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METAL FATIGUE

and its RECOGNITION

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Introduction

This bulletin was written to serve as a useful tool in the understanding and recognition of fatigue failures. Its primary objective is to aid Civil Aeronautics Board field investigators in their investigation of aircraft accidents; but the bulletin also has a secondary purpose, i.e., to provide general information to anyone interested in fatigue. The photographs contained herein were taken from the Civil Aeronautics Board's extensive accident files and from National Bureau of Standards reports prepared for the Civil Aeronuatics Board. The two tables are from *Why Machine Parts Fail*, by Charles Lipson, *Machine Design*, May–December 1950.

WHAT IS FATIGUE?

When a metal part or structure is placed under a steady, static load less than the known limit strength of the metal, the structure should theoretically last forever, provided proper precautions are taken against such things as corrosion and creep. If, however, the part or structure be subjected to repeated or fluctuating loads or loads with changes of direction, it may fracture at a stress level far lower than that required to cause failure under static conditions. This phenomenon is known as fatigue and has been found to be the most common cause of primary failures of metals in service. Laboratory tests have proven that a fatigue fracture is progressive in nature; after a number (often many millions) of cycles of stress, a small crack forms in the region of highest stress. Under continued stressing, this fatigue crack will grow in a direction generally perpendicular to the tensile stress until the cross section of the member is reduced to such an extent that the remaining area fractures from overload. Consequently, the surface of a fatigue fracture shows two characteristic regions which are usually quite different in appearance.

Because the first phase of the fatigue mechanism takes many cycles and often a long period of time, the progressive portion of the fatigue fracture will be relatively smooth. Two factors affect the smoothness of the fatigue portion, i.e., the continued rubbing that occurs between the two faces of the crack, and the fact that the crack tends to propagate in a straight line and thus tends to produce a smooth surface initially. That portion of the fracture which failed instantaneously, however, will have a rough, grainy surface. The stress required to initiate a fatigue crack is usually less than that required to cause plastic deformation. Therefore, the progressive portion of a fatigue fracture is characterized by its brittle nature, while the instantaneous zone will show some ductility.

Fatigue fractures can usually be classified as simple or compound. A simple fatigue fracture results from a single crack that spreads over the cross section and causes ultimate failure. A compound fatigue fracture results from two or more cracks that spread from different points on the periphery of the section and cause a joint effect on the fracture appearance.

Fatigue deformation is in essence a fluctuating plastic strain of fairly small amplitude. Although it has not been proven conclusively, pure fatigue appears to proceed primarily by localized fine slip.

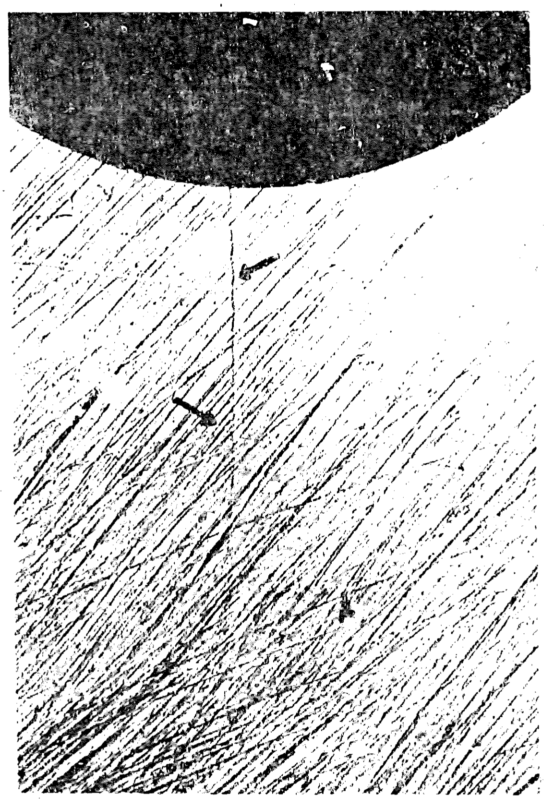

FIGURE 1.—*Magnified view of a fatigue crack. Note the straight line propagation of crack.*

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FACTORS AFFECTING FATIGUE STRENGTH

General

The fatigue strength of any part or component primarily depends upon the actual stress and strength of the metal in a highly localized area and not on the nominal stress or gross properties of the part. The fatigue strength of a part is also dependent upon the magnitude and frequency of loading and the manner in which the load is applied. This section is devoted to some of the more important factors affecting the fatigue strength of a part as it is related to material resistance.

Factors Which Impair

If a smooth, polished, sound specimen is placed into a fatigue testing machine and tested at a particular stress level, it will fail after a certain number of cycles. But if a notch is machined into a similar specimen and the piece is tested as before, i.e., at the same nominal stress level, the specimen will fail at a lower number of cycles than before. The ratio of the greatest stress in the region of the notch, or any other stress raiser, to the corresponding nominal stress is called the stress concentration factor.

Stress Raisers (Notches)

A notch may be defined as any change of section which alters the local stress distribution. This definition, therefore, includes keyways, circumferential grooves, holes, contour change, threads, scratches, etc.

Almost all structural materials are sensitive to notches and, as stated before, the fatigue life of a part with a notch is less than for one without a notch. In some types of materials, there is evidence to indicate that the harder or higher tensile strength alloy is more notch sensitive than the softer alloys. This is especially true for steel. The extreme notch sensitivity of the high strength steels makes it dangerous to use steel heat treated much in excess of 160,000–180,000 psi ultimate tensile strength unless great attention is given to fatigue considerations. Since notches as such cannot be completely eliminated from any design, the manufacturer must work toward lessening their harmful effects. Generous fillet radii will help to reduce the high stress concentration in some instances. There are many methods that may be employed to improve the fatigue life of threaded parts. Two such methods are to have the threads cold worked by rolling and by undercutting the shank adjacent to the last thread with a smooth, round bottom groove slightly deeper than the thread roots.

Many severe fatigue failures can be traced to notch effects. Failure will occur in an area containing a notch, rather than in an unnotched area, due to the resulting stress concentration. Because of this, in examining the wreckage after a structural failure accident, the investigator should give particular attention to fractures originating at changes in section, at bolt holes, etc. Of course, not all of these fractures will be fatigue failures, but if there is such a failure, it will probably occur at such a location.

Stress Raisers (Inclusions)

Although all metals have some inclusions (i.e., non-metallic particles encased in the metal matrix), only those near the surface of the part can appreciably affect its fatigue life. Due to the high quality control in the manufacturing of aircraft parts most inclusions are extremely small and the presence of an inclusion in a fatigue failure must usually be determined by microscopic examina-

FIGURE 2.—*A corrosion-fatigue failure of a steel sucker rod used in pumping an oil well.*

tion. However, there have been a few cases of fatigue failures that have been caused by inclusions which were clearly visible without magnification, but these cases are extremely rare.

Decarburization

Decarburization is the loss of carbon from the surface of a ferrous alloy as a result of heating in a medium that reacts with the carbon. The final result is a soft skin or "back" on the surface of the part, which reduces the fatigue properties considerably. Because the chromium-vanadium and silicon-manganese spring steels are especially susceptible to this effect, decarburization is an important consideration in spring design. Decarburization does occur in other steels, however, and fatigue failures originating from this source are found in bolts, forgings and other steel parts. To eliminate this difficulty, the usual procedure that is used is to machine the soft skin off the part. Decarburization usually occurs with a notch, and the accumulative effect is to make the notch more severe.

Corrosion

When a corroded part undergoes repeated loading, the normal fatigue life value for the metal is appreciably reduced. This reduction should be expected because the pits on the corroded surface act as notches and produce the same deleterious effects as notches. If the repeated stress is applied while corrosion is taking place, a special type of fatigue called "corrosion-fatigue" occurs. This simultaneous application of corrosion and repeated stress is much more harmful to the part than repeated stress being applied after the part is cor-

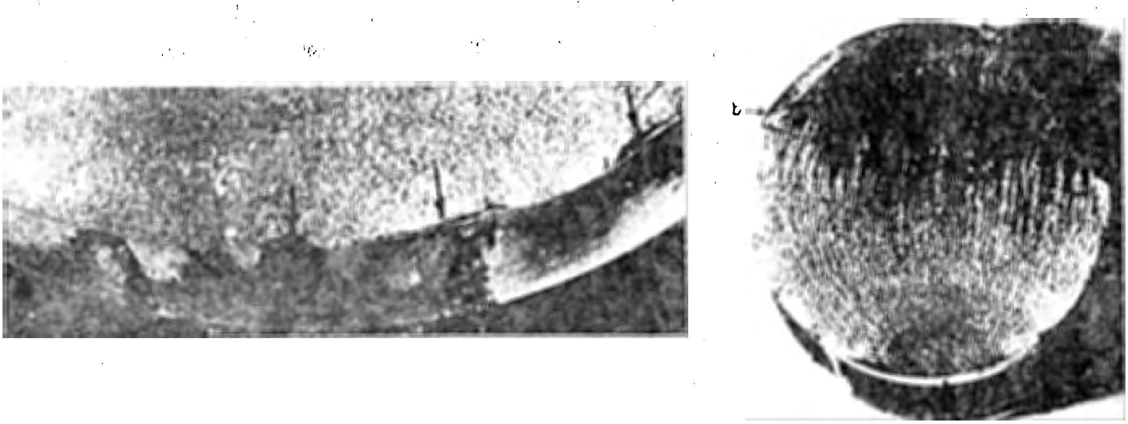

FIGURE 3.—*A fretting corrosion-fatigue failure of a propeller blade. (Right) fatigue fracture originated at arrow "a" and extended to arrows "b". (Left) portion of fracture and adjacent surface of blade showing the relation of dark areas (arrows) on the fracture to those on the external surface.*

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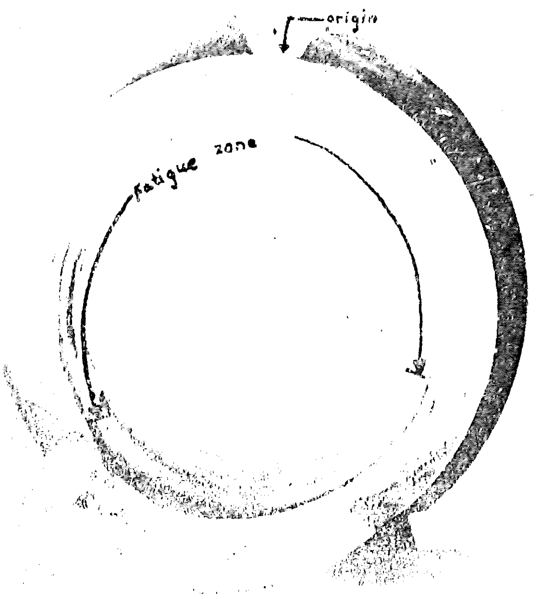

FIGURE 4a.—*A fretting corrosion-fatigue failure of a propeller blade. Fracture surface showing orgin and extent of crack propagation.*

roded. One explanation for this effect is that the notch or pit formed by corrosion is opened when the piece is subjected to tension and becomes filled with rust or other corrosive products. When the tension is released and closes upon the corrosion products it contains, these products exert a wedging action producing cracking. Under the simultaneous effect of fatigue loading and corrosion, steel has no definite endurance limit.

Fretting corrosion is a special type of corrosion-fatigue. Fretting corrosion occurs when two parts are press-fitted, clamped or shrunk together and subjected to vibratory loads. In steel a reddish-brown discoloration is visible on the affected surface while in aluminum or magnesium the discoloration is black. Fretting corrosion roughens the surface, inducing local stress concentration which results in early fatigue failure.

Internal Stress

Some fabrication processes or heat treatments may develop tensile or compressive stresses on the surface of a part. The introduction of tensile stresses into the surface of a part will lower the fatigue strength. The residual surface tensile stress will add to the design tensile stress and may produce a total stress higher than the designer had anticipated. If the piece is then subjected to repeated loading, the result will be early fatigue failure. Usually pertinent information regarding residual stresses can be gained only by a laboratory investigation or by a study of the history of the part. Cold working, heat treatment (including quenching practices), cold straightening, drawing or rolling, and other fabrication processes may all result in the introduction of residual stresses into the part.

Clamping and Press-Fit

When a shaft has a collar clamped to it, or when a press-fit assembly is made without any planned distribution of local stress, a condition is created similar to that produced by a sharp inside corner; i.e., a stress concentration is created. This concentration is due to the change in section size, clamping stresses and fretting. The change in section size is a critical consideration only when there is a load transmitted through the press-fit or clamp. In one case it was shown experimentally that when a collar was clamped to a smooth shaft, the shaft's endurance limit was reduced from 88,000 psi to 45,000 psi. Failures in engine parts are often attributed to stresses caused by clamping. A number of propeller blade failures have also been attributed to clamping stresses. Control system parts and helicopter shafting are sometimes similarly affected. In many cases, the initial crack originates in the press-fit and cannot be detected until failure occurs. It is the belief of some experts that the life of fuel-line tubing under vibration loading is primarily controlled by the fittings and clamps.

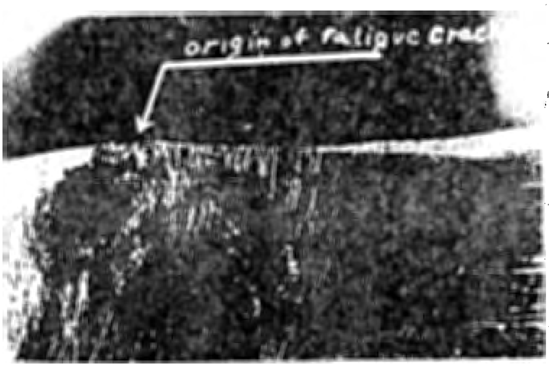

FIGURE 4b.—*Corrosion on side of blade, clearly visible.*

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RECOGNITION OF FATIGUE FRACTURES

Considerable information concerning the nature of a fatigue failure can generally be obtained from an examination of the face of the fracture. Information in relation to the magnitude and direction of loading and the presence or absence of stress concentrations can be obtained by a careful study of the fractured surfaces. Interpretation of the fracture, however, may not always be a simple matter, because each particular case may be influenced by many variables. Although some contributing factors, for example decarburization, can only be verified by laboratory examination; the presence of fatigue may in many cases be determined by a careful examination in the field.

In static failures there is generally considerable evidence of ductility or "necking down," whereas in fatigue failures there is no evidence of ductility in the fatigue portion of the fracture. It must be pointed out, however, that all brittle failures are not necessarily fatigue failures and this distinction must be used with other features before a final determination is made.

Most fatigue failures (with the exception of some torsion fatigue failures) occur on planes which are at right angles or approximately at right angles to the direction of the loading. On most parts the fatigue plane will be perpendicular to the axis of the part, and in the fatigue area the fracture will generally be in one plane. Irregular fractures, that is, when the fracture slips from one plane to another and when these planes are extremely different from a plane perpendicular to the loading or to the axis of the part, are very probably not fatigue fractures, although close examination is often required to see if some small area on the fracture surface does not conform to the basic requisites.

The two most readily recognizable features of a fatigue failure are (1) lack of deformation, and (2) the singular plane of fracture, usually a 90-degree cross section. In fact, in those cases when the fractured surfaces are mutilated during subsequent damage, these features may be the only ones available to distinguish between fatigue and static failures. In making determinations of this type, it is important that both halves of the fracture be available so that the sections can be fitted together and studied.

To discover whether a part has failed in fatigue, the investigator should first look for the two distinct zones which are characteristic of fatigue failure, i.e., the fatigue zone and the instantaneous

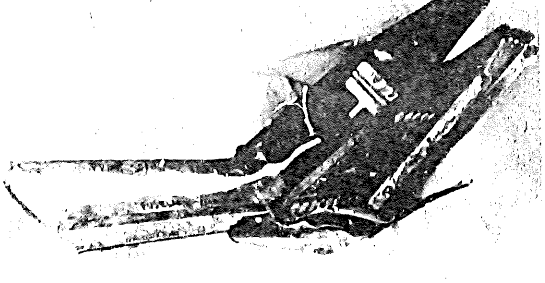

FIGURE 5a.—*Portion of a failed wing spar.*

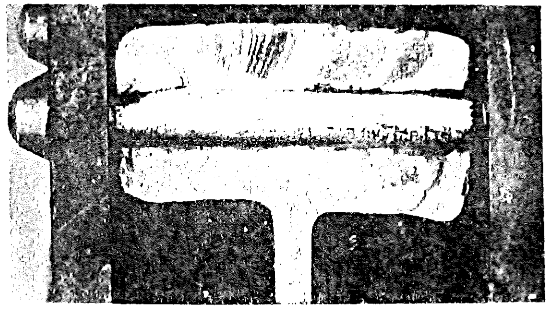

FIGURE 5b.—*An enlarged view of the lower spar cap. Note distinctive "clamshell" markings.*

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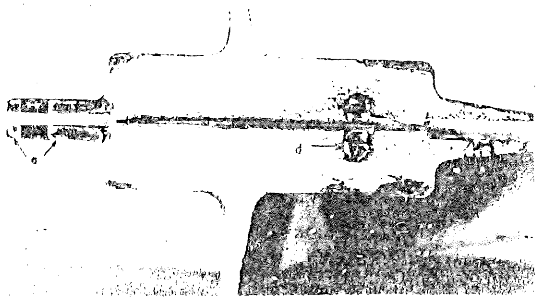


FIGURE 6.—*A one-way bending fatigue failure of a spar cap. Arrows "a" indicate fatigue origin at bolt hole; arrow "d" washer lodged between fracture faces after static failure.*

zone. In many fractures, more than one fatigue zone may be found, indicating that several fatigue cracks had developed and were progressing at the time of the final failure. In each fatigue zone, the origin of the fatigue crack can be found by locating the center of radiation of the fatigue waves. These fatigue waves are known as "clamshells," "oystershells," "stop marks," or "beach marks," and are found in most service fatigue failures. Fatigue waves are not, however, always present; for example, where certain aluminum alloys are involved, the fatigue may progress without leaving distinctive wave markings, although in these cases, the fatigue area can be identified by its smooth, rubbed, velvety appearance. Although the presence of progression marks is influenced by the type of material, it is primarily dependent upon the amount and uniformity of stress variation.

FIGURE 7.—*A one-way bending fatigue fracture of a nose landing gear axle. Fatigue crack, originated at arrow "a" and penetrated to arrows "b" before final failure.*

Bending Fatigue Failures

It is possible to divide bending fatigue failures into three general classifications according to the type of bending load imposed. These three classifications are one-way bending, two-way bending,

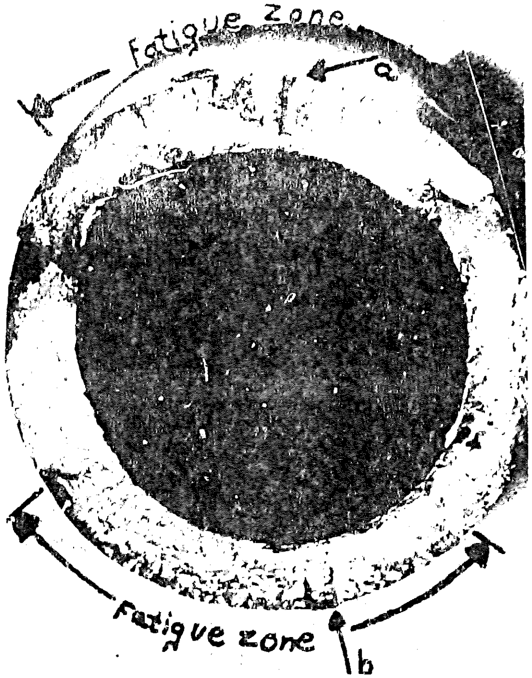


FIGURE 8.—*A two-way bending fatigue failure of main landing gear axle. Arrows "a" and "b" indicate multiple nuclei fatigue zones.*

and rotary bending. Most severe bending fatigue encountered will fall into one of these categories.

A one-way bending failure may occur when a fluctuating bending load causes one side of a piece to be stressed in tension and the opposite side in compression. The fatigue crack will start on the tension side of the bend. Fatigue failures due to bending are, therefore, similar to tension fatigue failures. Distinguishing features are usually found in the overload part of the fracture. Under

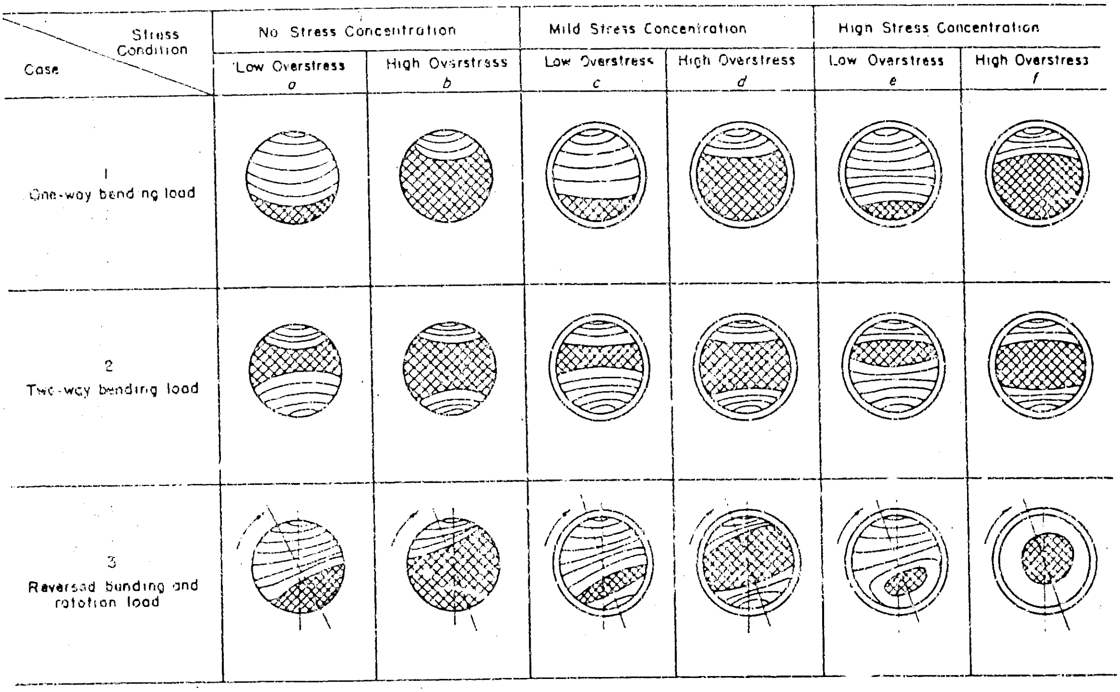


TABLE 1.—*Fracture Appearances of Fatigue Failures in Bending.*

two-way bending loading, the tensile stress alternates from one side of the neutral axis to the other, and when the stress level and number of loadings are of the right order, cracks will start on either side of the part and progress toward the center. Rotary bending occurs when a part is rotated while under a bending loading. A typical example of rotary bending is an engine crankshaft under service loading.

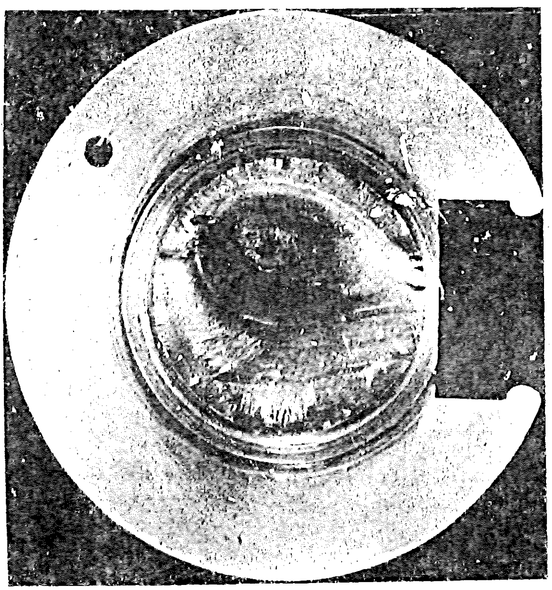


FIGURE 9.—*Fracture surface of a "D" roll from the Bureau of Engraving and Printing. The material was heat treated steel containing 0.45 percent carbon and approximately 3.00 percent nickel. The rolls were made with a double fillet joining the bearing surface to the working section of the roll. Fatigue cracks originated in the bearing surface fillet and penetrated through approximately 75 percent of the cross sectional area before complete failure occurred. Upon examination of the bearing surface fillet, relatively deep tool marks were discovered. Poor machining, failure to grind the fillets, and the low strength of the steel were all contributing factors to the cause for failure.*

Tension Fatigue Failures

Because of initial eccentricities in a part or because of eccentric loading, pure tension loading rarely occurs in service. Some amount of bending usually accompanies tension in axial loading. However, a number of fatigue failures under predominantly axial loading do occur in service and it

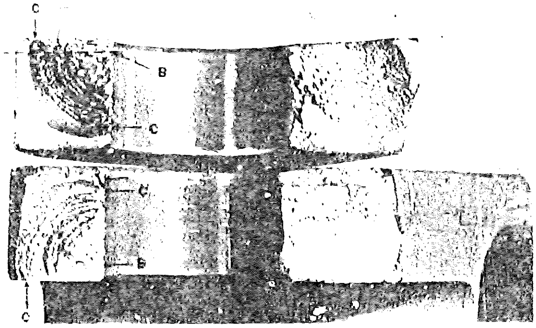


FIGURE 10.—*A tension fatigue failure of a helicopter rotor blade flapping link. Fatigue crack originated at arrow "b"; propagated to arrows "c".*

is helpful for the investigator to be able to distinguish these failures from bending and torsional failures. By an examination of the manner in which the fatigue crack has progressed into the part, tension fatigue failures can generally be distinguished from other types of fatigue. Parallel or constant curvature stop markings are characteristic of fatigue failures resulting from straight tensile loading. As in bending fatigue failures, the relative size of the fatigue zones and the instantaneous zone can be used as a measure of the stress level which produced the failure.

FIGURE 11.—*Torsional fatigue failure of a crankshaft. Fatigue crack originated at arrow "o". Below, an enlarged view of fracture surface.*

FIGURE 12.—*Fatigue failure of a punch-press shaft which was subjected to torsion and bending loads. The fatigue crack originated at a sharp fillet at a change in section.*

Torsion Fatigue Failures

Torsion fatigue failures occur in either of the two basic directions, i.e., (1) helical, at approximately 45 degrees to the axis of the shaft, along the plane of maximum tension, or (2) longitudinal, or transverse, to the axis of the shaft, along the planes of maximum shear. Fatigue stop markings cannot always be found on the surface of the fracture, and secondary means such as absence of ductility and observing the angle of the failure plane must often be used to identify torsion fatigue failures. Transverse fractures are usually very smooth from the rubbing of the two halves of the fracture before final separation and this characteristic may be used to identify this type. In many service torsional fatigue failures, the initial crack will originate in one plane and then slip off into another. Helical fractures usually occur when stress concentrations are present, while longitudinal or transverse fractures generally indicate the absence of stress concentrations. In looking for torsion fatigue failures, the investigator is usually aided by the knowledge that torsional loading is present in the service application. In this regard, torsion fatigue should be suspected when examining failures of crankshafts, flap drive torque tubes, coil springs, splined shaft members, etc.

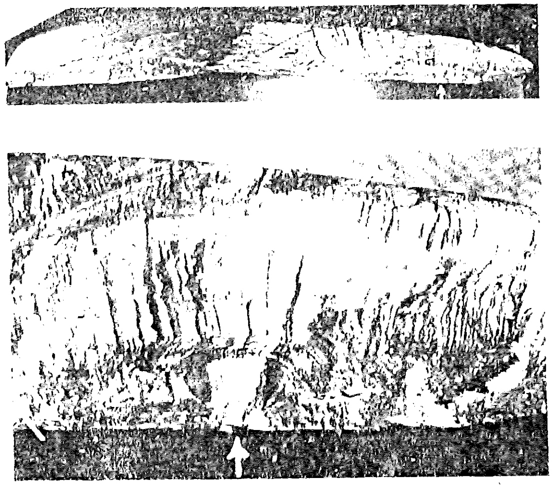


FIGURE 12.—*Fatigue failure of a propeller blade which was subjected to tension and one-way bending loads. Arrow indicates crack origin.*

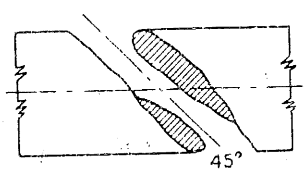
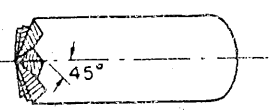
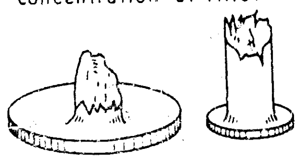
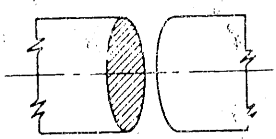
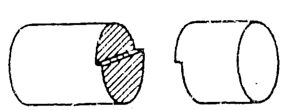
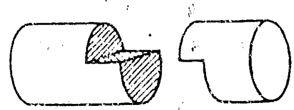
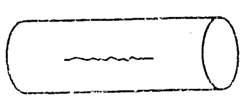
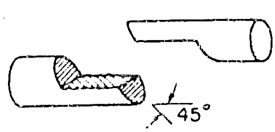
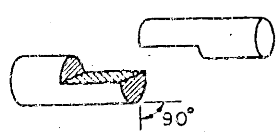
Type of Failure	Basic Pattern	Variations of Basic Pattern (a)	Variations of Basic Pattern (b)
Tensile 1		Star pattern 	Saw tooth due to stress concentration at fillet 
Transverse Shear 2		 Small step	 Large step
Longitudinal Shear 3			

TABLE 2.—*Typical Appearances of Torsional Fractures.*

THE FIELD INVESTIGATION

In most cases of fatigue failures, as in any other type of failure, certain pertinent information is absolutely necessary if the cause for failure is to be determined and the prevention of recurrence to be assured. The work involved in collecting all pertinent data is twofold: (1) a thorough field investigation to insure that the complete service history is known, and (2) a metallurgical examination of the failed material. In some cases a complete metallographic examination may not be necessary because the type of failure may become obvious solely by visual examination; however, the finding of fatigue does not, in itself, properly define the probable cause of an accident. More important, it offers little toward the solution of the problem. If a component has been subjected to maintenance or operational malpractice, the real cause of failure would be such malpractice. On the other hand, the cause may be attributed to improper design, manufacturing imperfections, or an unrealistically established service life. Without a complete field investigation such problem areas cannot be known and the time and money expended in the investigation may be wasted.

Although the field investigator does not have the necessary facilities for a complete examination of a failed part, there is much information he can and should obtain that will aid in the final determination of not only the type of failure, but the underlying reasons therefor.

The data obtained by the field investigator should include a description of the impact and fire conditions because this will have a direct bearing on the wreckage distribution and damage to the subjected parts. Weather conditions at the time of the accident should also be noted. This should include wind velocity and turbulence, clouds, and visibility, and the temperature as it affects the operation and performance of the aircraft. Environmental conditions after the accident should also be noted so that the effects of exposure on the part can be taken into consideration during the metallurgical examination. For example, if upon final examination the failed part shows signs of rust, it must be determined whether the part obtained the rust before or after the accident.

A description of the location of the failed part relative to other parts of the wreckage should also be submitted with the part. If possible, a photograph of the part before it is removed from the wreckage should be obtained or if a similar aircraft is available, a photograph of the properly installed part should be taken. This will compensate for any possible mistakes in parts catalogs and to serve as a reference if a parts catalog of the particular aircraft does not exist or is difficult to obtain.

The field investigator should also examine the aircraft to determine if any unauthorized modifications had been made. This information is needed to determine if the failed part was subjected to a higher nominal stress than that for which it was designed, and if these modifications affected the aircraft's airworthiness.

To expedite the investigation and the final determination of the cause for failure, proper part nomenclature must be used when labeling parts. This includes labeling the part with the proper part number and obtaining serial number of the aircraft (and of the part, if any).

The most important pertinent information that the field investigator can obtain is the total time on the failed part, the time on the part since its last inspection, and the time since the aircraft's last overhaul. These three time factors are needed in almost every investigation and they must be obtained if at all possible. Obtaining these time factors is of special importance if fatigue is suspected as the cause for failure because any metal part may fail in fatigue if it has been subjected to repeated stresses long enough. The inspection and overhaul times are of special importance in determining whether the facilities responsible for the inspection and overhaul fulfilled their respective responsibilities.

The field investigator should also refer to his file of Airworthiness Directives to determine if there are any existing AD's that are applicable to the particular accident or suspected part. Compliance with applicable AD's should, of course, also be investigated.

An examination of the aircraft's logbook should also be undertaken. Most, if not all, of the above required information can usually be obtained from the logbook. Any other pertinent information obtained from the logbook, such as any previous incidents or accidents, should also be noted.

In summary, when a field investigator submits a part for final examination and determination of the cause for failure, the following information should accompany it: (1) a description of the impact and fire conditions; (2) a description of the weather conditions at the time of the accident and the environment of the part after the accident occurred; (3) a description of the location of the failed part or a photograph of the part in the undisturbed wreckage or a photograph of the part in a similar aircraft; (4) examination for unauthorized modifications; (5) proper part nomenclature including correct part numbers and aircraft serial number; (6) examination of applicable AD's and determination of compliance with them; (7) examination of logbook, noting previous accidents or incidents, and most important of all; (8) the total time on the failed part, the time on the part since its last inspection, and the time since the aircraft's last overhaul.

Although in many cases it is impossible for the field investigator to obtain all of the aforementioned data, an effort should be made to obtain as much of it as possible. In most cases, if this information is not submitted with the failed part, time and money must be spent in conference with the field investigator and in otherwise acquiring these data. If the preceding facts are obtained by the field investigator and submitted with the failed part, the examination and determination of the probable cause for the part's failure will in most cases be determined without excessive cost or loss of time. Moreover, appropriate corrective action can be taken which, of course, is the desired end product of accident investigation.

Appendix

The photographs in this Appendix are large reproductions of those contained in the text and are repeated here to show more details of the different failed parts. It is hoped that these photographs will help increase the reader's ability to recognize fatigue failures.

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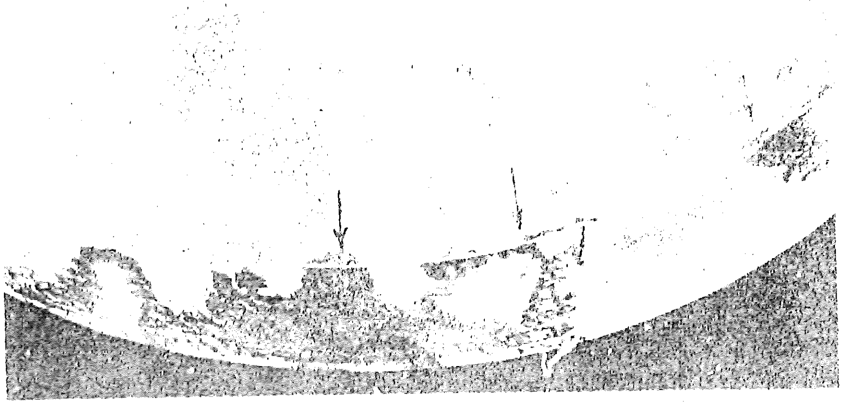
FIGURE 4. *Magnified view of a fatigue crack. Note the straight line propagation of crack.*



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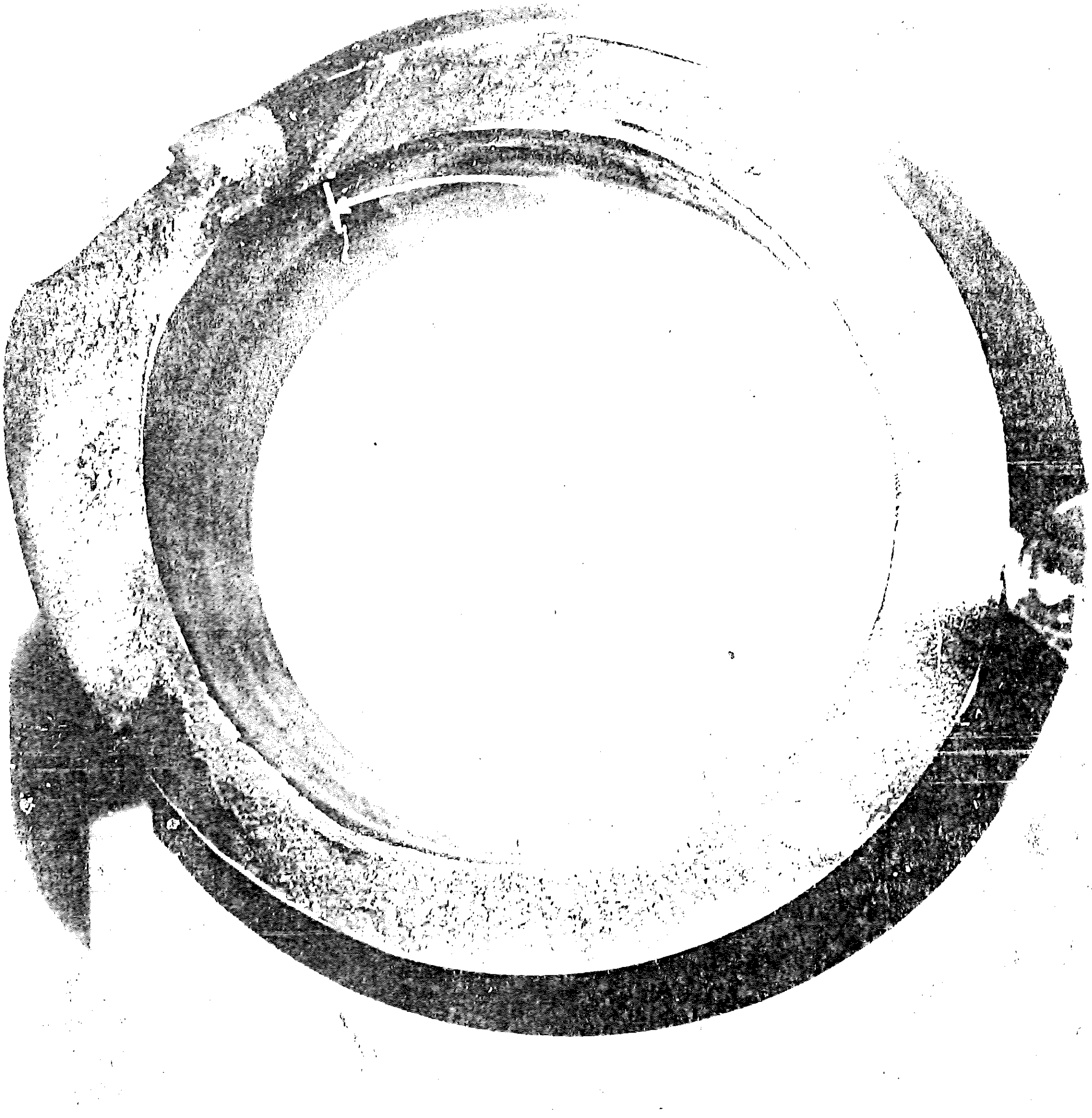

FIGURE 1a. A fretting corrosion-fatigue failure of a propeller blade. Fracture surface showing origin and extent of crack propagation.

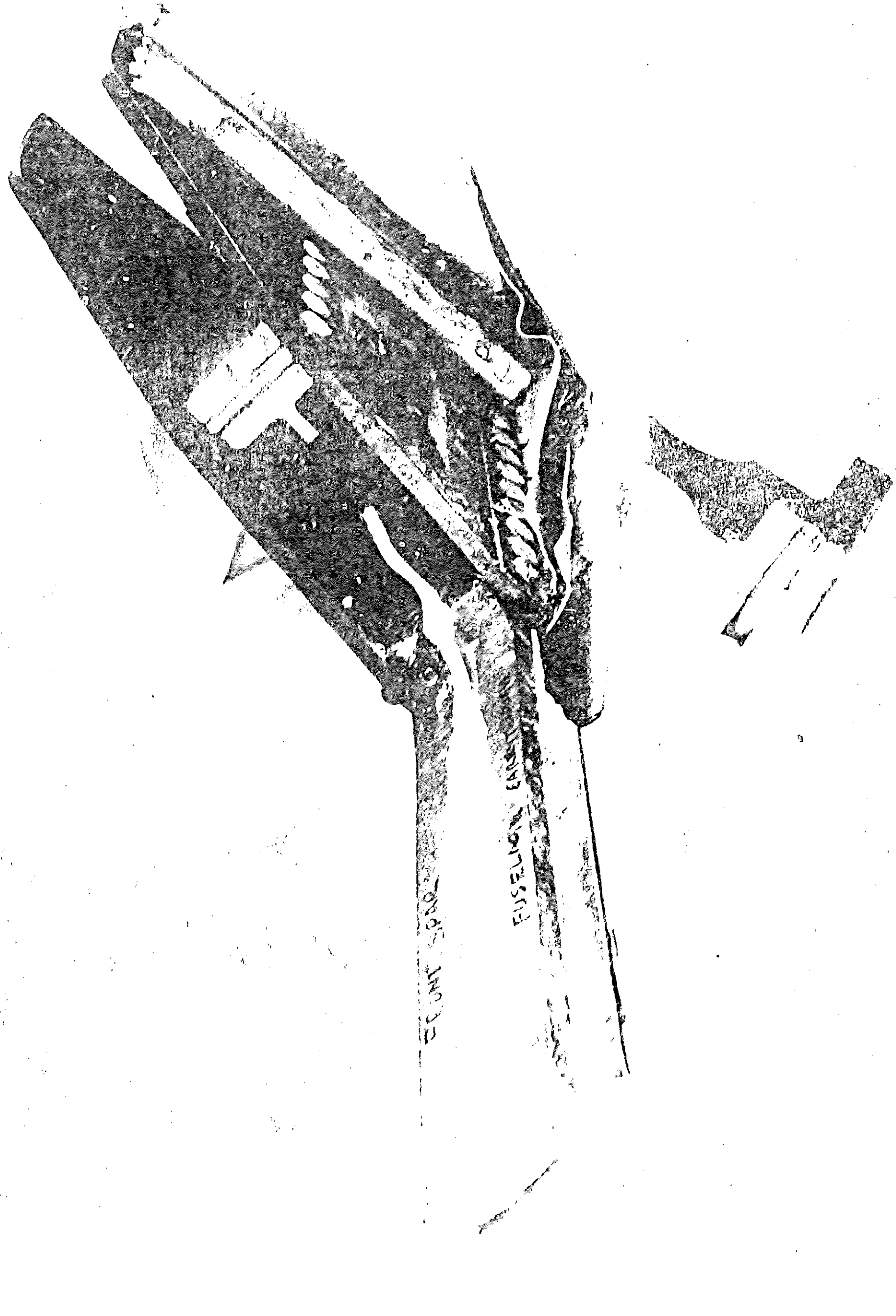

FIGURE 5a. *Portion of a failed wing spar.*

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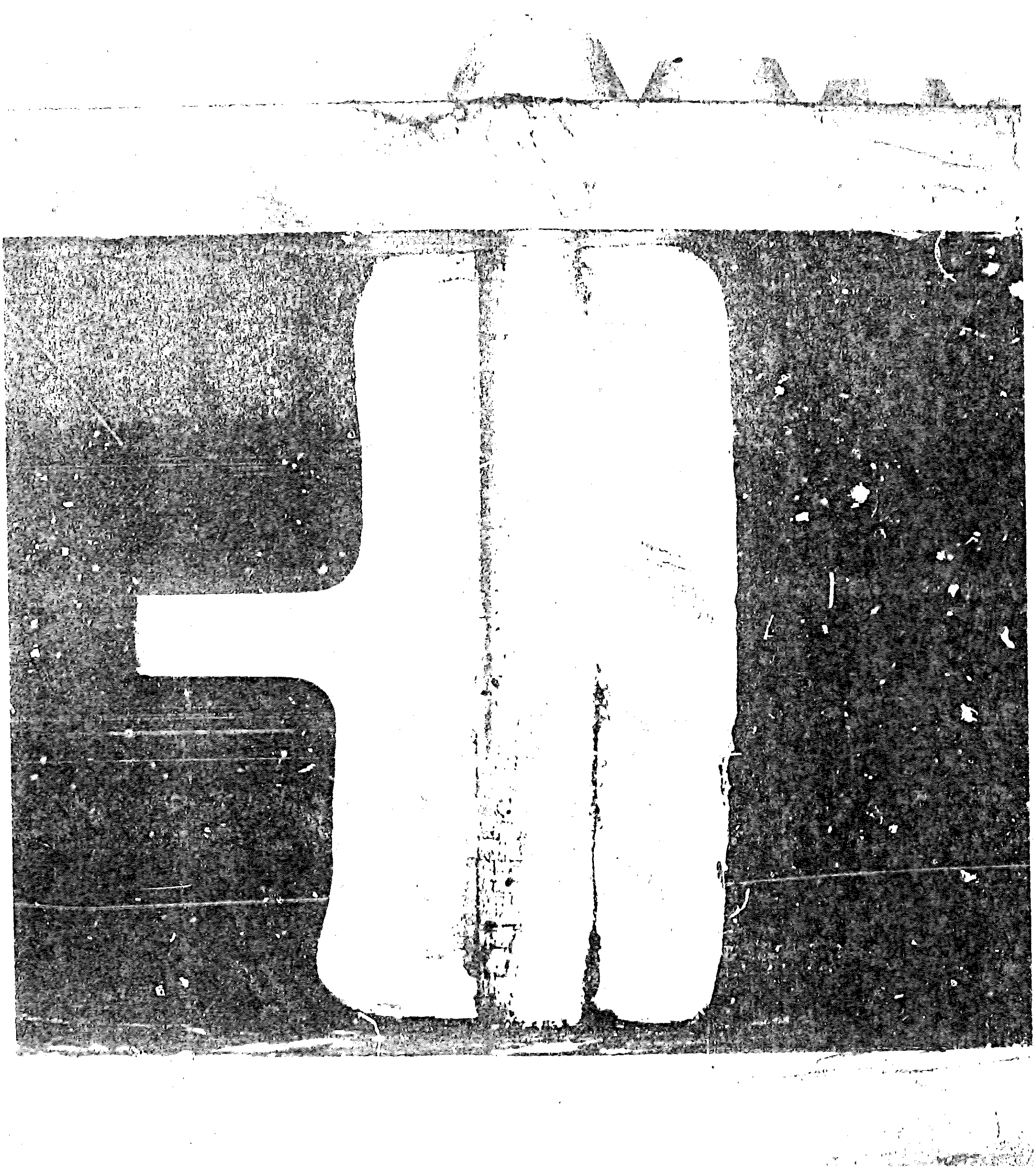


FIGURE 5b. *An enlarged view of the lower spar cap. Note distinctive "clam shell" markings.*

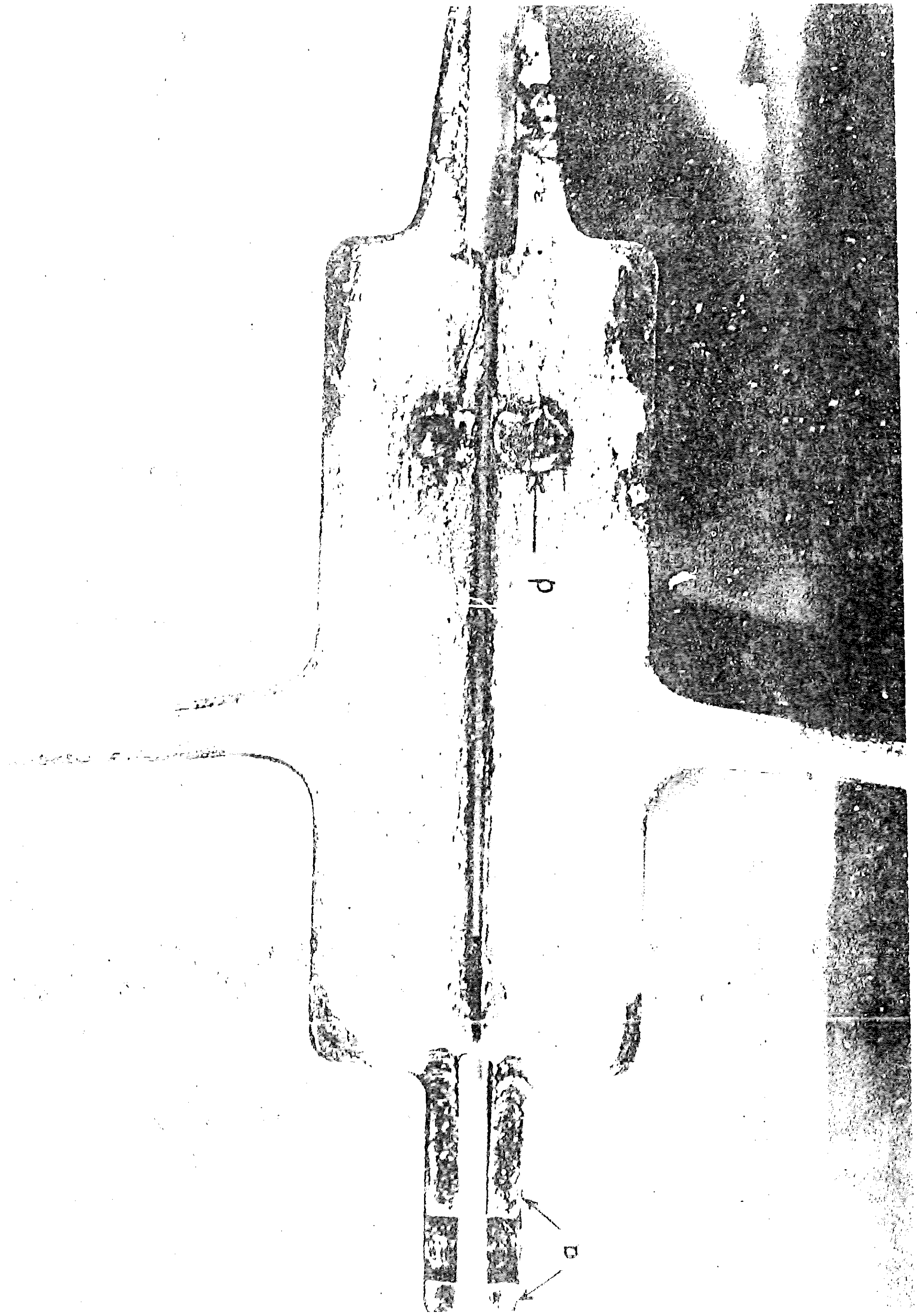


FIGURE 6. A one-way bending fatigue failure of a spar cap. Arrows "a" indicate fatigue origin at bolt hole; arrow "b" [illegible] between [illegible]

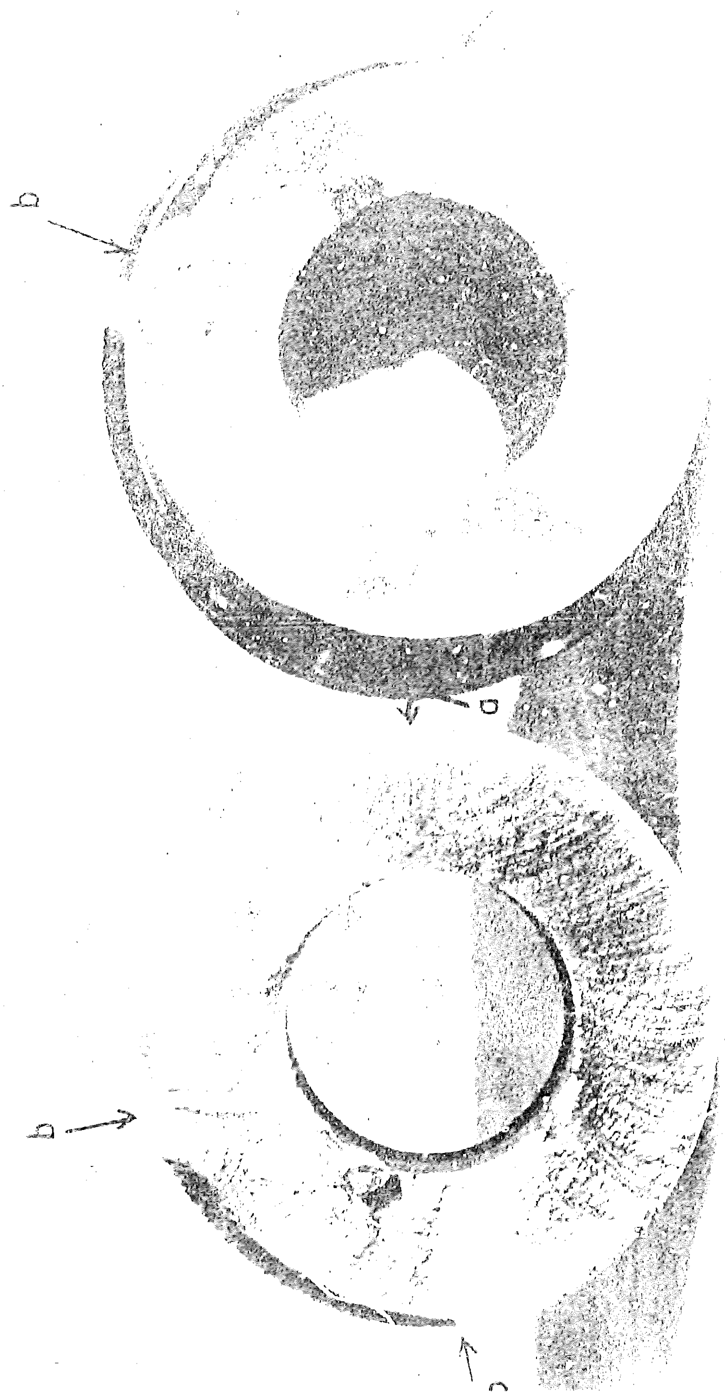
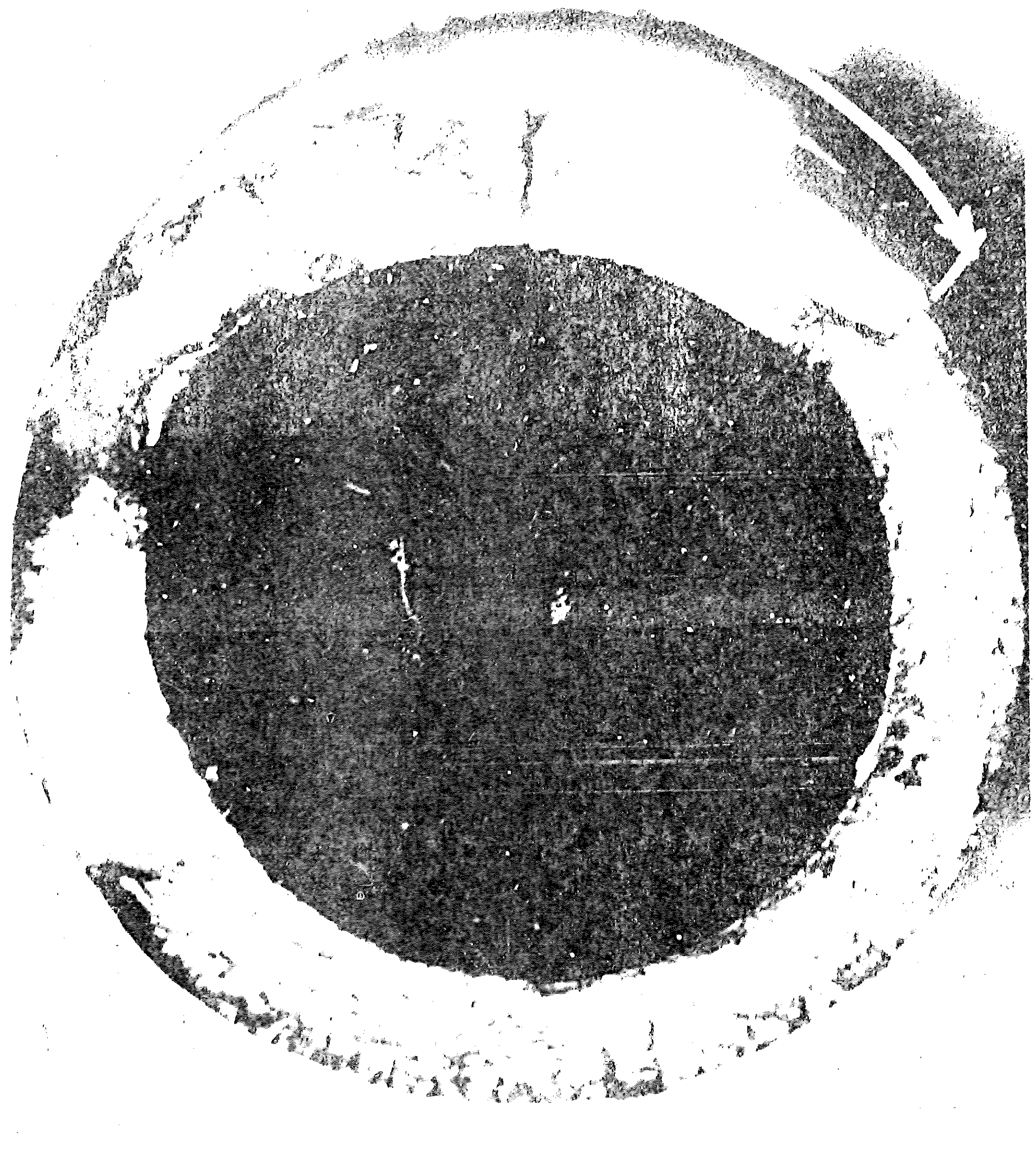
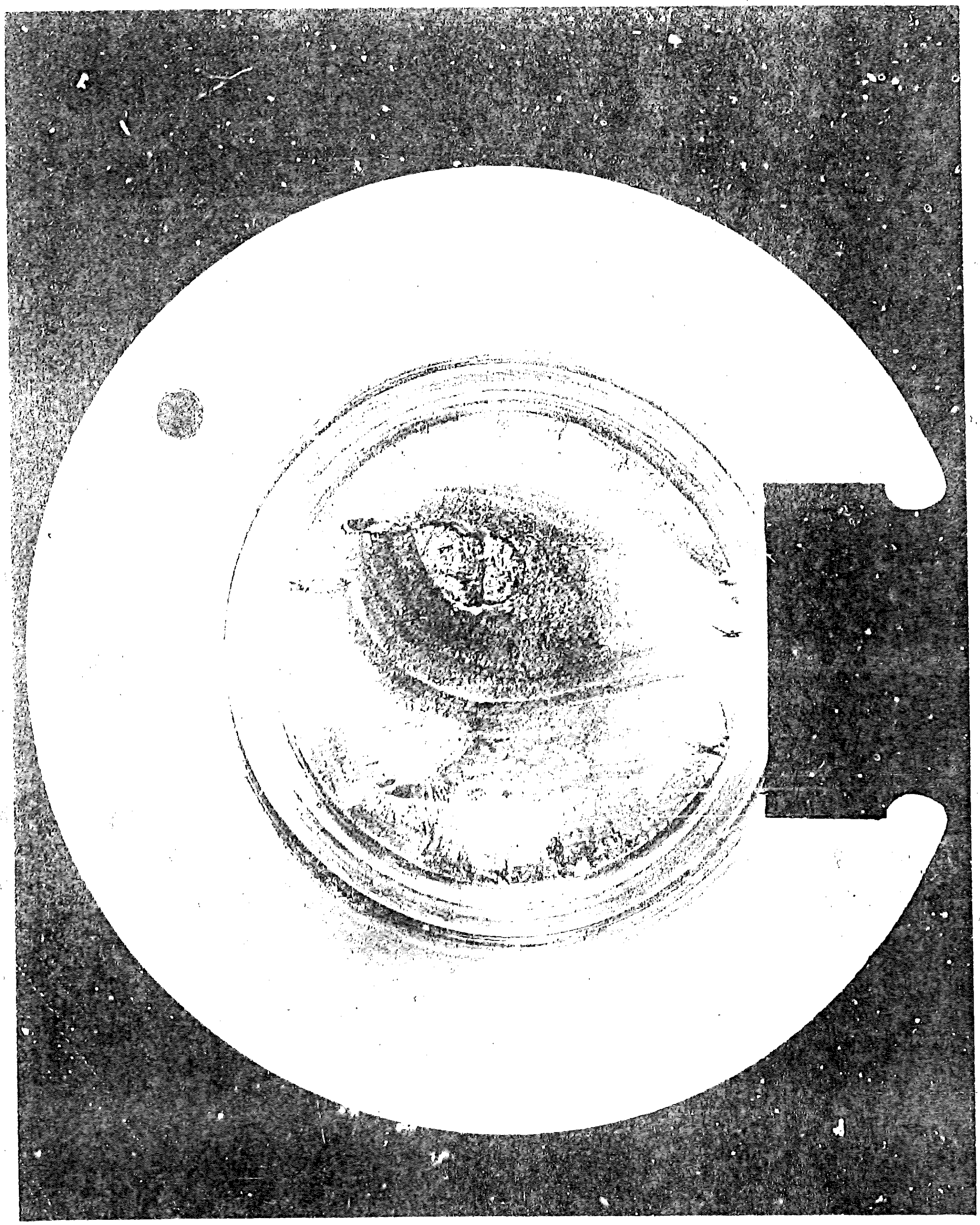


Figure 7. — [illegible] Fatigue crack, originated at arrow "a" [illegible]





F[illegible] Fracture surface of a "D" roll from the Bureau of Engraving and Printing. Poor machining, failure to [illegible] failure.

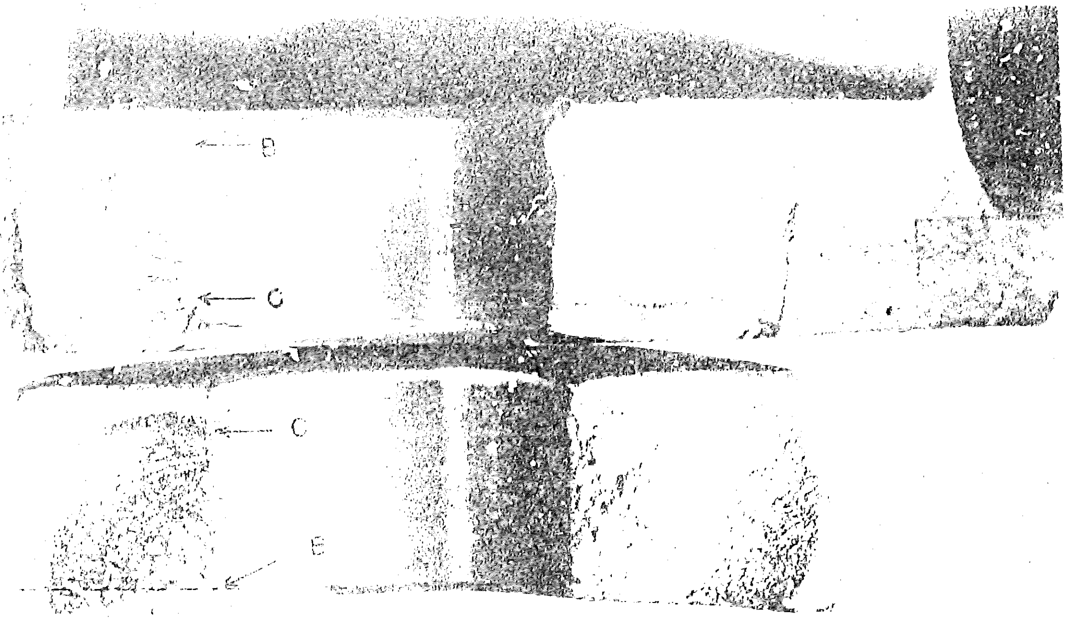
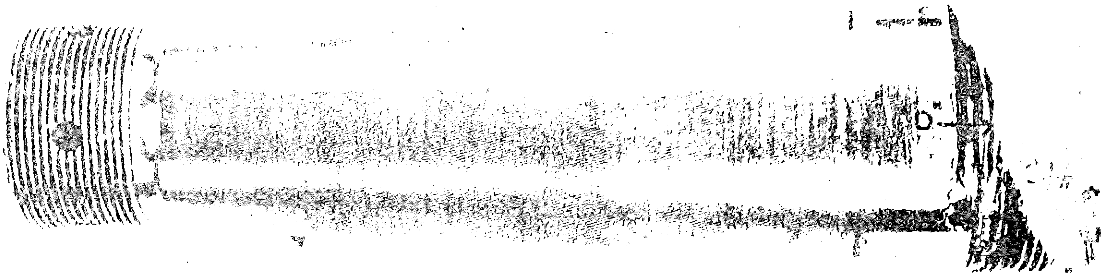
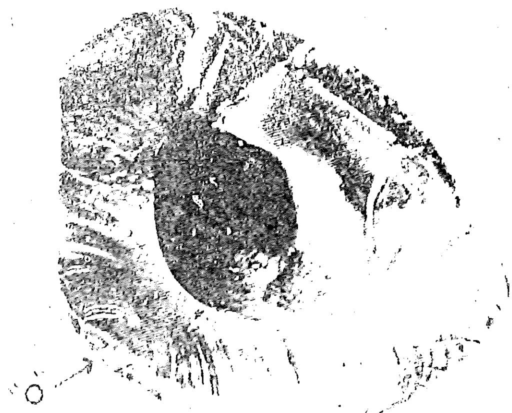


Figure 10. [illegible] blade [illegible] Fatigue crack [illegible]
[illegible]





[illegible] left. Fatigue crack originated at arrow "O". Below, an enlarged [illegible]

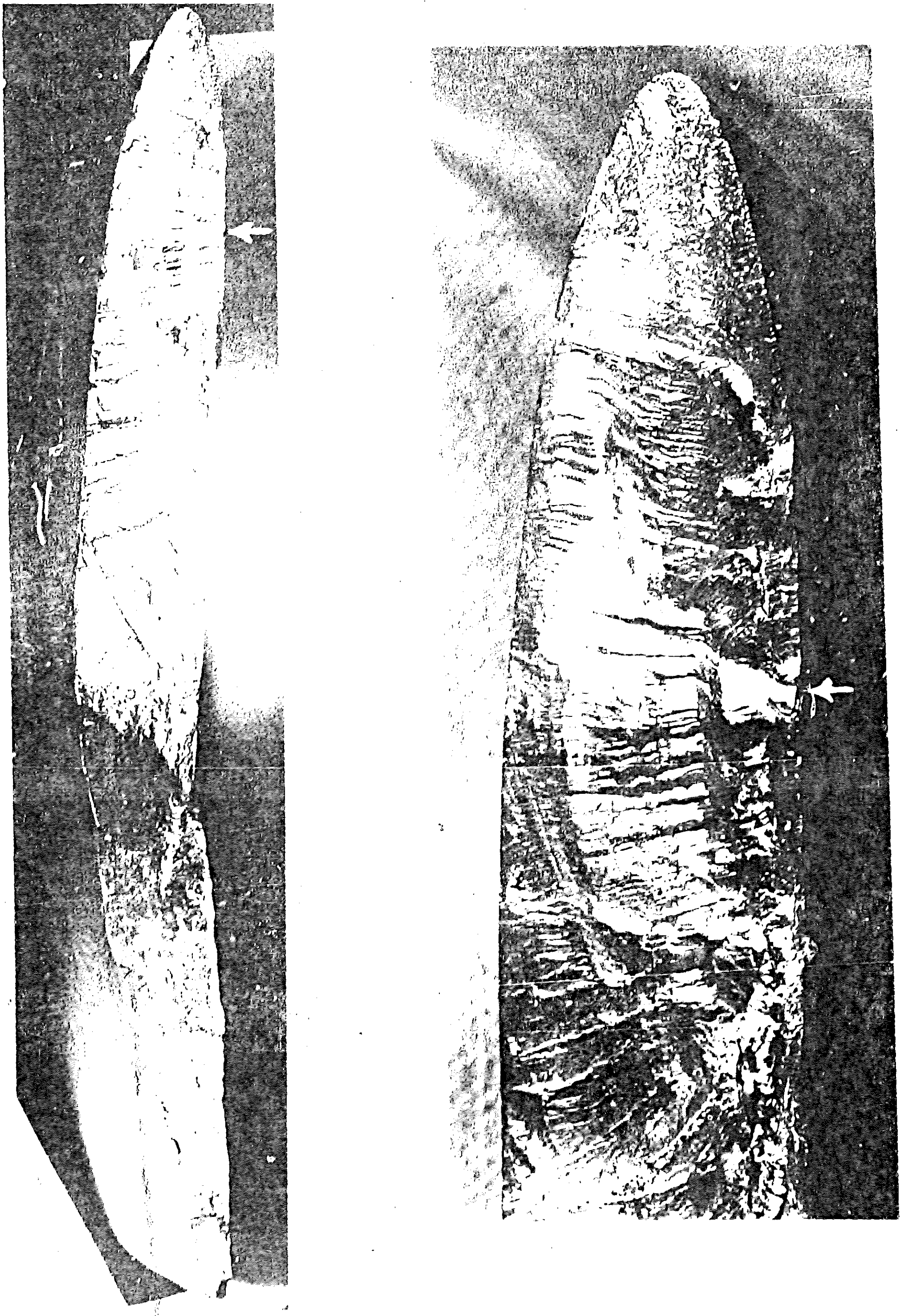


FIGURE 13. *Fatigue failure of a propeller blade which was subjected to tension and one-way bending loads. Arrow indicates crack origin.*

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