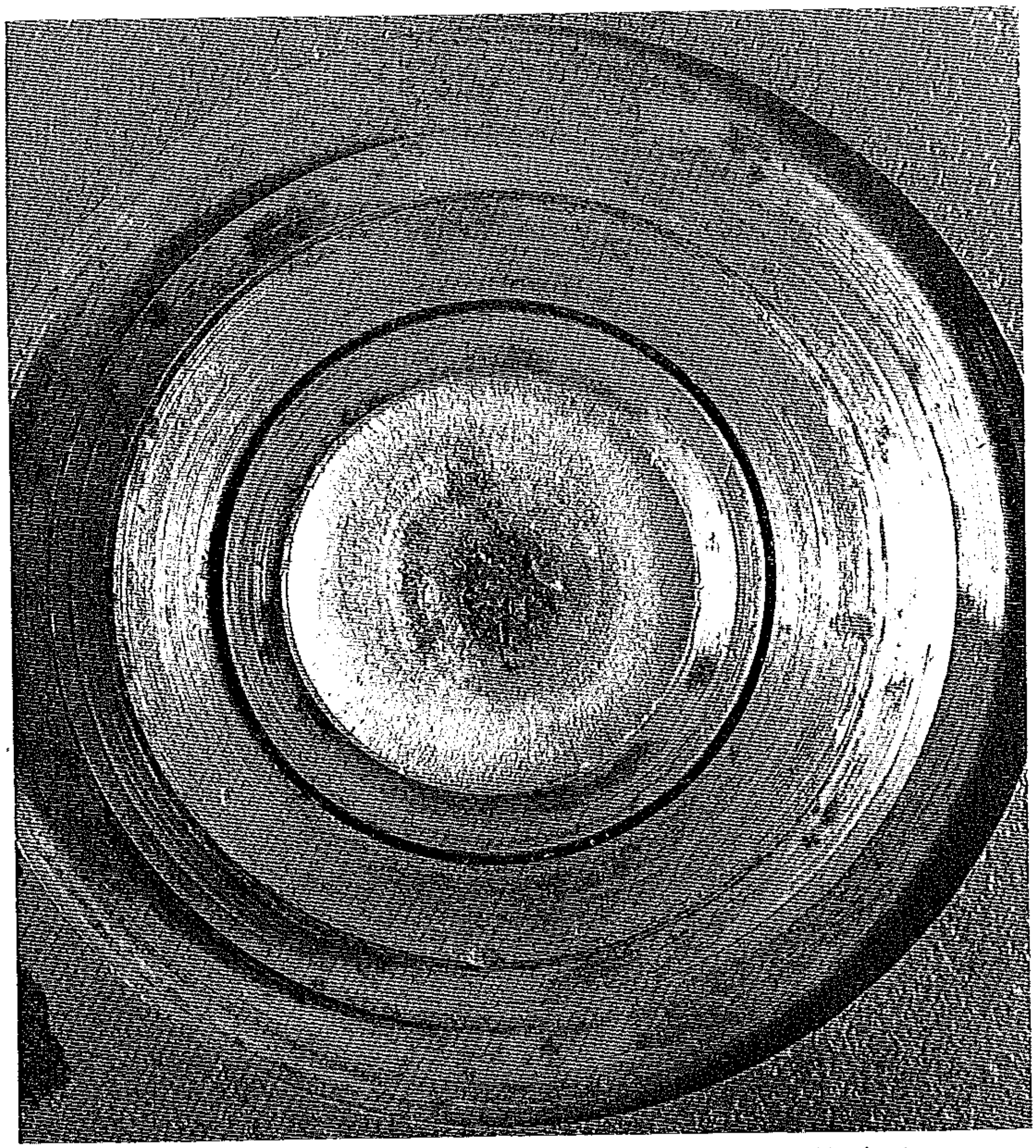
Fig. 21. Reversed bending fatigue of a flat 1/4-in. plate of a high-strength, low-alloy steel test specimen, designed with tapered edges to prevent fatigue origin at the corners.



The fatigue crack originated at the lower left corner of the keyway and extended almost through the entire cross section before final rupture occurred. A prominent beachmark pattern is visible, appearing to swing counterclockwise on this section because the rotation was in a clockwise direction.

Fig. 22. Rotating bending fatigue fracture of a keyed shaft of 1040 steel, approximately HRC 30.

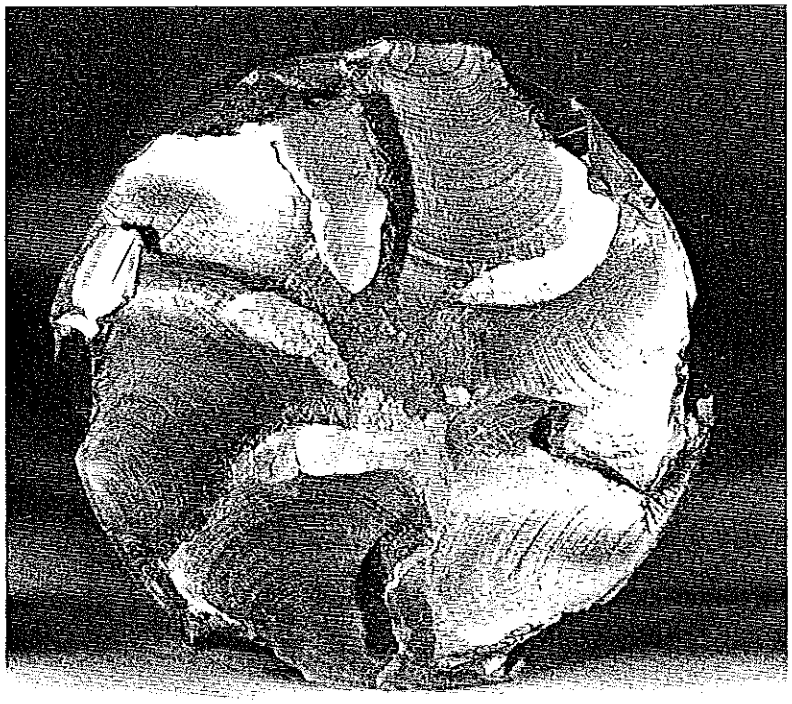
sharp edge, it may be possible to reduce the restraint by permitting the part to expand more uniformly when it is heated, instead of having just the sharp edge expand. If this is not practical, it may be possible to blunt the sharp edge by changing the shape, so that this action is not concentrated on a thin section. Or it may be possible to reduce the thermal gradient within the part by permitting more of the metal to be heated, or to design curves into the part so that expansion and contraction forces simply change the shape of the part instead of de-



The part was designed with a large radius joining the shaft to the shoulder, but it was machined with a sharp tool mark in the fillet. Multiple-origin fatigue around the periphery proceeded uniformly into the shaft, finally fracturing with a final rupture region in the center of the shaft.

Fig. 23. Rotating bending fatigue fracture of a 2-in.-diam 1035 steel shaft, hardness HB 143.

veloping potentially destructive tensile residual stresses. This is the reason that expansion loops are designed into high-temperature piping, such as steam lines. It is also the reason that expansion joints are necessary in bridge and road design. See Ref 7 for more information on thermal fatigue.



The fracture started in six fillet areas around the periphery, near the runouts of six grooves. The six fatigue areas penetrated separately, but uniformly, to final rupture at the center. The bright, shiny, flat areas are regions of postfracture rubbing against the opposite surface. Grinding damage in the fillet was the cause of this fracture.

Fig. 24. Rotating bending fatigue fracture in a 4817 steel shaft, carburized and hardened to a surface hardness of HRC 60.

As in so many types of metal failure, once the principles behind a problem are understood, then one can identify the problem and creatively seek ways to eliminate it.

Corrosion Fatigue

As if fatigue itself were not a complicated enough type of failure, it is further complicated by the addition of a corrosive environment. Corrosion fatigue is the combined simultaneous action of repeated or fluctuating stress and a corrosive environment to produce surface-origin fatigue cracking. In one sense, all fatigue fractures should be considered as corrosion fatigue fractures, for the action of the environment within the fatigue crack is critical to the success or failure of the part involved. The fatigue strength of a part or metal in an inert environment, where there is no corrosion, is higher than that of the same part in an aggressive environment where corrosion may play a significant role.

Both corrosion and fatigue are complex subjects that must be understood separately before they can be understood in combination. For

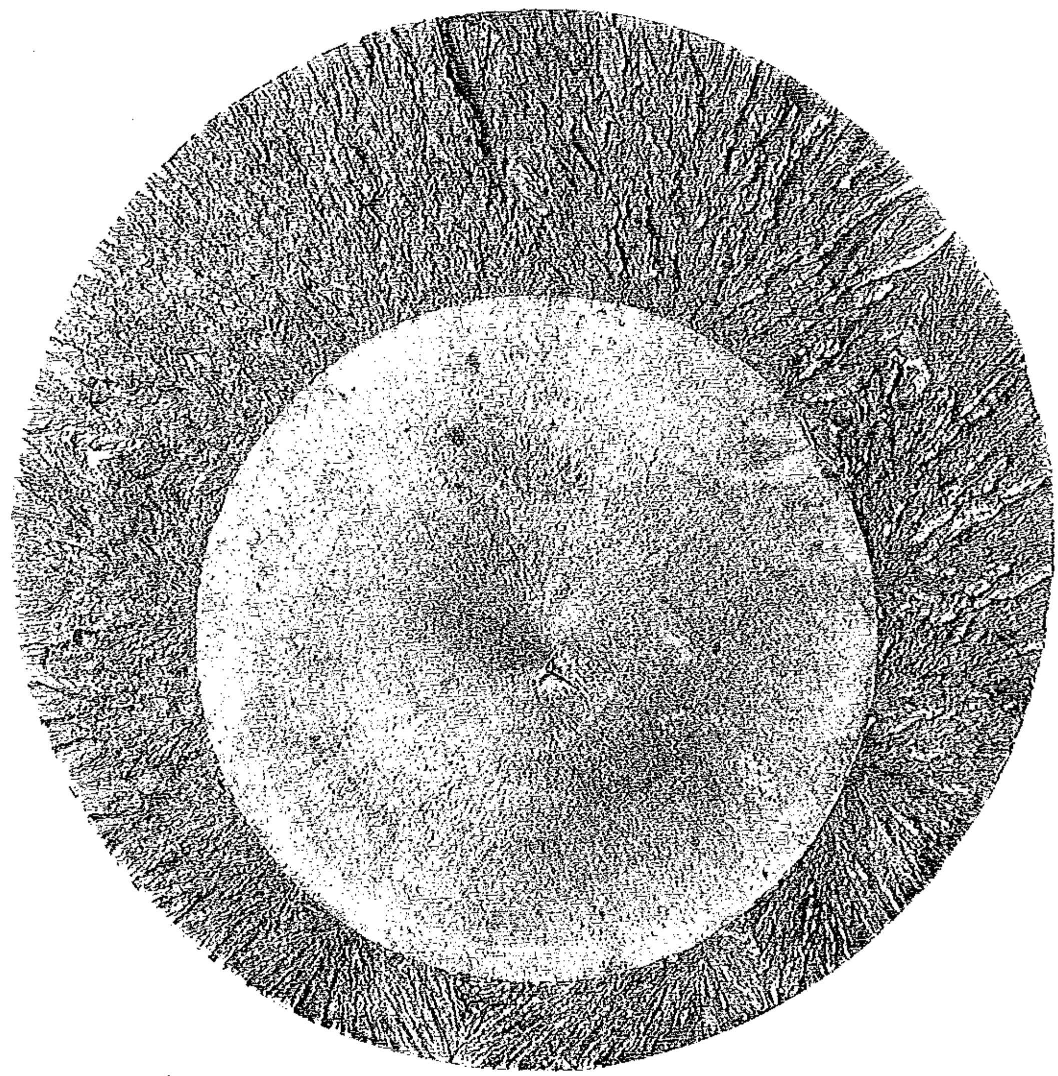
The very prominent steps and beachmarks were the result of severe overloading during starting and clutching with a very aggressive friction material in the clutch. Though this was a laboratory test, it was not operated continuously and thus more closely resembles fracture from actual vehicle service.

Fig. 25. Bending-fatigue fracture through the cheek of a diesel-engine crankshaft.

this reason, the subject of corrosion fatigue will be studied further in Chapter 13 on Corrosion.

Bolt Fatigue

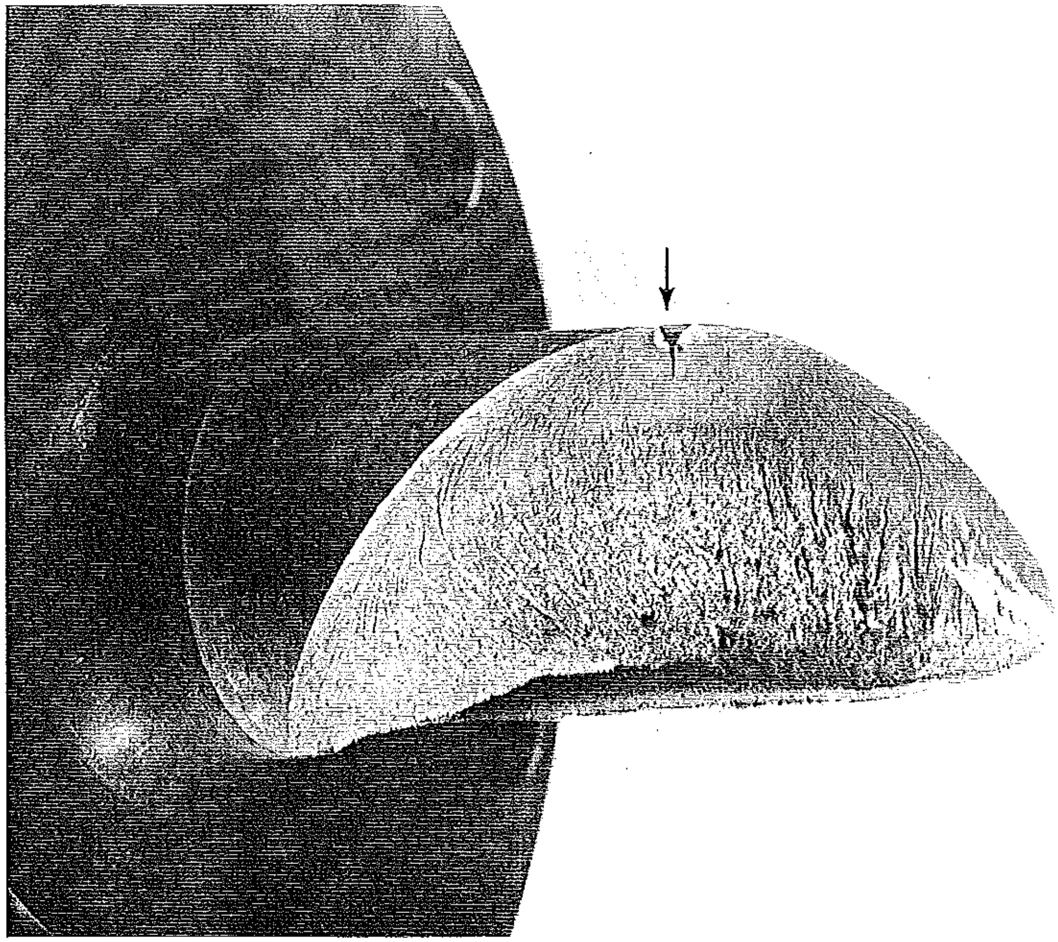
Assuming that a bolted joint is properly designed and assembled, and that the mechanical properties of the bolt and nut are normal, fatigue



In an axially loaded part such as this, fatigue fracture can start anywhere in the cross section. In this case, a forging "flake" caused fatigue to start near the center of the section and to grow outward in a circular fashion until it was about 5.2 in. in diameter, at which time final rupture occurred in one load application. At no time did the fatigue crack reach the surface of the large shaft. Use of a vacuum-degassed steel would have prevented the flake that caused this type of fatigue failure.

Fig. 26. Tensile fatigue fracture starting near the center of an 8-in.-diam piston rod of a forging hammer, made of low-carbon alloy steel hardened to HRC 24 at the surface and HRC 17 at the center.

fracture of the bolt cannot occur unless the cyclic separating force exceeds the clamping force of the bolt. This can occur if the cyclic separating force is too high or the clamping force is too low, or both. This principle is true no matter how the joint is loaded. It is simplest to illustrate with a model that assumes a tensile separating force, as shown in Fig. 14 (p 141) and explained in the following discussion.

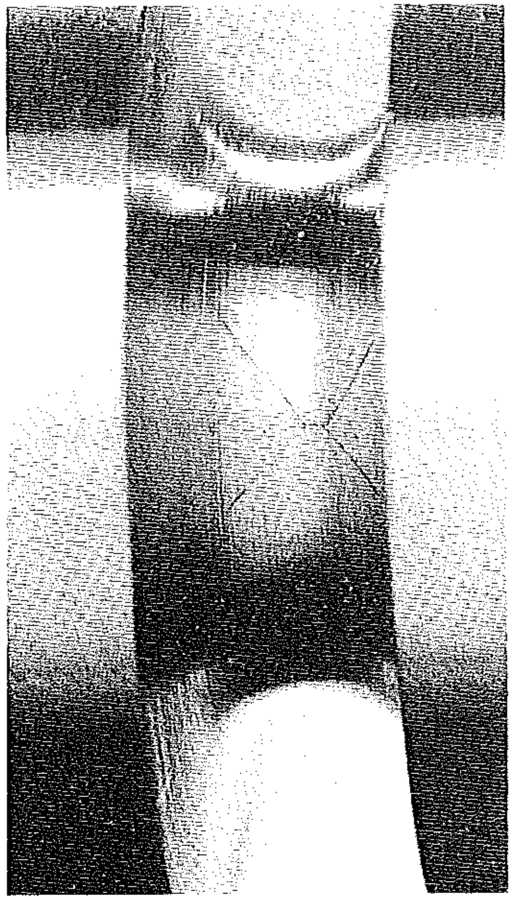


The arrow indicates the longitudinal shear fatigue origin, which then changed direction and grew to the small circular beachmark, or "halo." Final brittle fracture (note chevron marks in case) caused complete separation with the characteristic 45° brittle fracture in torsion.

Fig. 27. Torsional fatigue fracture of a 1050 steel axle shaft induction-hardened to about HRC 50.

A bolt is really a very stiff spring, because all metals are elastic. Figure 14(a) shows a typical bolted joint, in which a tensile force in the bolt O and tightened nut P squeeze parts R and S with a clamping force at the joint, as shown by the arrows. The tensile force in the bolt, caused by tightening of the nut, obviously is equal to the clamping force holding the joint together.

This principle can be demonstrated by replacing the stiff-spring bolt with a soft spring scale in a jointed frame. Figure 14(b) shows a 25-pound spring scale T which can be adjusted with a wing nut U to clamp the joint together. The separating force is provided by another



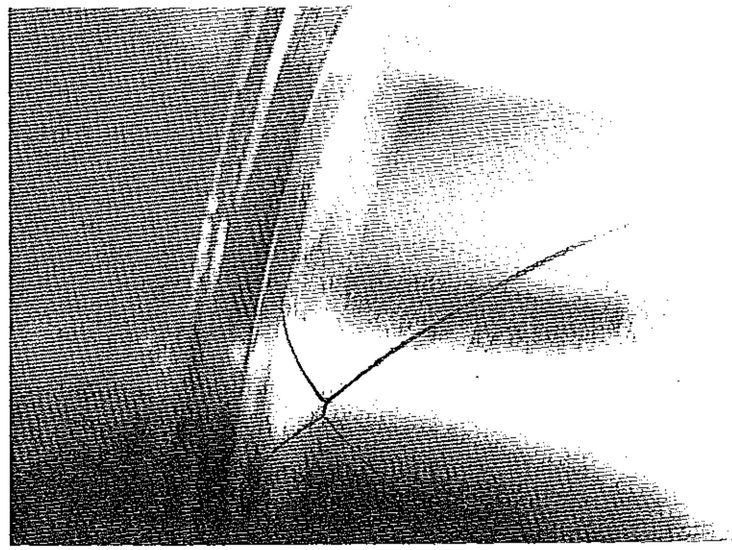
Reversed torsional fatigue causes approximately 45° spiral fatigue cracks on opposite diagonals. The original shear crack was in the longitudinal shear plane; then each pair of torsional fatigue cracks developed at a 45° angle to the shaft axis.

Fig. 28. Close-up of a reduced area on a medium-carbon steel drive-shaft showing the X-shaped crack pattern characteristic of reversed torsional fatigue.

spring scale V which can be pulled to various steady or cyclic loads by the handle.

If the clamping force is set at 20 pounds, the joint cannot separate nor can the force in the "bolt" (spring scale) exceed 20 pounds if the cyclic separating force does not exceed 20 pounds, as shown in Fig. 14(c), cycling between 5 and 15 pounds.

However, if the cyclic separating force is raised to a range of 15 to 25 pounds, the actual force on the "bolt" spring scale increases to 25 pounds because the forces are in series, as shown in Fig. 14(d). When this happens, the joint actually separates and the "bolt" undergoes a cyclic force that could lead to fatigue fracture.



In this case, the original crack was in the transverse shear plane, not in the longitudinal shear plane as in Fig. 28.

Fig. 29. Characteristic X-shaped crack pattern in a 1045 steel crankshaft after testing in reversed torsional fatigue in a special machine, not in an engine.

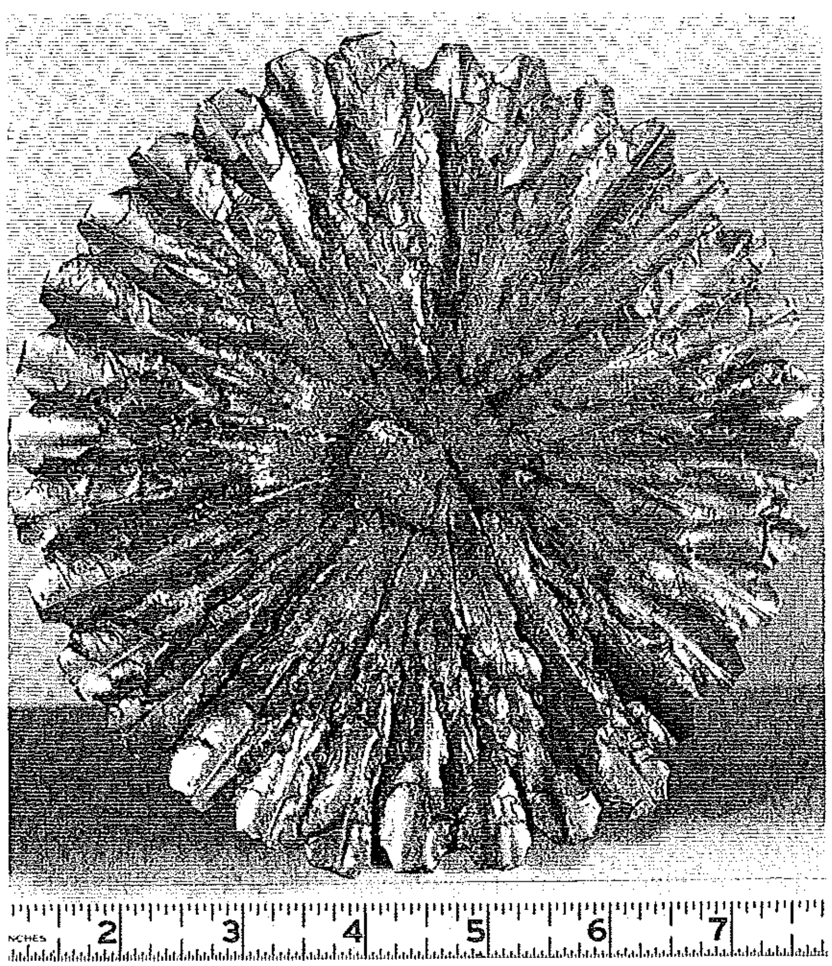
Similarly, if the clamping force drops to 10 pounds, cyclic forces in the "bolt" again can occur, although at a lower level, as shown in (e). When the actual force on the "bolt" exceeds the clamping force, the joint separates and the "bolt" again is subject to fatigue fracture. This principle is also discussed in some detail in Ref 8.

STATISTICAL ASPECTS OF FATIGUE

In discussion of laboratory fatigue testing, the term "scatter" was used to describe the variability of results, or the fact that not all specimens tested at a given load or stress fracture at the same life, or number of stress cycles. Supposedly, the specimens are identical; actually, however, they cannot be identical even though they have the same nominal dimensions, chemical composition, heat treatment, etc. The reason is that each specimen is composed of a very large number of different grains, or crystals, each of which has different orientation and imperfections. Before the fatigue test, we have no idea where or when fatigue will originate and propagate to fracture.

Let us try to explain this variability with a simple analogy:

Assume that the critical area has a million grains, as was done

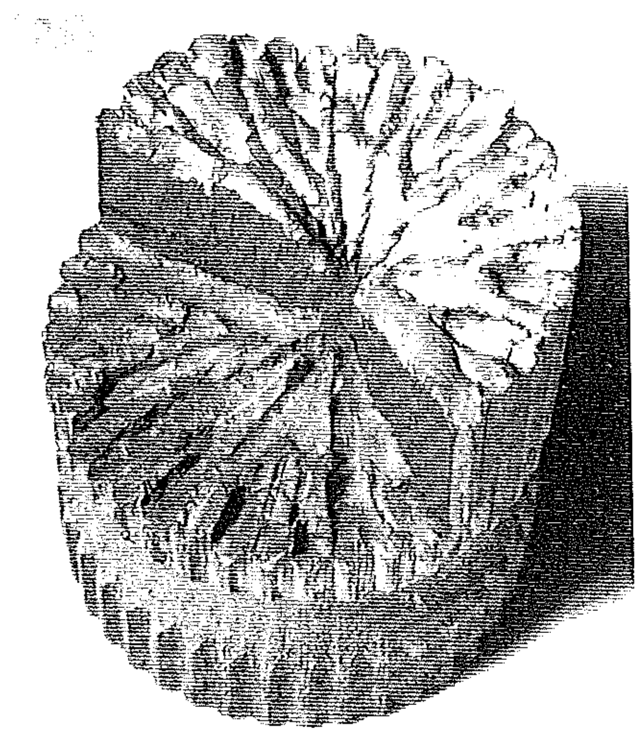


Each of the 32 spline teeth has two fatigue cracks, each at 45° to the shaft axis, that form a V-shaped region. In addition, there are longitudinal radial fatigue cracks that penetrate nearly to the center of the shaft. This type of fatigue progresses at each location where a shaft enters an internal spline, and is repeated if there is an internal spline at another location on the shaft. These cracks surround portions of the metal, forming essentially wedge-shaped segments, somewhat like those of an orange.

Fig. 30. Reversed torsional fatigue of a $6^3/_4$-in.-diam spline shaft showing the characteristic "starry" pattern of multiple fatigue cracks.

earlier when discussing fatigue origins, or that we have a population of a million "identical" parts to operate at one load or stress level.

Compare these "identical" grains or parts with a million "identical" kernels of popcorn, which are actually miniature pressure vessels. When all kernels are placed in the same environment (hot air or hot oil), the internal pressure in each kernel increases as the moisture turns to steam. Eventually, the internal pressure (or stress) will equal the strength of the hull, the strong exterior of the pressure vessel. When this hap-



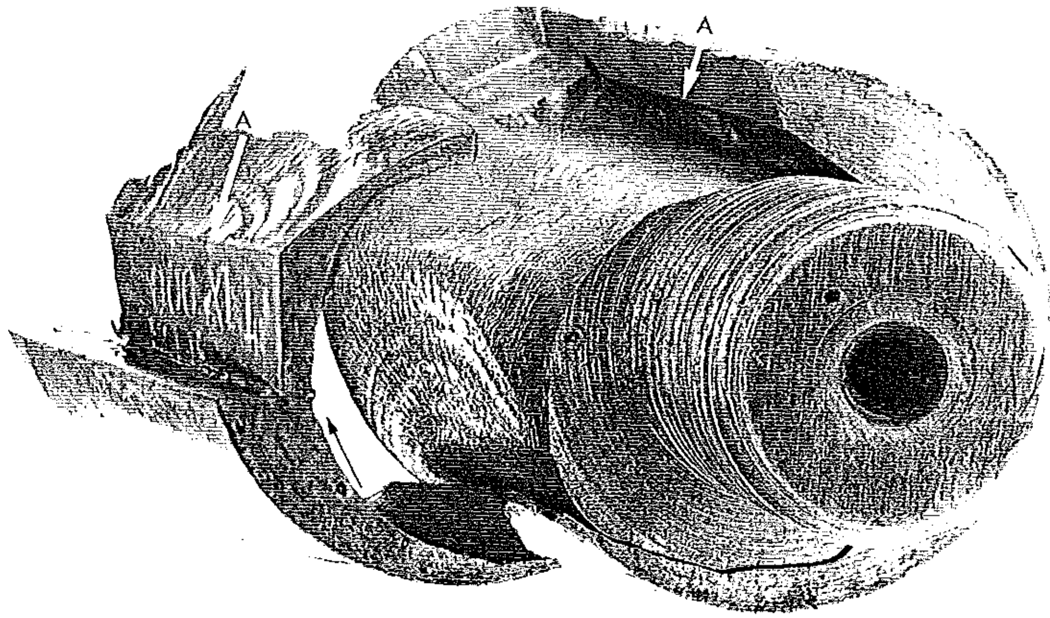
Torsional fatigue has caused many of the surrounded segments to fall out of the shaft. Note that the longitudinal cracks penetrated nearly to the center of the shaft. This part is made from low-carbon alloy steel with a hardness of HRC 24 in the shaft area.

Fig. 31. A "starry" spline fracture similar to that in Fig. 30 due to reversed torsional fatigue on a 1½-in.-diam spline.

pens, the hull will fracture, the steam is released, and we say that a kernel has "popped."

However, note the way in which the kernels fracture, or "pop." The million kernels do not go "bang" all at the same time, but instead first one pops, then another, and another, until they are popping furiously. Gradually, the popping tapers off until a few are left that do not fracture (and we throw them away!).

The "random" sequence of popping (actually fracturing) can be explained as follows: The first kernel to pop is the one in which the internal pressure first reaches the fracture strength of the hull. The next one to pop is the next in the sequence, and so on. The kernels that do not pop at all are those in which, for some reason, the moisture content is low, the strength of the hull is high, or the hull had a hole or crack that permitted the steam to leak out without building up pressure to the fracture stress.

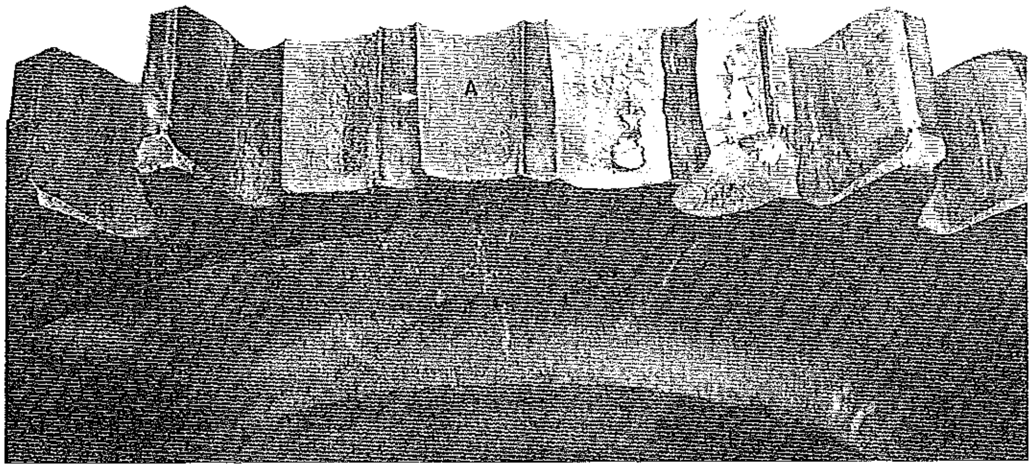


The fatigue crack originated in the corner A of the keyway from pressure of the key aligning a large hub to the shaft. The fatigue crack progressed completely around the shaft, under the keyway, and started around again, all in a clockwise direction, before final separation occurred and nearly broke off the "wing" at left. The only thing necessary to prevent this type of fracture is to make sure that the large nut which forces the hub to fit tightly against the tapered surface does not come loose. If the nut is loose, the key and keyway, rather than the frictional fit of the conical joint, carry the torsional force.

Fig. 32. Torsional fatigue fracture in a $3^3/_8$-in.-diam keyed tapered shaft of 1030 steel characterized by "peeling" that progresses around the shaft.

The point is that there is no way that we can determine in advance which kernels will pop first, which will be in the main group, or which will not pop at all. The popping occurs in a rough distribution curve of the entire "pop"-ulation, although there are some "runouts" that do not fracture, as in fatigue testing near the fatigue limit. The variation in time to pop is analogous to the scatter in cyclic fatigue life of a group of specimens that are as supposedly identical as are the popcorn kernels.

Because of the scatter in fatigue-testing results and in parts subject to fatigue loading in service, there have been many statistical methods used to try to describe and control this problem. All have limitations in trying to predict the fatigue behavior of a group of parts. Some of the suggested references contain statistical information which is beyond the scope of this work.



It can be seen that tooth A fractured first, for it has the largest fatigue area, originating in the fillet on the arrow side of the tooth. Gear teeth are carefully shaped cantilever beams and can be diagnosed in this way. Fracture of the first tooth caused abnormal loading on the adjacent teeth and they also rapidly fatigued, for the mating gear did not now mesh properly with them. Considerable smashing and battering of adjacent teeth is normal after gear-tooth fracture.

Fig. 33. Bending fatigue fractures in several teeth of a 8620 steel spur gear, carburized and hardened to HRC 60 in the case.

EXAMPLES OF FATIGUE FRACTURE

Since there are a very large number of types of parts and materials that can undergo fatigue fracture, it is impossible to show examples of all combinations. However, a few of the most common types are shown schematically in Fig. 15 and 16 and in the photographs (Fig. 17–33) that follow. Many others are shown in Volumes 9 and 10 of *Metals Handbook*, Eighth Edition, and many of the other publications devoted to the subject of fatigue and fatigue fracture.

SUMMARY

Fatigue fracture is a progressive type of fracture that may occur under normal service operation in three stages: (1) initiation, by a submicroscopic shear, or slip, mechanism that causes irreversible changes in the crystal structure of the metal; (2) propagation, by an increasingly rapid progression of the tip of the fatigue crack in microscopic advances; (3) final rupture, which is final separation, or fracture, into two or more parts by a single load application.

Fatigue fractures have several microscopic and macroscopic features that may enable them to be properly identified. These include lack of permanent deformation in the origin area, striations, beachmarks, and ratchet marks. Unfortunately, these features are not always present or readily observable on the fracture surfaces, depending upon the characteristics of the metal itself, the type of operation to which it was subjected, and possible obliteration by pre- or post-fracture damage by mechanical and/or chemical action.

Compression fatigue and thermal fatigue are understood most easily with the aid of residual-stress principles.

Fatigue fracture is highly subject to statistical variations because of the submicroscopic origins and internal differences in parts. Thus, there is usually considerable variation, or scatter, in fatigue life of supposedly identical parts. For this reason, fatigue fractures are difficult to predict with any accuracy, except in terms of statistical probability, as discussed in several of the references.

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3. *Metals Handbook,* 8th Ed., Vol 10, American Society for Metals, 1975, p 97
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Selected References for Further Study

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