NBS CIRCULAR 550

Mechanical Failures of Metals in Service

UNITED STATES DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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Mechanical Properties of Metals at Low Temperatures — Circular 520

Many mechanical devices and equipment operate at low temperatures; and the consequent embrittlement of materials, accompanied by brittle failures, is of concern to designers, manufacturers, and users. The subject continues to increase in importance with the steady growth of the refrigeration industry and the expanding demand for the liquefaction, transportation, and storage of many gases.

This volume presents results of studies conducted both in industry and in government to further knowledge of the behavior of metals at low temperatures, which is important to an understanding of their fundamental rheological properties. The papers were initially presented at the Symposium on the Influence of Low Temperatures on the Mechanical Properties of Metals held at the National Bureau of Standards on May 14 and 15, 1951, during the fiftieth anniversary of the founding of the Bureau.

Papers included in the volume cover recent European work in the field; manufacture of steels, development and application of chromium-copper-nickel steel, and application of metals in aircraft for low-temperature service; tensile properties of copper, nickel, and some copper-nickel alloys, properties of austenitic stainless steels, and mechanical properties of high-purity iron-carbon alloys at low temperatures; dimensional effects in fracture; and brittle fractures in ship plates.

National Bureau of Standard Circular 520, 206 pages, 129 figures, 50 tables, $1.50.

Mechanical Properties of Metals and Alloys — Circular 447

This Circular is a summary of the results of a comprehensive survey of the technical literature on the strength and related properties, thermal expansion, and thermal and electrical conductivities of ferrous and nonferrous metals and alloys at normal, high, and low temperatures. In general, the data are presented in tabular form, although graphical representation is often used to indicate the effects of changing composition or conditions on the properties. Data on aluminum, copper, iron and steel, lead, magnesium, nickel, tin, zinc, a number of miscellaneous metals, and their alloys are included. The Circular is not limited to conventional engineering materials but contains data on the properties of many materials not usually classed as such. Literature references to the sources of the data are included.

National Bureau of Standards Circular 447, by J. L. Everhart, W. E. Lindlief, J. Kanegis, P. G. Weissler, and F. Siegel, 479 pages, 68 tables, 209 figures, $3.50.

Characteristics and Applications of Resistance Strain Gages — Circular 528

This publication presents proceedings of symposium held November 8 and 9, 1951, at the National Bureau of Standards. It reports some of the latest results, both experimental and theoretical, in the study of resistance strain gages by many leading institutions in the United States and Abroad.

Though resistance strain gages are a comparatively new tool in the study of materials and structures, they have consistently found wider use. Strain gages have been used in measurement of mechanical quantities such as acceleration, impact force, and dynamic pressure. They have been applied as the sensing element in a multitude of instruments, and have been used to determine strain distribution in structures, from airplane wings to bridges.

Papers presented at the symposium covered these applications and also reported new work in progress on strain gages consisting of a conducting coating applied by an evaporation technique, on special temperature compensated gages, on gages for strain measurements well beyond the elastic range, and on the application of strain gages to the determination of dynamic properties of materials and to the measurement of very large static forces. Eleven papers are reported in the volume along with transcriptions of the discussions that followed.

National Bureau of Standards Circular 528, 140 pages, 143 figures, 15 tables, buckram bound, $1.50.

(List continued on cover page III)

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Mechanical Failures of Metals in Service

John A. Bennett and G. Willard Quick

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Mechanical Failures of Metals in Service

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For many years the National Bureau of Standards has made examinations of metal parts that have failed in service for evidence bearing on the causes of failure. Thirty-five such cases, representing the most frequently observed types of failures are described, and the factors of design, fabrication, or use contributing to these failures are presented. The characteristics by which the various types of fractures can be recognized are discussed, and recommended precautions that should be observed to reduce mechanical failures of metals in service are included.

1. Introduction

For many years the National Bureau of Standards has been requested to examine metal parts that have failed in service for evidence bearing on the causes of these failures. These examinations have been undertaken at the request of other Government agencies; for example, aircraft parts have been submitted by the Civil Aeronautics Board, the Civil Aeronautics Administration, and the Bureau of Aeronautics, Navy Department; motor vehicle parts by the Interstate Commerce Commission; marine engine and propeller parts by the U. S. Coast Guard; and fractured ship-hull plates by the Ship Structure Committee. The results of these examinations have been reported only to the agency that submitted the specimens. Because it was believed that the results would be of interest and value to many people, it was considered desirable to publish a Bureau Circular illustrating some of these failures and pointing out the principal factors involved.

A great many examinations of failed parts have been made over the past years, and numerous examples of those made prior to 1940 were used in reference [1].[1] The examinations from which the examples in this Circular were taken were reported between 1940 and 1951, inclusive.

It is hoped that the examples shown in this Circular will serve to emphasize the need for care in the design, fabrication, and use of even a simple metal part in order to reduce the probability of service failure.

2. Types of Failures

The mechanical failures of metals that have been investigated at the National Bureau of Standards may be broadly classified into (a) those in which the metal deformed to such an extent that the part was no longer serviceable, and (b) those in which the part fractured. Wear, although it is a major source of trouble in metal machine elements, does not usually result in catastrophic failure, and involves many factors, such as lubrication, which are beyond the scope of this Circular. Consequently, examples of failures in which wear was the sole difficulty encountered have not been included. Also, because the fracture of a part is apt to be more disastrous than excessive deformation, only one example of the latter type of failure is included.

The science of engineering has advanced to the point where it is unusual for a structure or machine to fail in normal service due simply to loads greater than the strength of the parts. This may happen, of course, if the designer has underestimated the service requirements or if the materials are not as strong as the designer had assumed. Much more common are failures where factors other than the static loading of the parts are involved, such as, fluctuating stress, corrosion, and rubbing between supposedly fixed members.

The nature of the stresses, and other factors, have a profound influence on the nature of a fracture, so that a knowledge of the appearance of the several types of fractures provides a powerful tool in ascertaining the causes of failures in service. Some of these types will be discussed briefly in order to provide a better understanding of the examples presented in the next section.

2.1. Static, or Overload, Fractures

When a metal member fails because of a single application of a load greater than the strength of the member, there is usually considerable plastic deformation prior to fracture. This deformation is often readily apparent on inspection of the fractured parts; for instance, case 2, section 3, shows the large amount of bending that occurred

[1] Figures in brackets indicate the literature references at the end of this Circular.

in a landing-gear part prior to fracture. This ability of a material to deform plastically is known as ductility, a property that is a function not only of the material but also of the geometry of the member, the type of stress to which it is subjected, the rate of loading, and, in many materials, the temperature. For example, figure 1 shows the effect of geomertry on the ductility of steel; these two specimens are made of the same steel, and both were originally the same shape. Both were loaded in the same way, namely, by supporting the ends and striking the middle with a heavy pendulum. The lower specimen was struck on the side containing the notch and was deformed a large amount but did not fracture. The upper specimen was struck on the side opposite the notch and broke in a brittle manner with relatively little plastic deformation.

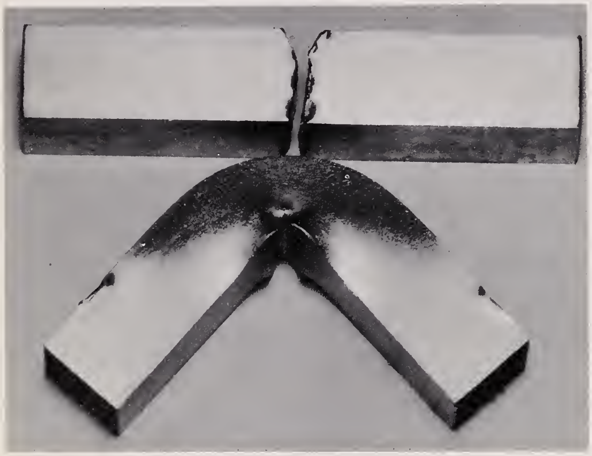

FIGURE 1. *Effect of geometry on the ductility of a steel specimen.*

Identical specimens with a notch in one side were loaded by supporting the ends and striking the middle with a heavy pendulum. The upper specimen was struck on the side opposite the notch; the lower one on the side containing the notch. × 2.

In considering the factors that affect the ductility of a metal part, it can be said in general that the ductility is decreased by (1) increasing the strength of the metal by cold-working or heat treatment (2) sources of stress concentration, such as notches, fillets, holes, scratches, inclusions, porosity, (3) increasing the rate of loading, and (4) decreasing the temperature.

Although there are very few engineering applications of metals where it is necessary for the part to deform appreciably in service, some ductility is essential to permit yielding of the metal at sharp notches. Such notches are almost universally present in commercial metals due to inclusions, fabricating defects, scratches, corrosion pits, etc. The stress at the bottom of a severe notch may be several times as large as the average stress on the section; a ductile material will deform plastically in the small highly stressed region and so redistribute the stress that its peak value will be reduced. If conditions are such that the material behaves in a brittle manner, a crack will be formed before plastic deformation can take place. Frequently, this crack will propagate at high velocity through the rest of the section. This type of fracture is characterized by very little deformation adjacent to the fracture and often by markings known as "herringbone" or "chevron" patterns on the fracture surface. Figures 2 and 3 show a fracture of this kind produced in the laboratory. It will be noted that the pattern points toward the source of the fracture. This fact is often of value in studying service fractures.

As the ductility of a metal is affected by the temperature and rate of loading, changes in these conditions may result in brittle fracture of a part that would normally deform plastically before fracture. The load required to cause fracture under brittle conditions may be less than that which the part could normally withstand. For this reason, brittle fractures have been differentiated from other overload fractures in section 3.

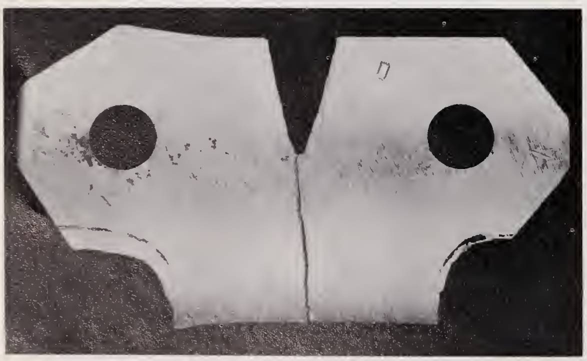

FIGURE 2. *Notched specimen broken in tensile test in the laboratory.*

Holes were used to apply the load in line with the bottom of the notch. × 1.

FIGURE 3. *Fractured surfaces of specimen shown in figure 2.*

The specimen broke by tearing from the root of the saw-cut notch, and it will be noted that the "chevron" markings point toward the source of the fracture. × 1½.

The strength of engineering metals generally decreases as the temperature increases. Consequently, parts that have adequate strength at room temperature may fail if the operating temperature becomes high, and the fracture may occur after many hours under constant load. If the temperature is sufficiently high, the strength of the grain boundaries in the metal will be reduced to such an extent that intergranular cracking will occur, and the fracture of parts will show very little ductility. Two fractures of this type have been classified as "overload" failures in section 3.

2.2. Fatigue Fractures

When a metal is subjected to repeated or fluctuating loads it may eventually fracture at stresses much lower than those which would be required to cause fracture under static conditions. This phenomenon is known as fatigue and is the most common cause of primary failures of metals in service. Laboratory tests have established the fact 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 where the stress is highest. Under continued stressing this crack grows 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. Because of this mechanism, the surface of such a fracture shows two characteristic regions which are usually quite different in appearance. This is clearly shown in figure 28.1 where the area of the fatigue fracture at the bottom can be seen to be much smoother than the overload fracture portion at the top.

Because the stress required to initiate a fatigue crack is usually less than that required to cause plastic deformation of the metal, a fatigue fracture is characterized by its brittle nature Figure 4 shows this effect demonstrated with laboratory specimens. These specimens are made of the same steel, and both were originally the same shape. The lower one was bent by the application of a single load, whereas the upper one was subjected to many cycles of reversed bending load, which resulted in a brittle fatigue fracture. In most fatigue fractures that occur in service the fatigue crack extends only part way across the section, and there is a considerable area broken by overstress. As this part will show some ductility, fractures of this type will not fit together well when the parts are replaced in approximately their original relationship, as the fatigue crack portion will be held apart by the deformed overstress portion.

The surfaces of fatigue fractures frequently show characteristic markings known as "beach" or "clam-shell" markings, which represent the outline of the fatigue crack at various points in its growth. When these markings are present (see, for example, fig. 15.3) they provide a means of locating the origin of the fracture accurately.

FIGURE 4. *Effect of repeated stress on ductility.*

Identical specimens were loaded by bending. The upper one was subjected to many cycles of reversed loading, and failed with a typical fatigue fracture, showing no ductility. A single high load was applied to the lower specimen, which bent without breaking. × 2.

Fatigue fractures are often erroneously blamed on "crystallization" of the metal by persons unfamiliar with the nature of the phenomenon. All structural metals are crystalline from the time they solidify from the molten state, so the term "crystallization" in connection with fatigue is meaningless and should be avoided.

2.3. Stress-Corrosion Cracking

When a metal is subjected to a load in the presence of a corrosive environment, fracture may occur, even through the stress is less than that required to cause fracture in the absence of corrosion. The corrosion necessary to initiate stress-corrosion cracking need not be severe, and frequently will not cause noticeable corrosion on the surface. In many instances this type of fracture may occur in parts that are subjected to no external load whatsoever due to the internal stress developed in the part during fabrication. For example, "season cracking" of cold-drawn yellow brass is caused by the combination of internal stress resulting from the fabricating operation and the mild corrosive action of the atmosphere.

This is also a progressive type of fracture, beginning with a small crack and progressing across the section perpendicular to the tensile stress. The resulting fracture is brittle, as stress-corrosion cracking can occur under stresses less than that required to cause plastic deformation. It differs from a fatigue fracture in that there are usually numerous cracks that tend to "wander" through the metal, giving a coarse appearance to the fracture surface. A polished section through metal damaged by stress-corrosion cracking usually shows a network of fine cracks.

3. Examples of Failures

Several factors were considered in selecting the examples of service failures to be shown in this Circular. First, an attempt was made to include examples of all the common types of primary failures, that is, failures in which the part examined was the first one to fail. The few secondary failures included to illustrate certain types of failures are indicated as such. Second, the examples selected were largely ones in which one of the several causes contributing to the failure was much more important than the others, so that the discussion could be simplified and the importance of that factor better emphasized. Practically none of the parts are still available, so it was necessary to use photographs from the files. Many interesting cases had to be omitted because the photographs in the original report were not suitable for a general presentation of this type.

The purpose of these examples is solely to point out past errors in order to lessen the chance of future failures. Consequently none of the parts are identified more closely than is considered necessary to describe the causes of failure. It is unavoidable, of course, that some of the examples will be recognized by persons familiar with the equipment involved. For this reason it should be pointed out that the inclusion of a brief discussion of a particular case in this Circular does not have any bearing on the complete conclusions given in the original report. These original re-

TABLE 1. *Examples of service failures*

Case	Part	Type failure [a]	Factors	Material [b]	Page
1	Bolts	D	Decarburization	Fe	5
2	Retract strut	O	Result of accident	Fe	6
3	Shafts	O(T)	do	Fe	6
4	Prosthetic ankle	O	Design, porosity	Al(C)	7
5	Fuel line	O	High temperature	Al	8
6	Turnbuckle	O	do	Cu	8
7	Cable	O	Previous fire	Fe	9
8	Hinge fitting	O	Local overheating	Fe	10
9	Brake drum	O	Heat checking	Fe(C)	10
10	Oxygen cylinder	B	Wrong material	Fe	12
11	Rod end	B	do	Fe	13
12	Fracture pin	B	Design; excess hardness	Fe	14
13	Pulling yoke	B	Quenching cracks	Fe	14
14	Ships	B	Design, materials	Fe	15
15	Crankshaft	F	Fretting	Fe	17
16	Propeller blade	F	do	Al	18
17	Steering arm	F	do	Fe	19
18	Rotor link	F	Design	Al	20
19	Cylinder	F	Sharp fillet	Fe	20
20	Nose yoke	F	do	Al	20
21	Propeller hub	F	Design	Fe	20
22	Propeller blade	F	Forging defect	Fe	22
23	do	F	Manufacturing defect	Fe	22
24	Cylinder pad	F	Porosity	Al(C)	24
25	Helical spring	F(T)	Design	Fe	24
26	do	F(T)	Surface pit	Fe	25
27	Torsion rod	F(T)	Inclusion	Fe	26
28	Front axle	F	Decarburization, scratches	Fe	26
29	Tubular spar	F	Decarburization	Fe	28
30	Torque indicator	F	Secondary failures	Fe	28
31	Pump plunger	F	Corrosion	Fe	30
32	Square tubing	SC	Residual stress	Al	31
33	Hinge fitting	SC	Force fit	Al	32
34	Window anchor	SC	Wrong material	Cu	33
35	Attach angle	SC	Stress due to assembly	Al	34

[a] D, Excessive deformation; O, overload; B, brittle; F, fatigue; SC, stress-corrosion cracking; (T), failure due to torsional load.
[b] Principal element only; (C) casting.

ports are the property of the submitting agency, and except for a few that have been made part of a public record, are not available.

The photographs are unretouched except for lettering to indicate significant points and masking out of background. Where there is more than one figure for a case, corresponding letters in the different figures refer to the same points on the part.

The factors at the end of the figure captions indicate the ratio of the size of the photographs to the size of the actual parts, for example, × ½ means one-half of the full size. The factors are approximate, but they do not deviate more than 25 percent from the actual values.

Table 1 lists the examples included in section 3. These have been grouped according to the type of failure, as described in section 2. This grouping has been made on the basis of as few categories as possible for convenient reference. Some of the cases cannot be properly classified in this way, so the categories should not be considered as being descriptive of each case. For example, case 5 would be properly referred to as "stress rupture" and case 9 as "heat-checking," but it was not thought that such a detailed classification would be useful.

Case 1: Aircraft bolts (steel). The threads stripped before the recommended torque values were reached. The surface of the bolts was decarburized, that is, there had been a loss of carbon from the surface during fabrication or heat treatment. This decreased the strength of the threads to such an extent that they deformed in shear under the normal applied loads. There was some indication of excessive play between the bolt and the nut. This may have been a factor in the failure.

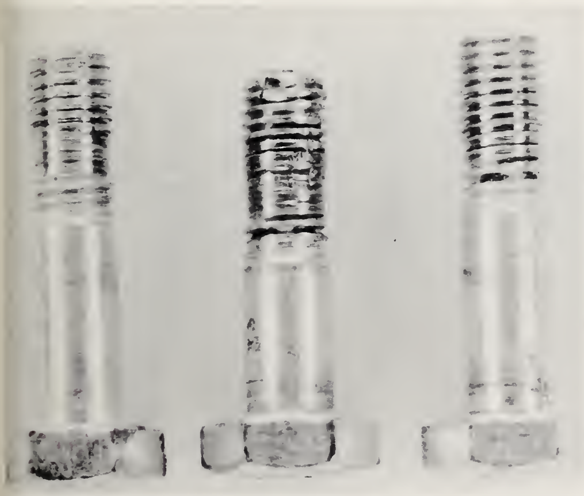

Figure 1.1. *Stripped threads on three aircraft bolts.* × 2.

Figure 1.2. *Soft decarburized tip of thread that deformed when loaded below the recommended torque.*

Etched with nitric acid in alcohol. × 100.

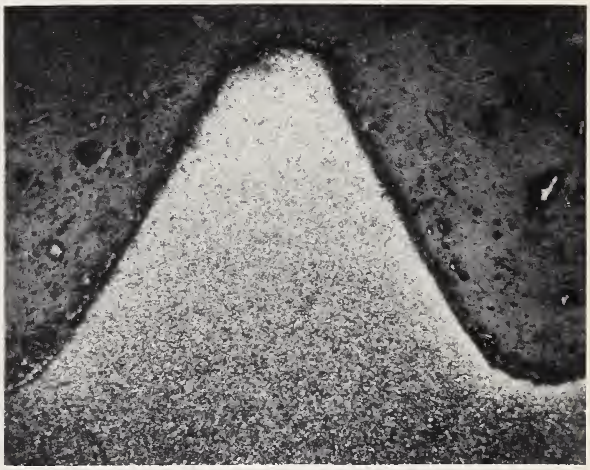

Figure 1.3. *Photomicrograph of unused thread, showing depth of decarburization at the tip.*

Etched with nitric acid in alcohol. × 100.

FIGURE 2.1. *Fractured piston parts fitted together in approximately the position they had occupied at the time of final fracture.*

The extensive plastic deformation that had occurred prior to fracture is evident. × 1.

FIGURE 2.2. *Fractured surfaces of the tube viewed from the compression side of the bend.*

Checks in the chromium plate indicate that considerable plastic deformation occurred some distance from the fracture. × 2.

Case 2: Landing-gear retracting-strut piston (steel, chrome-plated). History of material was not available, but it is thought that this fracture was not a primary failure. This example is included to illustrate the characteristics of fractures due to overload. The tubular part, originally straight, had bent through approximately 75° before final fracture occurred. The extent of the plastic deformation can be seen by the checks in the chromium plate.

Case 3: Accessory drive shafts from aircraft engines (SAE 6150 steel). These parts were removed from the engines of a plane that had crashed and apparently had failed because of the sudden stopping of the engines. The shafts apparently failed owing to the excessive torque applied to them when the propellers were stopped by impact with the ground. This example is included to show the type of fracture found in ductile materials subjected to torsion. The absence of deformation remote from the fracture is due to the stress concentrating effect of the grooves and the high rate of loading. This fracture might easily have been mistaken for fatigue, but on close examination of the fracture surfaces it was evident that the metal had been extensively deformed in shear.

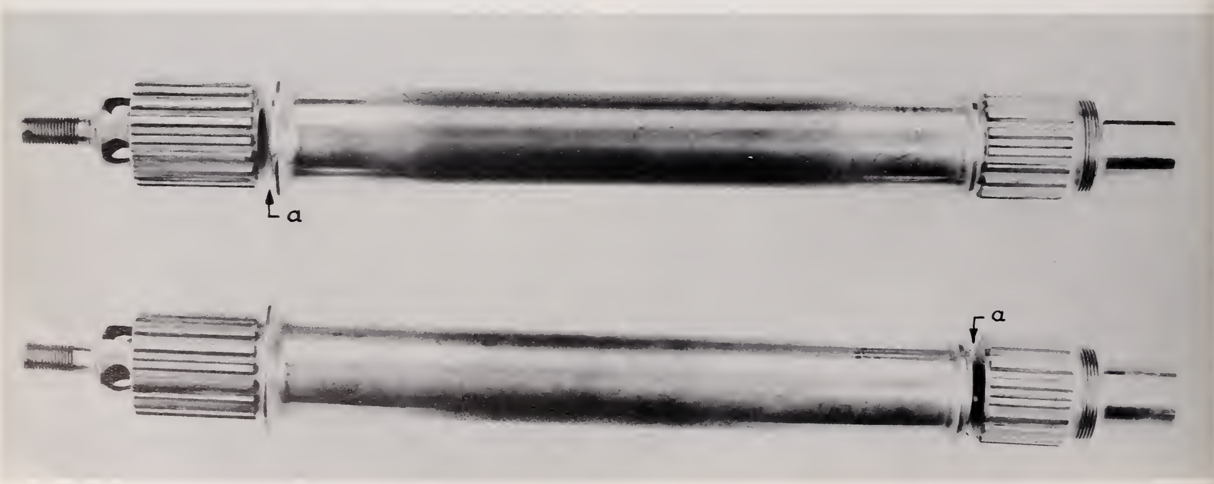

FIGURE 3.1. *Accessory drive shafts fractured at arrows a*

The geometry of the parts and the high rate of loading localized the deformation in the grooved portions of the shafts, which were nearly identical at the two ends. The torsion load caused no dimensional change in the shaft before fracture such as a tension load would have caused. × ½.

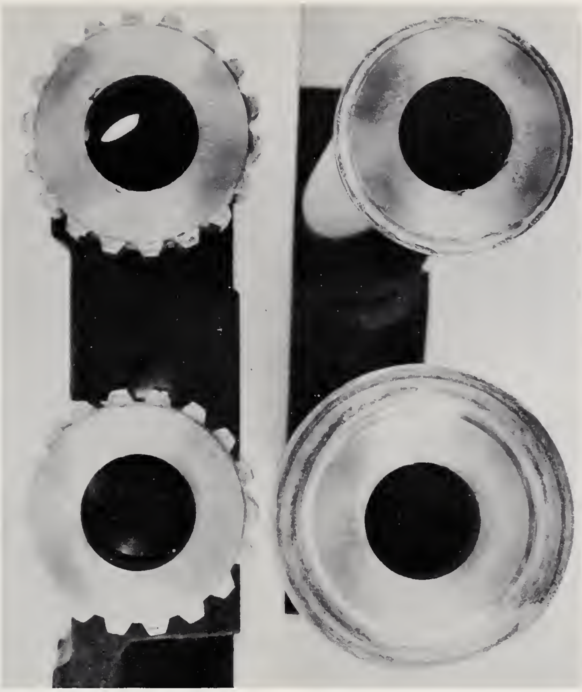

Figure 3.2. *Surfaces of the fractures.*

The smooth surfaces are due to the fact that the deformation and fracture occurred under torsional load, so the metal was distorted only by shear in planes parallel to the fracture. × 1.

Case 4: Prosthetic ankle (aluminum alloy casting). This part was typical of a number that had failed in normal service. The design of the part was poor, in that the key groove reduced the cross section at the section where clamping stresses were highest. The groove and the reentrant angle at the back of the clamp acted as points of stress concentration that would reduce the strength of the relatively brittle casting. In addition, the casting was of poor quality, containing numerous voids.

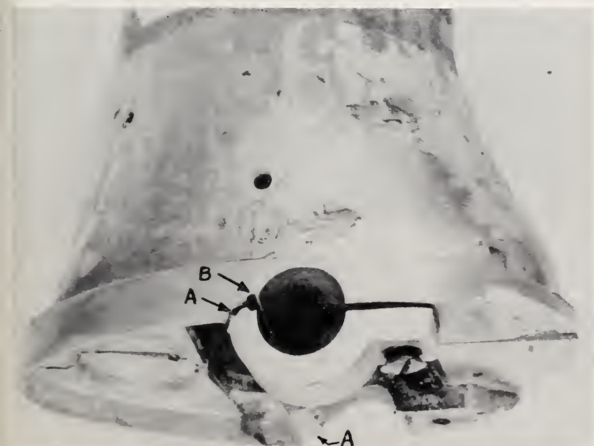

Figure 4.1. *Aluminum-alloy ankle casting.*

The fractures, A, occurred at the back of the clamp where the key grooves, B, reduced the cross section. × 1.

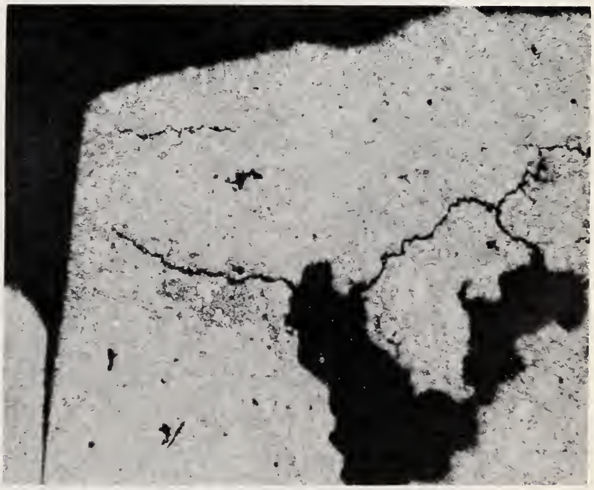

Figure 4.2. *Section perpendicular to the fracture (top) showing porosity, which greatly reduced the strength of the casting.*

Etched with HNO_3, HCl, and HF in water. × 100.

Case 5: Fuel line (aluminum alloy). The metallurgical examination showed that the line had burst while subjected to a high temperature.

FIGURE 5.1. *Failed aluminum-alloy fuel line.* × 1.

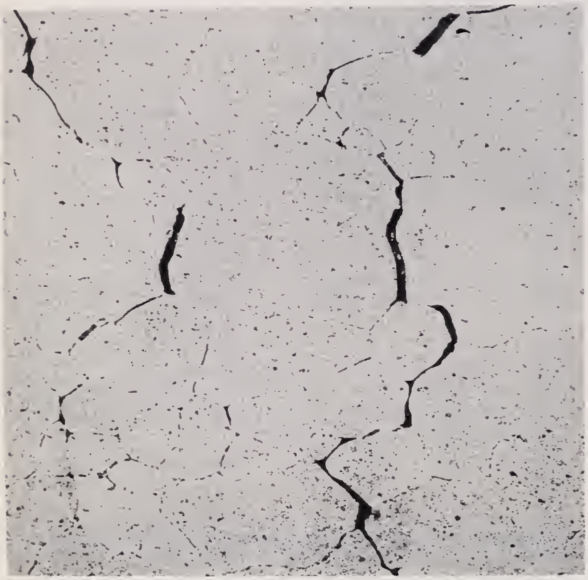

FIGURE 5.2. *Microstructure on a longitudinal section of the tube near the fracture shows numerous intergranular cracks that are typical of material that has been subjected to stress at high temperature.*

Etched with HNO_3, HCl, and HF in water. × 100.

Case 6: Turnbuckle from aircraft control system (brass). Removed from an airplane that had been involved in an accident. It was evidently not the primary failure. The part had broken while heated to a very high temperature. The fracture surface shows extremely coarse grains and little ductility. The temperature at the time of failure was sufficiently high to reduce the strength of the grain boundaries in the metal, which resulted in facture, with little or no ductility.

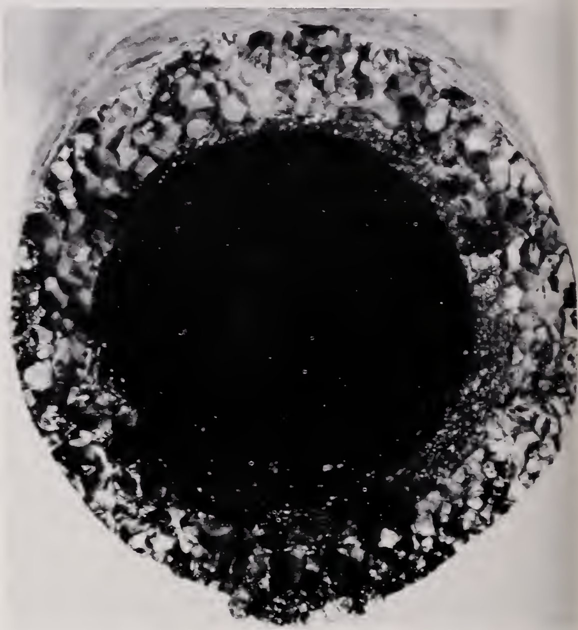

FIGURE 6.2. *Fracture surface showing extremely coarse grains due to elevated temperature.* × 8.

FIGURE 6.1. *Parts of two broken turnbuckles removed from a crashed airplane.* × 1.

Case 7: Aircraft rudder cable (steel). The rudder cable broke during normal operation. The aircraft had been subjected to fire some time previously and supposedly repaired. Sufficient heat had been applied to the cable during the fire to completely alter the microstructure, resulting in much lower strength. This weakened portion of the wire was unable to withstand the normal applied loads and failed in a ductile manner.

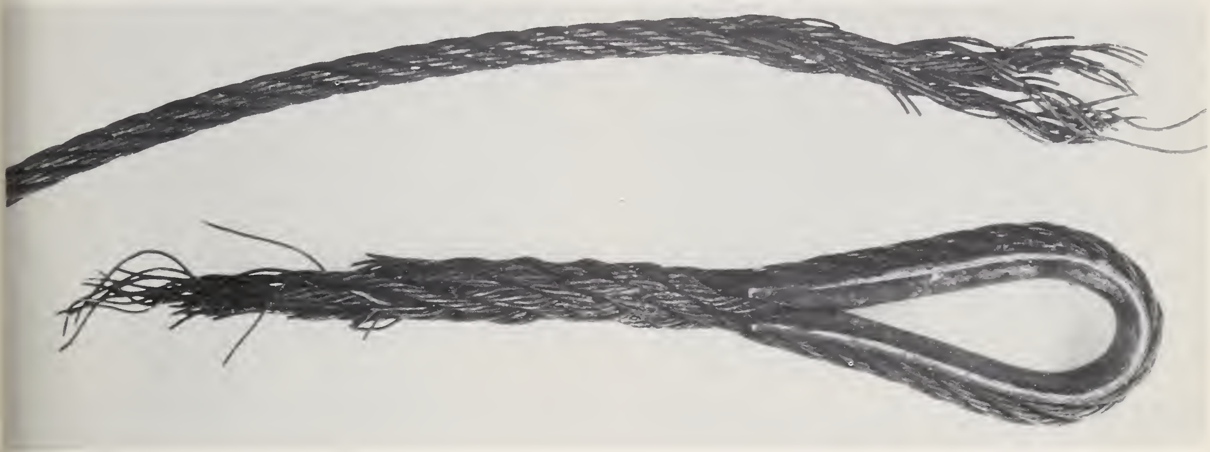

FIGURE 7.1. *Broken rudder cable.* × 3.

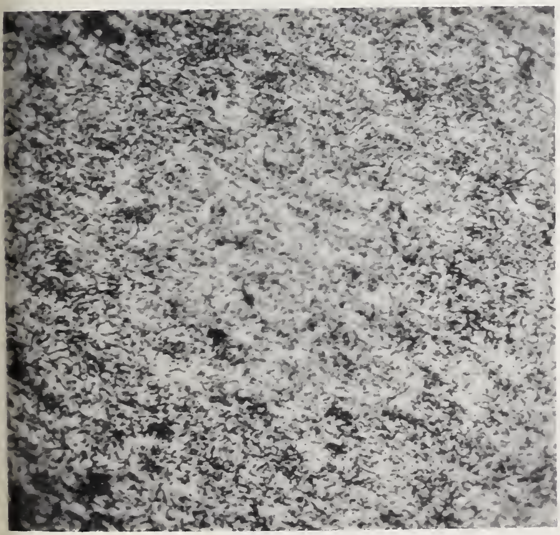

FIGURE 7.2. *Microstructure of a longitudinal section of a wire near the fracture indicates that this portion of the cable had been heated sufficiently to spheroidize the carbides and reduce the strength of the cable.*

Etched with nitric acid in alcohol. × 1000.

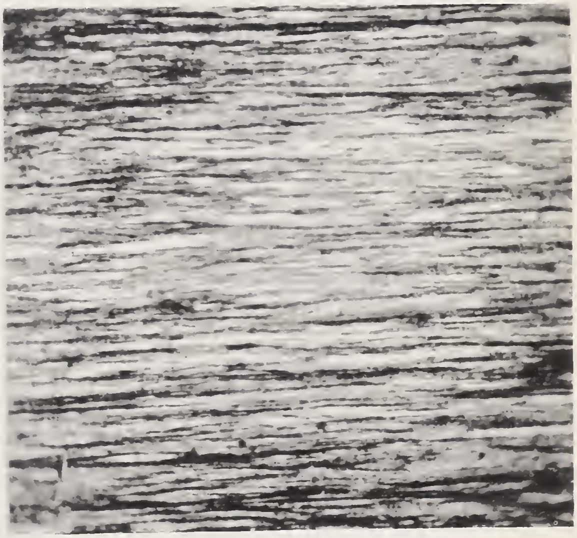

FIGURE 7.3. *Microstructure of a longitudinal section of a wire 2 feet from the fracture shows the normal structure of severely cold-drawn steel wire.*

Etched with nitric acid in alcohol. × 500.

Case 8: Wing hinge fitting (SAE 4340 steel). The extremely coarse grains visible on the fracture surface on one side of the lug, and the intergranular oxidation in this area was apparently caused by severe local overheating after forging but before heat treating. The resultant structure had so little intergranular strength that it fractured under normal service loads.

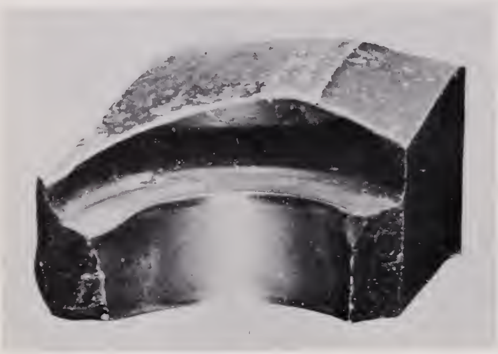

FIGURE 8.1. *Fractured lug showing a brittle fracture on the right and a normal ductile fracture on the left.* × 1.

FIGURE 8.2. *Surface of the brittle fracture, showing the extremely coarse grains revealed by the fracture.* × 5.

FIGURE 8.3. *Microstructure of steel adjacent to the fracture.*

The very large grains are outlined by a network of oxides, which reduced the strength of the metal. Etched with nitric acid in alcohol. × 100.

Case 9: Brake drum from highway truck (cast iron). The drum had become severely cracked in service; cracking of this kind was known to have caused complete fracture of similar drums. The inner surface of the drum had been heated by friction to a sufficiently high temperature to transform the normal pearlite matrix of the iron to martensite in some spots. As martensite occupies more volume than pearlite, the transformation set up high internal stresses in the metal, which, combined with the applied stress, were sufficient to cause cracking adjacent to the transformed areas. This type of cracking is often referred to as heat checking.

Figure 9.1. *Cracked brake drum, as received.*

The cracks are easily visible because of the brake lining material that had been scraped off and forced into them. ×⅙.

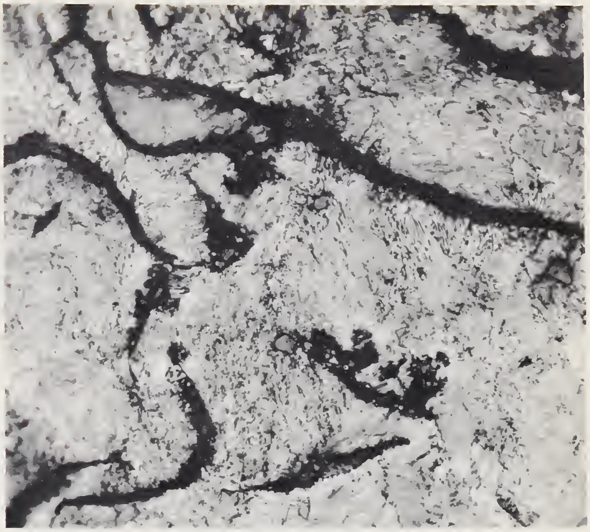

Figure 9.3. *Typical microstructure in the interior of the drum.*

Graphite flakes are interspersed through the pearlite matrix. Etched with nitric acid in alcohol. × 500.

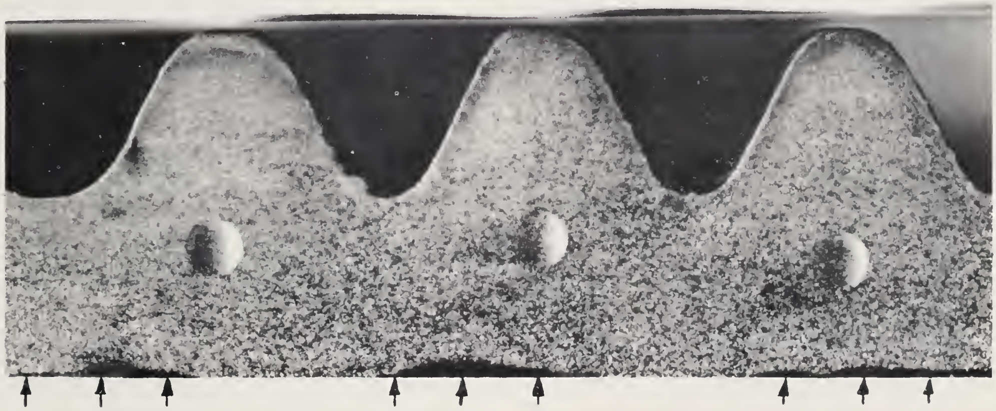

Figure 9.2. *Etched section of drum showing numerous transformed areas (dark) indicated by arrows along the inner surface at bottom.*

The hardness of the original material was 265 Vickers, whereas that in the dark areas was as high as 450 Vickers. × 2.

Figure 9.4. *Microstructure in the dark-etching areas along the inner surface of the drum.*

The pearlite has transformed to hard, brittle martensite. Etched with nitric acid in alcohol. × 500.

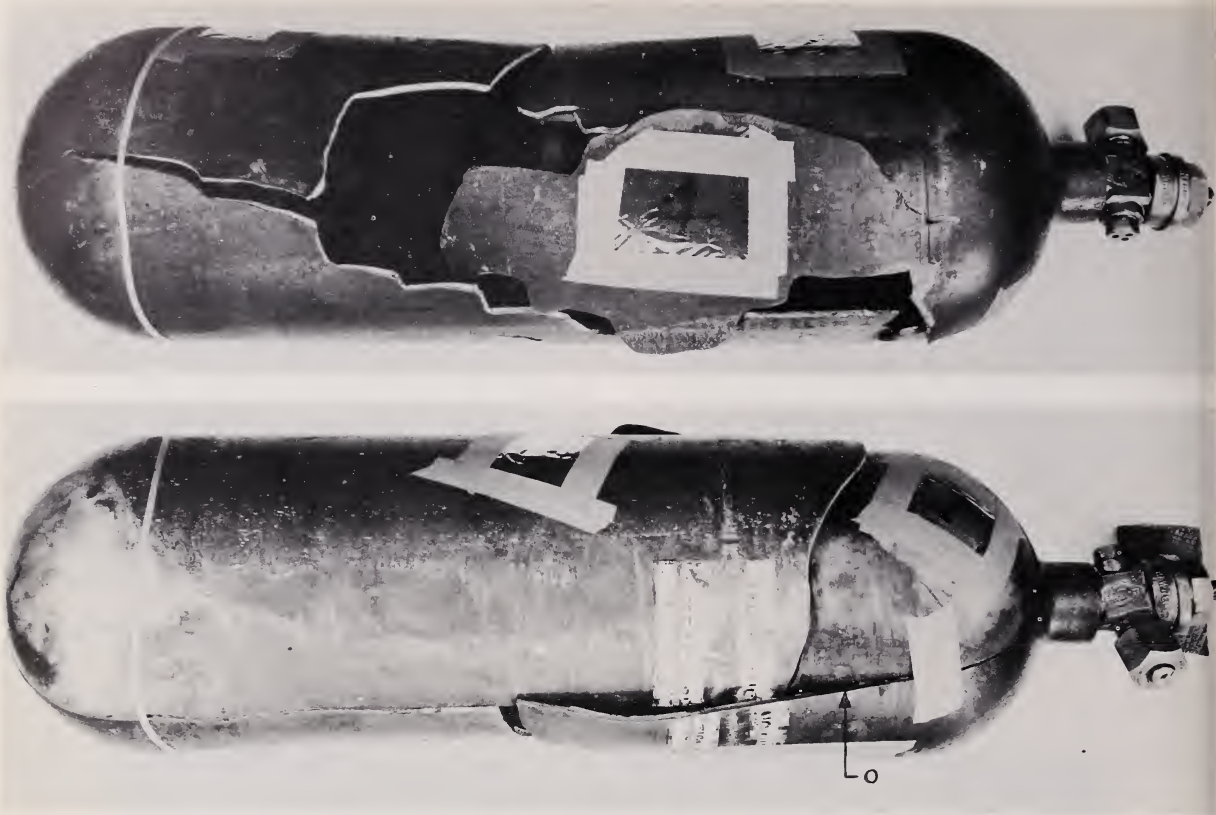

Figure 10.1. *Appearance of exploded cylinder with pieces fitted approximately in their original positions.*
By following the indications of the markings on the fracture surfaces, the origin of the fracture was located at arrow O. × ⅓.

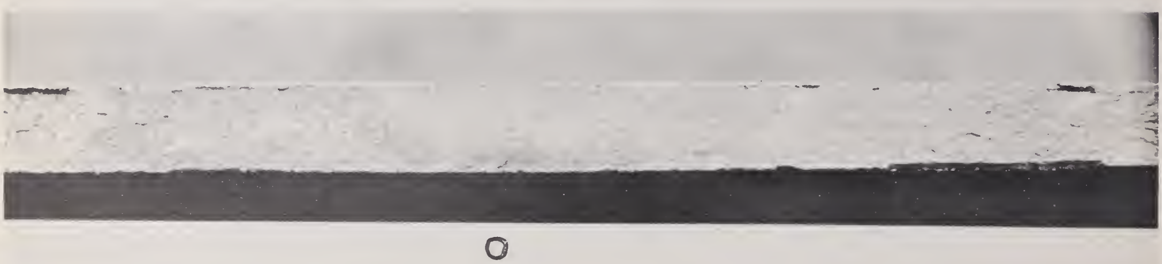

Figure 10.2. *Surface of the fracture, in the region of the origin.*
Note that the "chevron" markings near the top and bottom of the photograph both point toward the middle, indicating that the origin was near O. × 4.

Case 10: Oxygen cylinder (alloy steel). The cylinder had been in service for approximately 4 years, and an explosion occurred several hours after charging. The temperature at the time of failure was at least 80° F. The steel used for this cylinder was not of the composition specified. Although it did not conform to any of the common steel specifications, it contained alloying elements in sufficient quantity to cause it to harden on air-cooling. Consequently, the steel was much harder and more brittle than the specifications permitted. The hardness was 50 Rockwell C, and the elongation measured in a tensile test of the material was less than one-fourth of that specified.

The fracture started in an area that had been abraded on the surface of the cylinder. It is probable that scratches in this area caused sufficient concentration of stress to result in the formation of a small fatigue crack under the fluctuating load when the cylinder was filled and emptied. However, this crack did not grow to sufficient size to be observed because the material was so brittle that a very small crack produced sufficient stress concentration to initiate a brittle fracture.

FIGURE 10.3. *Surface of the cylinder near the origin of the fracture, showing the abrasions apparently caused by a clamping tool.* × 3.

It should be noted that while the steel used in this cylinder was stronger than that specified, it failed because of the highly deleterious effect of notches in this brittle material.

Case 11: Rod end bearing from the wing strut of a light plane (free-machining steel). Fracture of part during apparently normal flight caused a crash. The numerous large inclusions in this material greatly reduce its ductility transverse to the rolling direction. The fitting was cut from bar stock, so that the inclusions were parallel to the length of the shank. Thus the tensile stress at the top of the eye was applied in a transverse direction, and the strength of the thin section was inadequate to support normal flight loads. In order to avoid loading in a transverse direction in a part of this kind, it is generally necessary to use a properly designed forging. The free-machining steels are unsuitable for critical parts subject to high stress in service because of poor transverse properties and great variability.

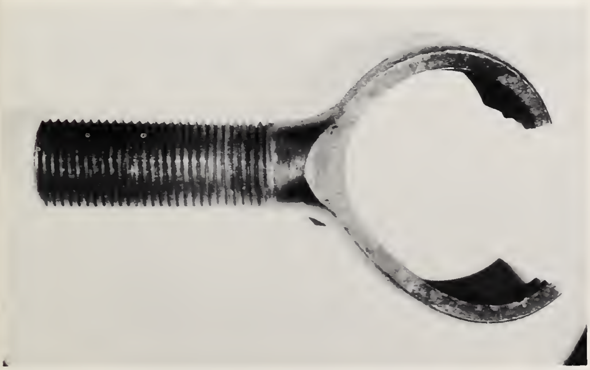

FIGURE 11.1. *Rod end bearing which fractured in service.*
The fracture showed almost no local ductility. × 1.

FIGURE 11.2. *Surfaces of the fracture; note the "woody" appearance caused by the large number of inclusions in the steel.* × 5.

FIGURE 11.3. *Bend tests on sections cut from the eye of unused bearings, showing the difference in ductility in different directions.*
Top, section cut from top of eye so the bending stress was transverse to the direction of rolling. Bottom section from side of eye. × 2.

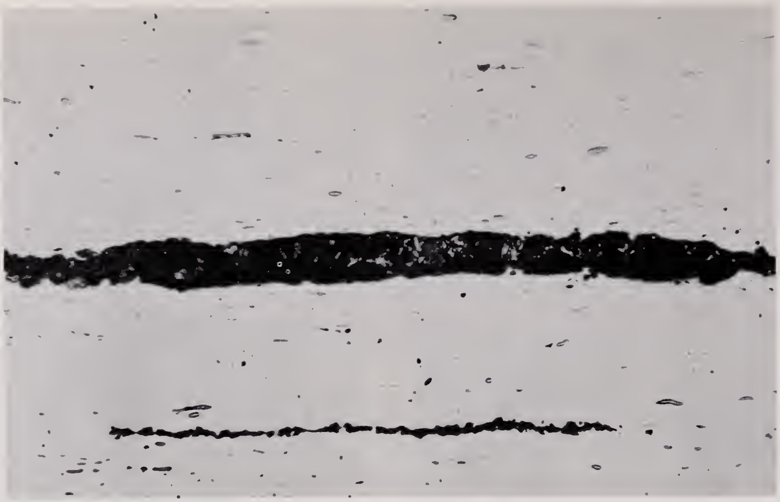

FIGURE 11.4. *Large inclusions observed on a longitudinal section of the steel*

The numerous small inclusions shown in this micrograph are typical of those found on all sections examined. No etch. × 100.

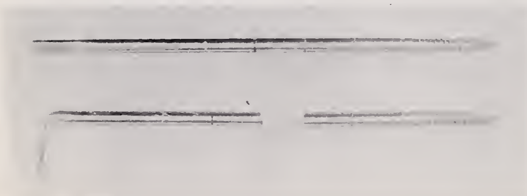

FIGURE 12.1. *Mandibular fracture pin as received (upper) and a similar pin that had been tested in the laboratory.*

The fracture occurred under a bending moment of 5.7 in-lb, and closely resembled the fractures that had occurred in service. There was almost no plastic deformation before fracture. When the pin was clamped near the head, it supported a moment of more than 8 in-lb and bend 90° without fracture. × 2.

FIGURE 12.2. *Contour of a typical groove machined in the pins for depth indication during driving.* × 30.

Case 12: Mandibular fracture pins (AISI 440C stainless steel). These pins were used by surgeons in setting broken bones. Several cases had been reported of pins breaking while being driven. Circumferential grooves had been machined in the pins to provide an indication of the depth to which they had been driven. These grooves, in a material of high hardness (550 to 600 Vickers), resulted in a great loss of strength, particularly under impact conditions. Laboratory tests indicated that the static bending strength of the pins was reduced about 50 percent by a groove, whereas the resistance to bending impact was reduced about 90 percent. Although no bending load would be required to drive the pin, it is probably very difficult to avoid applying such a load accidentally.

Case 13: Pulling yoke for a testing machine (SAE 4340 steel). The yoke had been made for use in the Engineering Mechanics Section of the National Bureau of Standards. The calculated stress at fracture was only 30,000 $lb/in.^2$ It was found that the piece contained numerous intergranular cracks, probably due to improper forging practice or heat treatment. In addition, the hardness and strength of the steel were much higher than that specified, (45 Rockwell C compared to a specified value of 34) with consequent greater brittleness. The combination of these factors reduced the strength of the part much below that of sound material of lower hardness.

FIGURE 13.1. *Fractured yoke with the initial fracture, A fitted together.*

The fracture at B resulted from the eccentric loading after the initial fracture. × ⅙.

FIGURE 13.2. *Surface of the initial fracture.*

The dark area near D is a crack that occurred during fabrication or heat treatment, and caused the brittle fracture under load. The darkening is due to oxide scale, which shows that the steel was heated to a high temperature after the cracks were formed. × 1.

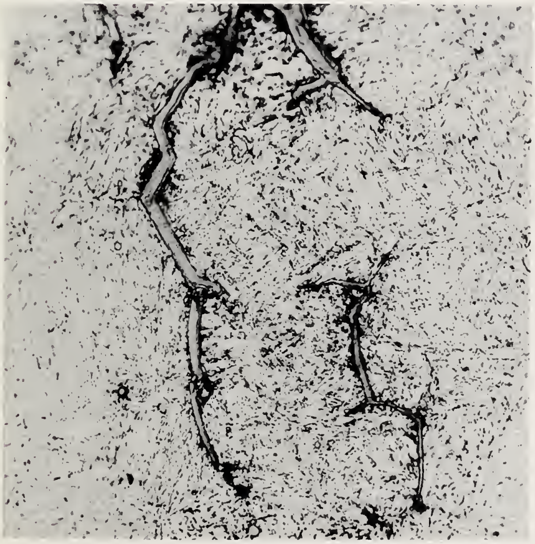

FIGURE 13.3. *Inner end of a crack similar to those which caused the fracture.*

The path of the crack appears to be along the boundaries of prior austenitic grains, which is typical of cracks due to improper forging or quenching. Etched with nitric acid in alcohol. × 500.

Case 14: Ships (steel). One of the major projects of the Metallurgy Division in recent years has been the examination and testing of plates removed from fractured ships. Since 1947 this work has been done under the sponsorship of the Ship Structure Committee of the National Research Council. The results of this work have been summarized recently [5] and will be discussed here only briefly. The fractures in ship plates are almost without exception brittle fractures which occur by the propagation of a crack at high velocity. As discussed in the introduction, these fractures show "chevron" markings, which can be used to locate the source of the fracture. The following generalizations apply to almost all of the cases that were studied: (1) The fractures occurred at low temperature. (2) The fractures originated at points of stress concentration caused by geometrical or metallurgical notches, such as cut-outs, hatch corners, welding defects, or changes in section. (3) Considering the whole ship as a beam subjected to bending, the origins of the fractures were in areas where the stress would be high, i. e., near the middle of the length and in either the top (deck) or bottom, which are most remote from the neutral axis.

Marked reductions in the frequency of ship failures have been effected by changes in design, which have eliminated or reduced stress concentration in critical areas. Improved quality of welding has also been a major factor in the greater reliability of ships built in recent years. Studies of the properties of the steels have shown, however, that these must also be controlled if the possibility of failure is to be eliminated.

The property of a steel which is important in resisting brittle fracture is usually measured by an impact test. The upper specimen in figure 1 (sec. 2) is a Charpy V-notch impact specimen that has been broken by supporting the ends and striking the side opposite the notch with a heavy pendulum. If the energy required to break the specimen is determined at various test temperatures, it will be found that as the temperature is lowered the nature of the fracture changes from ductile to brittle and the energy drops sharply. The temperature range of this ductile-brittle transition in the ship steels has been found to be be significantly different in plates in which the fracture originated as compared with those plates which the fracture went through and those in which it ended. The following table summarizes all of the data of this type on the ship plates that have been investigated on this project.

Type of plate	Number of plates	Average transition temperature
		° F
Source	38	100.7
Through	52	67.4
End	40	53.0

The "through" plates represent approximately the normal distribution of properties found in the plates used in ship construction during this period. The table indicates that the chance of a fracture starting in a given plate is greater if that plate has a high transition temperature, whereas plates with low transition temperatures are more apt to stop the crack. The latter difference is less significant than the former because many factors other than the properties of the material are involved in stopping the crack. It is almost impossible to eliminate all notches in a large structure such as a ship, so if a plate with a high transition temperature (low resistance to brittle failure) is in a critically stressed location, there is a good possibility that it will fail.

Figure 14.1. *Tanker that broke in two at dock, viewed from port side.*

The position of the two parts of the vessel are an indication of the bending load which caused the fracture. U. S. Coast Guard photograph.

Figure 14.2. *Starting point of the fracture shown in figure 14.1.*

This clip had been welded onto the heavy deck plate very close to a large chock, thus forming a sharp notch. × ½.

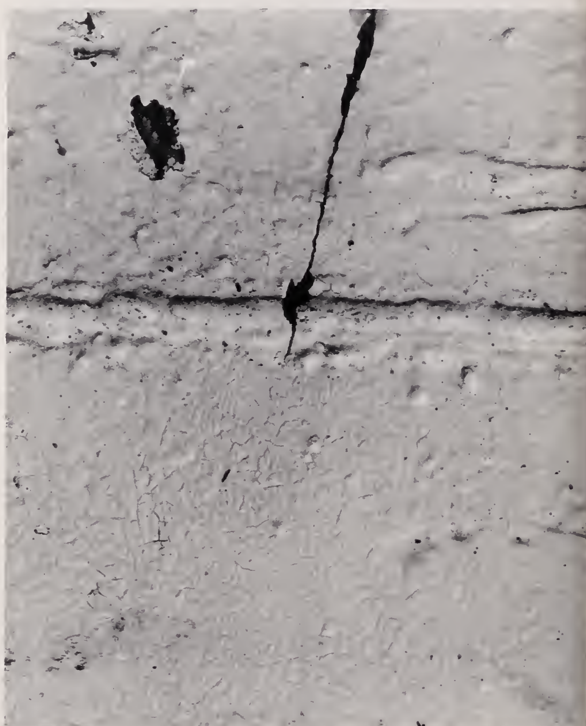

Figure 14.3. *Area near the end of a fracture.*

The crack propagated through the upper plate in typically brittle manner, leaving the paint uncracked except along the fracture. The plate below the weld had greater resistance to brittle fracture and was able to deform plastically, as shown by the cracked paint. This deformation resulted in the crack stopping about ½ inch below the weld. × ½.

Case 15: Aircraft engine crankshaft (alloy steel). The crankshaft fractured after a total of 220 hours of service. The fatigue crack originated in an area where fretting had occurred under the propeller hub. Fretting is the term given to the action that results in surface damage when there is relative motion between solid surfaces in contact under pressure. The action may be produced by extremely small motions and causes a severely pitted condition of the surface. In this case the pits concentrated the stress to such an extent that the peak stress was greater than the fatigue strength[2] of the steel.

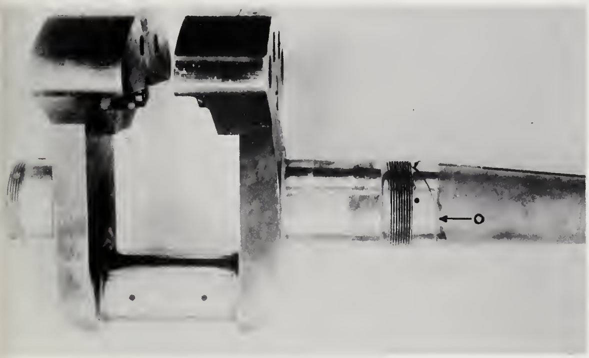

FIGURE 15.1. *Crankshaft with broken parts fitted together.*

The fracture originated at arrow "o" in an area where rubbing had occurred. × ¼.

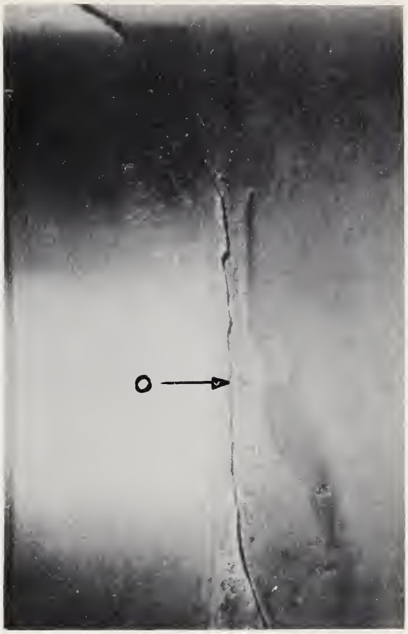

FIGURE 15.2. *Appearance of the surface near the origin.*

The pitting was caused by a small amount of motion between the shaft and the propeller hub clamped to it. × 2.

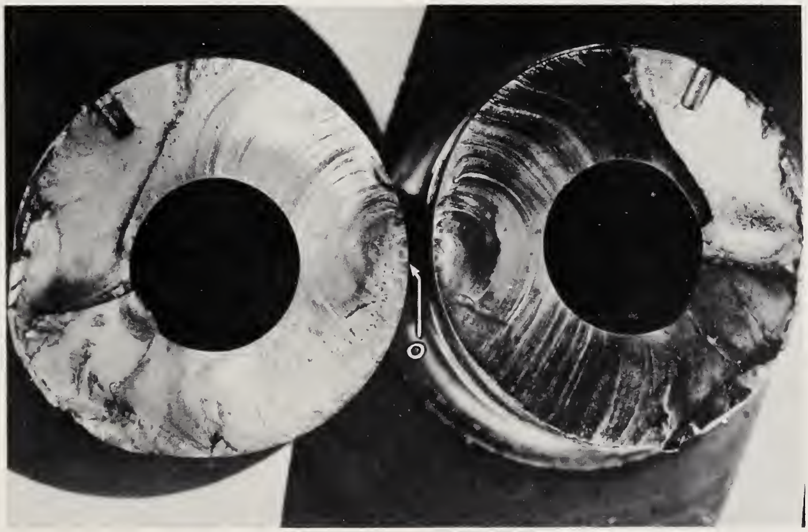

FIGURE 15.3. *Surfaces of the fracture.*

The "beach" or "clam shell" markings, which are apparent on this fracture, show the way in which the fatigue crack progressed across the shaft. × 1.

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[2] "Fatigue strength" is used in this circular in a general sense to denote the resistance of a metal to failure by fatigue.

Case 16: Aircraft propeller blade (aluminum alloy). The fatigue fracture originated in an area where fretting had occurred between the blade and the hub under the hub ring clamp, resulting in surface pits similar to those shown on the crankshaft of case 15. In addition, the clamp caused an effective change in the stiffness of the blade assembly with consequent stress concentration.

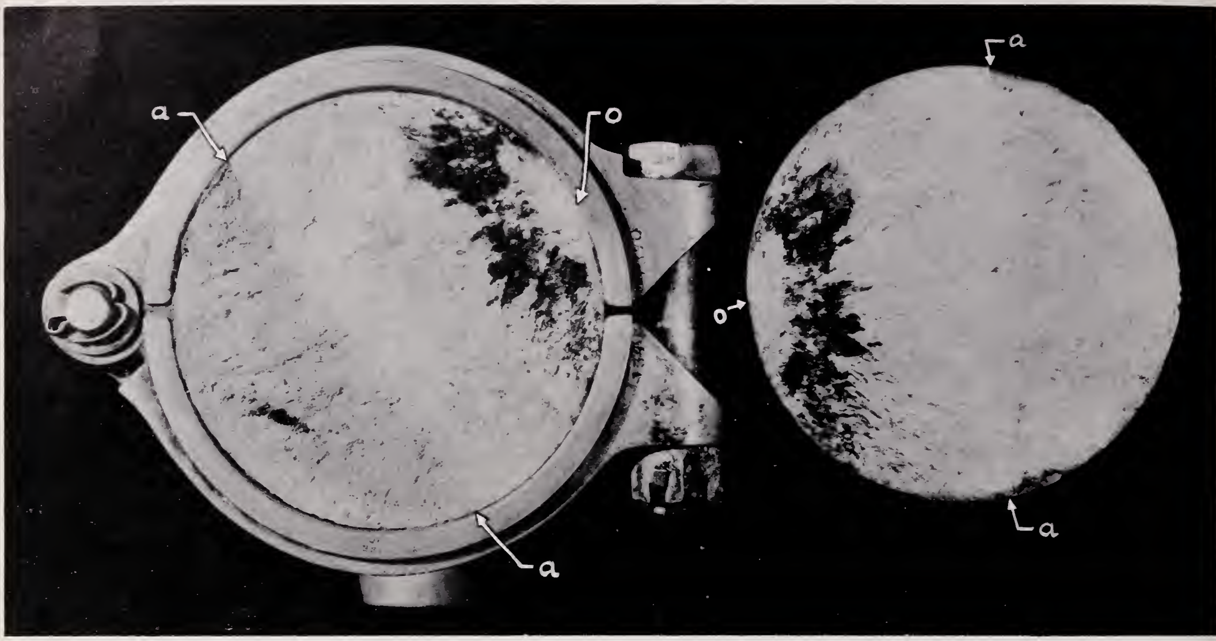

FIGURE 16.1. *Surfaces of the fracture which originated under the hub ring clamp at arrow O.*

The fatigue crack extended to "a"; then the remaining area broke from overload. The dark areas were believed to be caused by the finely powdered material formed by the rubbing action between the blade and hub surfaces, which worked into the crack as it progressed. × ¾.

FIGURE 16.2. *Surface of the blade near the origin of the fatigue crack.*

The dark areas are those that have rubbed against the hub and contain numerous pits. × 1.

Case 17: Steering arm from a highway truck (steel). It was reported that considerable difficulty had been experienced with breakage of these parts. There had apparently been a poor fit between the tapered portion of the arm and the mating piece. This had allowed rubbing and consequent fretting to take place, and the resulting pits had caused the initiation of fatigue cracks.

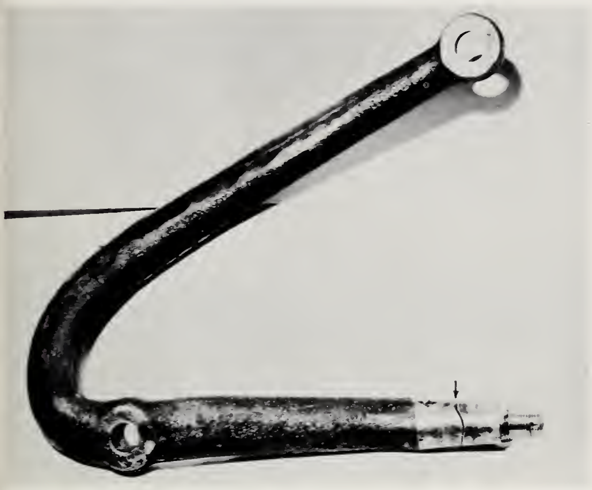

FIGURE 17.1. *Broken steering arm from a highway truck.*

The origin of the primary fatigue crack is indicated by the arrow. × ¼.

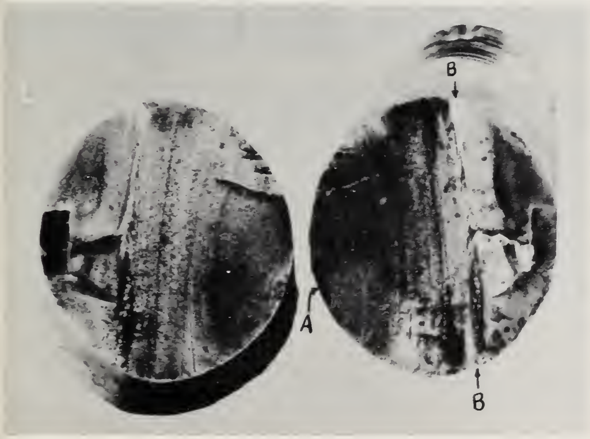

FIGURE 17.2. *Surfaces of the fracture shown in figure 17.1.*

The first fatigue crack started at A, and other cracks started on the opposite side of the piece. These progressed across most of the section before the final overload fracture broke the remaining metal along line BB. The small proportion of the section involved in the overload fracture indicates that the working stresses were relatively small. × 1.

FIGURE 17.3. *Longitudinal section of the arm near the origin of the fatigue crack.*

Pits similar to that shown here are believed to have concentrated the stress to such an extent that the crack was initiated under relatively low applied load. Etched with nitric acid in alcohol. × 100.

FIGURE 17.4. *Surface of the arm near the origin of the fatigue crack.*

The severe pitting is evident in areas where fretting had occurred as contrasted with undamaged areas where the original tool marks are still visible. × 4.

FIGURE 18.1. *Failed helicopter rotor link.*

The fatigue fracture occurred in the lower lug. The broken piece of this lug has been fitted back in approximately its position at the time of final fracture. The upper lug failed from overload after the fracture of the lower one. × ¼.

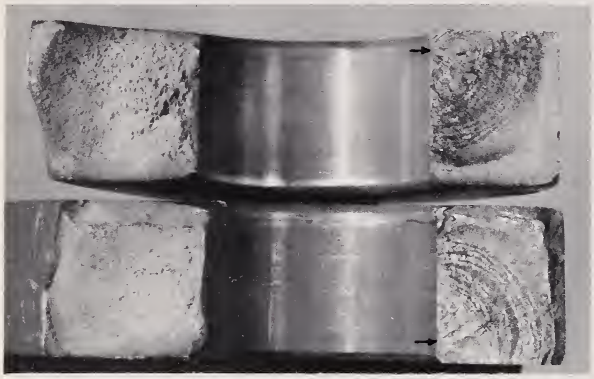

FIGURE 18.2. *Lower lug of Fig. 18.1 showing the origin of the fatigue fracture (arrow) on the inside of the hole at the point where the inserted bushing ended.*

The surface of the fatigue fracture appears rough at this magnification, but it was actually made up of numerous facets, giving it an appearance similar to the fracture in a brittle substance like coal. The contrast between this fracture and a similar one in a steel forging is apparent when this figure is compared with figure 22.2, which is at the same magnification. The concentric rings were caused by variations in the rate of progress of the crack due to changes in stress. The left side of the lug failed due to overload after the right side had broken. × 1.

Case 18: Helicopter rotor link (14S aluminum-alloy forging). The link failed in service, causing a fatal accident. No metallurgical defects were found that might have influenced the failure of the part. The example is shown primarily to illustrate the appearance of a typical fatigue fracture in a light-alloy forging, as it is quite different from that in steel. As there was a steady tensile load on this part in addition to the fluctuating load, the surfaces of the fatigue crack were held apart and the surface features were preserved.

Case 19: Aircraft engine cylinder (steel). The steel was properly hardened and tempered and was of good quality. The sharp notch at the cut-out for the hold-down nut had resulted in sufficient stress concentration to initiate a fatigue fracture.

FIGURE 19.1. *Lower part of the failed cylinder, showing the fatigue fracture which originated at the cut-out for the hold-down nut, (arrow) and progressed first diagonally, then circumferentially around the cylinder.* × ½.

FIGURE 19.2. *Section through the intersection of the cut-out and the cylinder, showing the sharp corner with a minimum radius of approximately 0.025 inch.* × 50.

Case 20: Fitting from aircraft nose wheel yoke (aluminum alloy). The fracture of this fitting caused the collapse of the nose gear, with resulting damage to the plane. The fillet at the change of section was so poorly machined that there was a very small radius at the junction with the journal instead of the ½-inch radius specified in the drawing. This resulted in sufficient stress concentration to cause the initiation of a fatigue crack. The small fatigue crack reduced the strength of the part to such an extent that fracture occurred at the time of high stress on the part during the aircraft landing.

Case 21: Aircraft propeller (steel). The design of the hub was such that there was a severe notch at a point where the two parts of the hub were joined. This served to increase the stress due to operating loads to several times its nominal value, and resulted in the initiation of a fatigue fracture. If enough brazing alloy had been used to completely fill the space between the parts, the stress concentration would have been reduced.

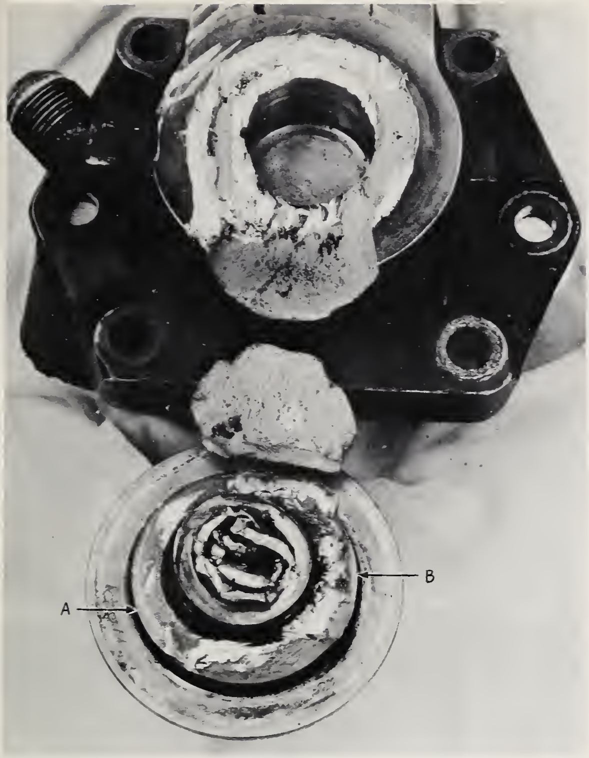

FIGURE 20.1. *Fractured fitting as received.*

Fatigue cracks A and B originated in the fillet, which joined the large section on the upper piece to the small diameter part below, which fitted inside a steel sleeve. Because of the high stress concentration, the cracks progressed around the periphery more rapidly than they did into the section. × ½.

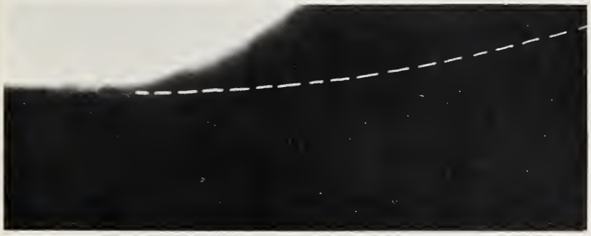

FIGURE 20.2. *Profile of the fillet adjacent to the small diameter (left).*

The dashed arc shows for comparison how a ½-inch radius fillet would appear at this magnification. × 17.

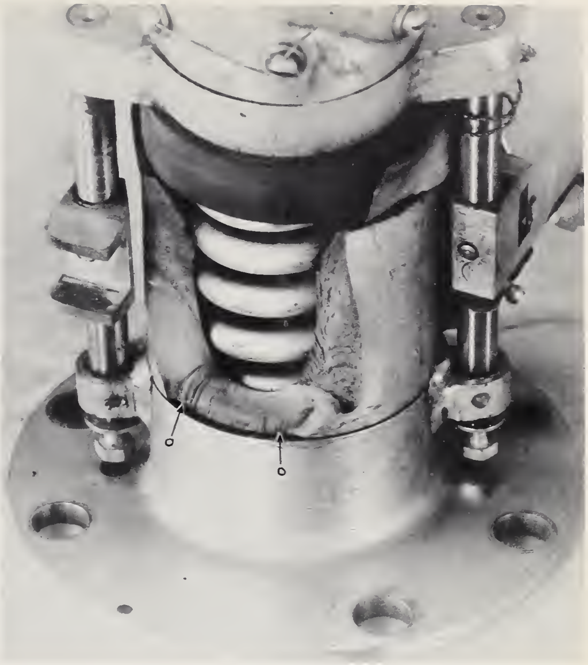

FIGURE 21.1. *Surface of the fracture in the propeller hub where the arm holding one blade broke completely out of the hub.*

The markings of the fracture surface indicate that several fatigue cracks originating in the area O–O grew together to form a single crack.

FIGURE 21.2. *Cross section of the hub showing the method of assembly.*

The two parts were brazed along the lines indicated by the arrows, leaving a circumferential notch A. The fatigue fracture started at the root of this notch. × ½.

FIGURE 22.1. *Hub end of the fractured blade.* × ⅓.

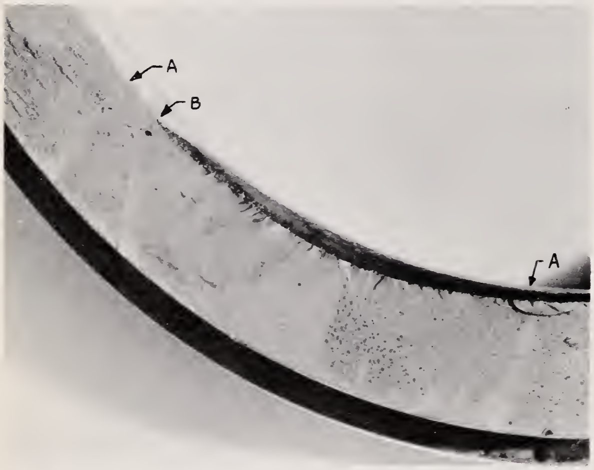

FIGURE 22.2. *Fracture surface near the origin of the fatigue crack.*

Points A, A, mark the extent of the fatigue crack. There was an indentation in the inner surface of the blade (one end of which is indicated by arrow B) caused by improper forging practice. × 2.

Case 22: Aircraft propeller (SAE 4320 steel). The propeller fractured in flight, causing the engine to be torn from the plane. The hub end of the blade had been formed by an upset forging operation. This operation had not been properly carried out, resulting in a fold and fissures on the inner surface of the blade. The fatigue crack had started at a point where stress was concentrated at these defects.

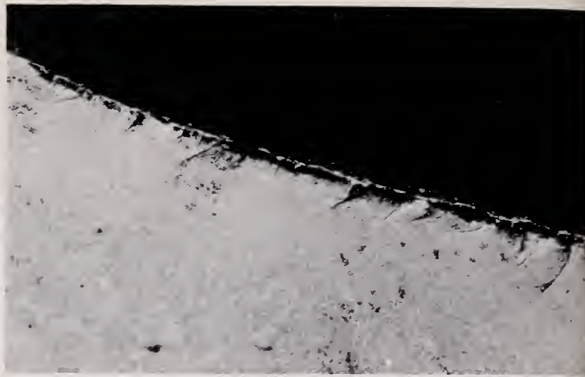

FIGURE 22.3. *Surface of the fatigue crack adjacent to the indentation.*

The black band near the surface is oxide scale, showing that the fissures that caused the fatigue crack were present before the final heat treatment of the blade. × 10.

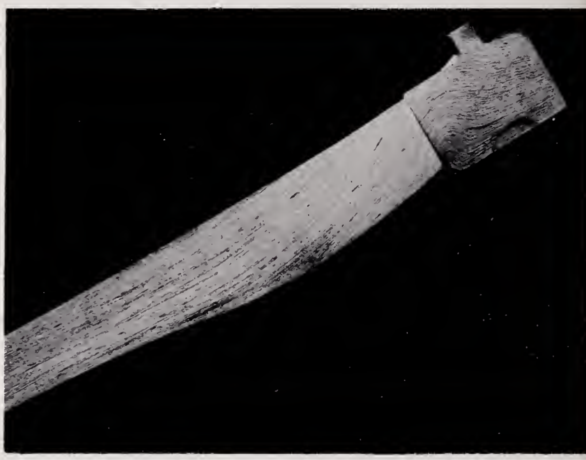

FIGURE 22.4. *Longitudinal section of the blade intersecting the fatigue crack.*

The specimen was deeply etched and shows the wrinkling of the flow lines due to the upset forging operation. It can be seen clearly that the indentation was formed during this operation and it is probable that the fissures were also. × 1½.

Case 23: Aircraft propeller blade (steel). The hollow blade failed due to a fatigue crack that originated at one of several defects on the inside of the blade. These defects, which occurred prior to heat treatment and painting of the blade, appeared to have resulted from a gouging, or galling, action, probably due to scraping against a mandrel.

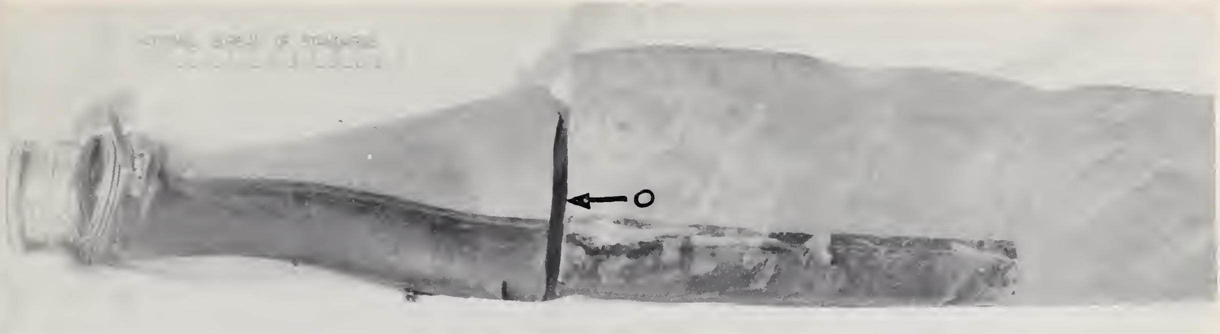

FIGURE 23.1 *Flat side of the broken propeller blade.*
The fatigue crack started on the inside surface near arrow O.

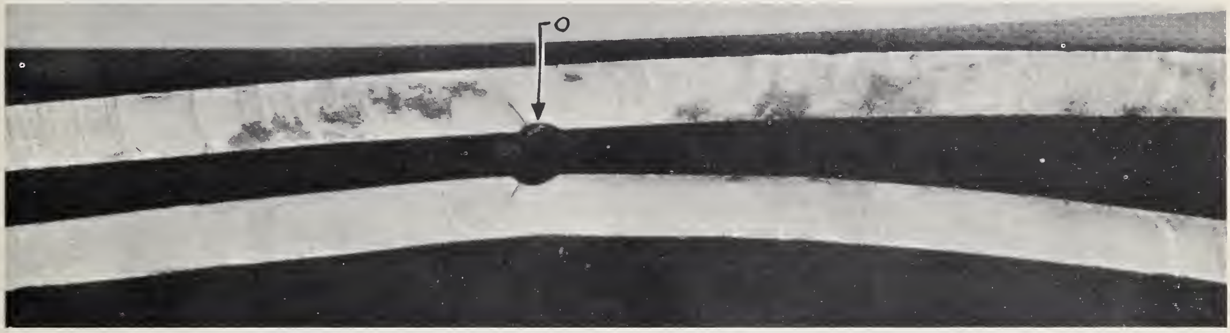

FIGURE 23.2. *Fracture surfaces near the origin of the fatigue crack, arrow O.* × 3.

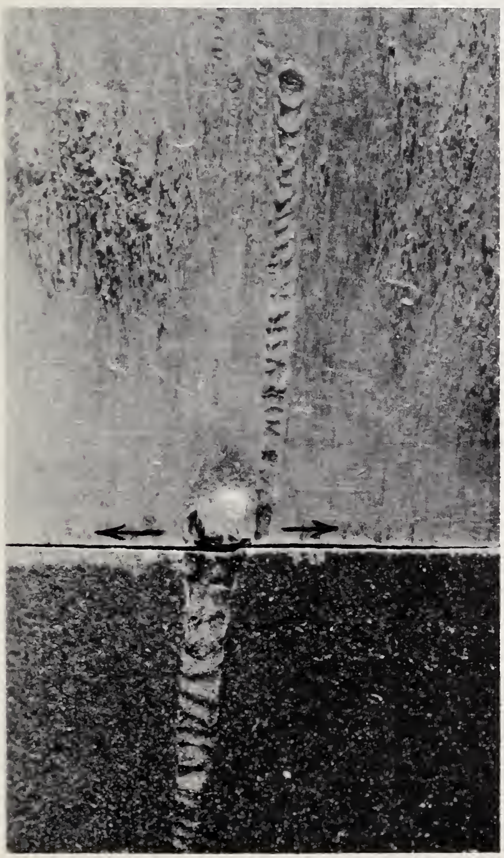

FIGURE 23.4. *Longitudinal section through the defect shown in figure 23.3.*

The serrations were caused by the galling action of another surface being dragged across this one. The action is analogous to the chattering of a machine tool against the work. Etched with nitric acid in alcohol. × 100.

FIGURE 23.3. *Inner surface of the blade showing the defect at which the fatigue fracture started.*

Arrows beside the fracture indicate the directions of growth of the fatigue crack. × 4.

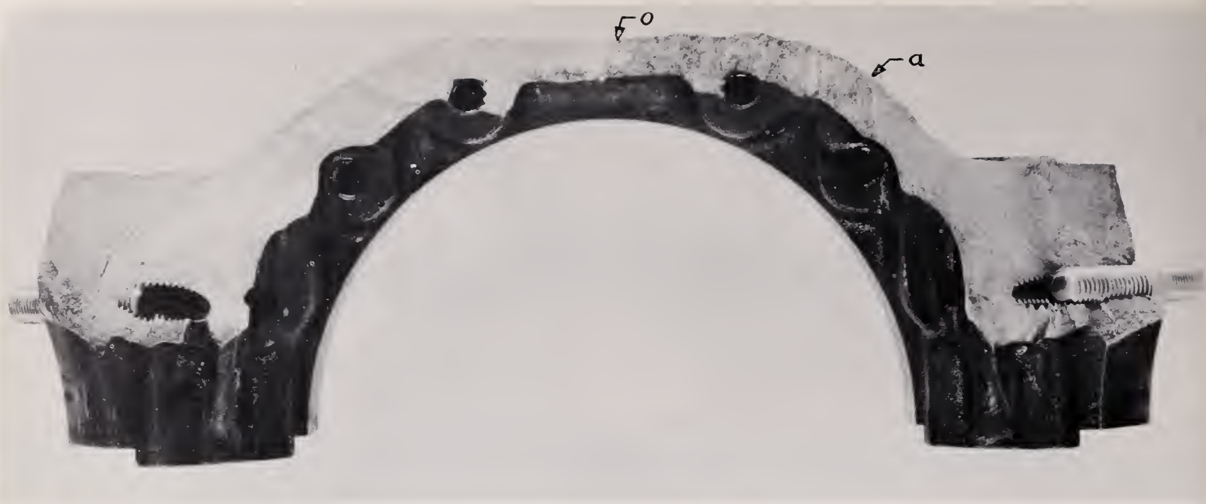

Figure 24.1. *Surface of the fracture in the cylinder pad.*

Origin of the fatigue fracture was at arrow O. The darker zone between arrows O and "a" showed excessive porosity. × ⅔.

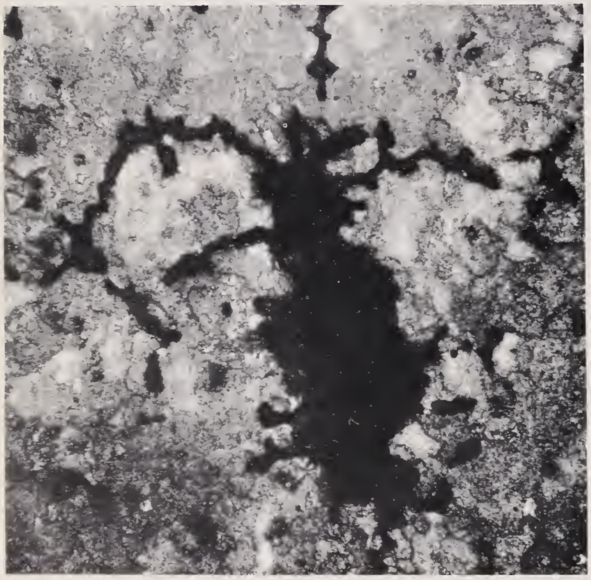

Figure 24.2. *Microstructure of the metal in the porous zone near the origin.*

Etched with HNO_3, HCl, HF in water. × 100.

Case 24: Cylinder pad from aircraft engine (aluminum-alloy casting). Fracture of this part caused failure of the engine on a light airplane. Certain portions of the casting were defective in that they contained excessive porosity. While preparing sections from these parts of the casting for metallographic examination, oil was observed to ooze out of the metal, indicating the magnitude of the porosity. This condition reduced the strength of the casting to such an extent that the fluctuating loads applied in normal operation were sufficient to cause the initiation of a fatigue fracture.

Case 25: Helical spring (steel). This case is included to show a failure typical of fatigue under torsional stress. In the absence of stress raisers, the first cracking in torsion usually occurs in planes of maximum shearing stress, which are parallel and perpendicular to the length of the rod. Because of the directional properties of the rod from which the spring was wound, the resistance to fatigue was less in the parallel direction than the perpendicular, so the crack developed as shown in figure 25.3. When this crack had progressed to a considerable extent, it caused sufficient stress concentration to initiate a crack due to tensile stress in a direction approximately 45° to the length of the rod. This second crack progressed only a short distance before the rest of the section failed due to overload.

FIGURE 25.1. *Fractured helical spring showing the origin of the diagonal fracture on the inside of the coil at arrow "a".* × ½.

FIGURE 25.2. *Fracture surface on one part of the spring.*

The small dark area (arrow) is the tension fatigue crack which originated at the longitudinal (shear) crack. × 3.

FIGURE 25.3. *The two parts of the fracture fitted together.*

The piece on the right has been ground to show the extent of the longitudinal crack (arrow) away from the fracture. × 2.

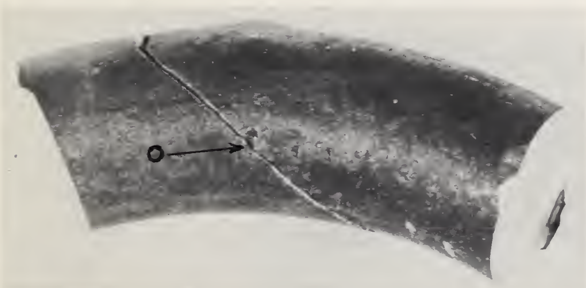

FIGURE 26.1. *Fractured pieces of spring fitted together to show surface pit at nucleus of fatigue fracture, arrow O.* × 2.

FIGURE 26.2. *Surfaces of the fracture; the fatigue crack progressed from the origin at arrow O across nearly half of the section before overload fracture occurred.* × 2.

Case 26: Helical spring (steel). In contrast to case 25, the fatigue fracture in this spring started on a plane normal to the tensile stress. The surface of the spring was somewhat pitted, and the stress concentration at one of these pits was sufficient to cause the initiation of the fatigue crack. The fatigue crack progressed over nearly half of the cross section of the rod before final fracture occurred, indicating that the applied stress was relatively low and showing the severe decrease in fatigue strength caused by a surface defect.

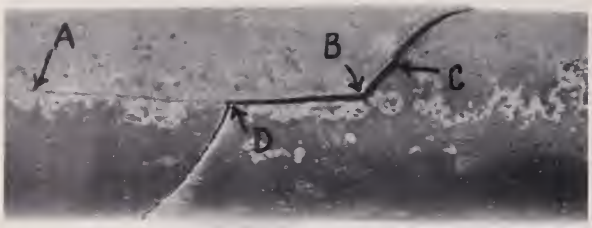

FIGURE 27.1. *Fractured portion of the torsion bar.*

The longitudinal fatigue crack extended from A to B, the tensile fatigue crack from B to C, and the final overload fracture from C around the bar to D. × 1.

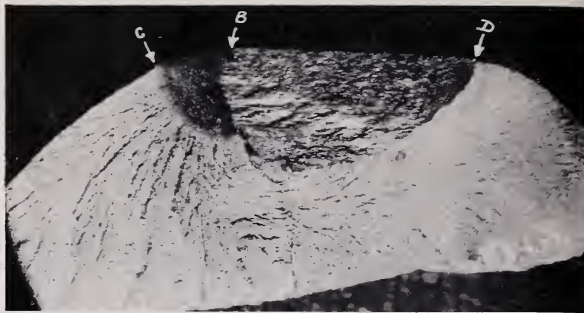

FIGURE 27.2. *Surface of the fracture.*

The dark fatigue crack areas at the top are easily distinguished from the lighter overload portion. The tensile fatigue crack from B to C is on a plane making an angle of approximately 45° to the plane of the paper. × 1.

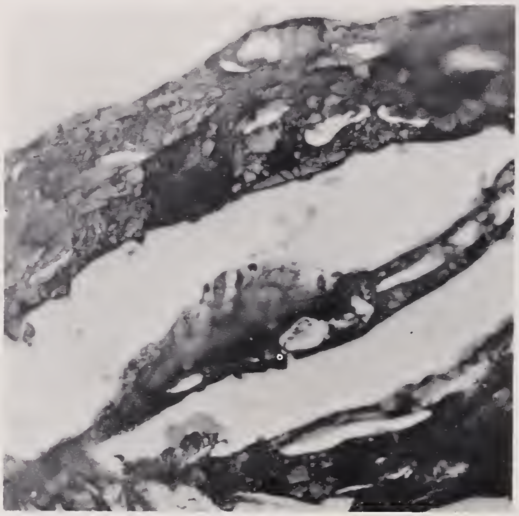

FIGURE 27.3. *Micrograph showing large nonmetallic inclusions found at several locations on a section through the rod.*

Unetched. × 500.

Case 27: Torsion bar from a highway bus (steel, heat treated to a tensile strength of about 200,000 lb/in.^{2}). Fracture occured when the bus was traveling at low speed on city streets. Metallographic examination showed several locations where there were stringers of oxide inclusions in the steel. Apparently these inclusions served as nuclei for a fatigue crack on a shear plane parallel to the length of the rod. After this crack had progressed to a considerable extent, another crack, perpendicular to the tensile stress, started at the end of the longitudinal one. This progressed only a short distance before the remainder of the area fractured from overload. Torsion bars of this type are among the most highly stressed members in common use, and this failure emphasizes the importance of having material free from large inclusions for such service.

Case 28: Front axle from motor vehicle (forged steel). The axle had failed by fatigue. The surface of the axle was badly decarburized, and in addition there were transverse grooves where the forging flash had been removed. Both of these factors seriously lowered the fatigue strength of the part.

FIGURE 28.2. *Bottom surface of the axle adjacent to the fracture, showing the transverse grooves apparently due to shearing off the forging flash.*

The cracks originated at the edges of this scratched area. × 1.7.

FIGURE 28.1. *Surface of fracture in front axle.*

Two fatigue cracks originated near the middle of the bottom and formed the vertical line as they progressed at slightly different levels. The end of this line indicates the merging of the cracks. More than half the cross section of the axle was cracked before the remaining portion failed from overload. × 1.

FIGURE 28.3. *Section of the lower part of the axle a short distance from the fracture, showing the extensive decarburization of the surface.*

Etched with nitric acid in alcohol. × 1.7.

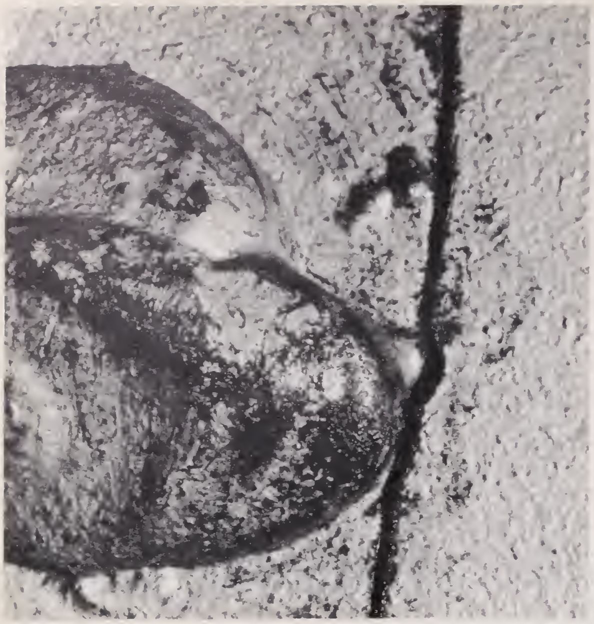

Figure 29.1. *Surface of the fractured spar tube showing the origin of the fatigue crack at the toe of a weld.* × 5.

Figure 29.2. *Transverse section of the tube and weld inboard of the fracture.*

The section was etched in nital and the light areas near both the outside and inside surfaces of the tube are due to decarburization in these areas. × 7.

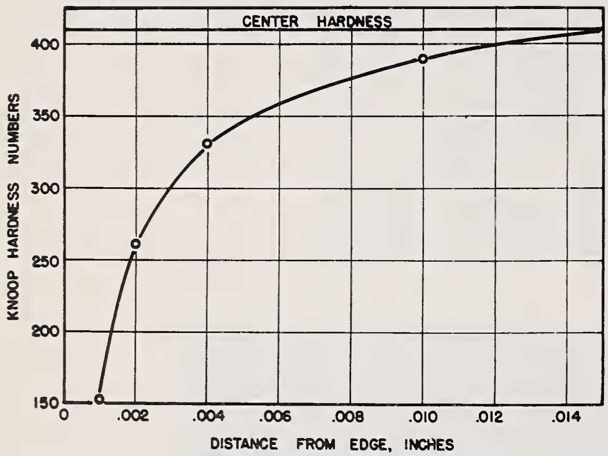

Figure 29.3. *Results of microhardness measurements made on a cross section of the tube.*

The hardness at the center corresponds to a tensile strength of approximately 170,000 lb/in.², whereas that nearest the edge indicates material having a strength of not more than 70,000 lb/in.²

Case 29: Lower flange of tubular wing spar (steel). This plane was used in mail pickup service. It crashed due to the fatigue fracture of the lower flange of the wing spar. The type of service in which this plane was used caused higher fluctuating loads on the wings than would be expected in normal service. In addition, the decarburized condition of the tubing greatly reduced its resistance to fatigue, as fatigue cracks almost invariably start at the surface. Laboratory tests (see Trans. Am. Soc. Metals, vol. 39, p. 45, 1947) on homogeneous and decarburized specimens indicate that the fatigue strength of the fractured tube would be approximately half that of material that had not been decarburized.

Case 30: Numerous parts of a torque indicating system from an aircraft engine (steel). Loss of pressure in the torque-indicating system caused automatic feathering of the propeller, resulting in a crash landing. In examining a failed assembly in an effort to discover the primary failure, the presence of a fatigue fracture is frequently considered sufficient evidence as to which part broke first. This case is cited to show that this is not necessarily true. Five of the six pistons in this indicator had definite fatigue fractures, but it was determined that these were probably secondary, having been caused by excessive fluctuating pressures. This malfunction is thought to have been caused by excessive wear that resulted in the fatigue fracture of one ball end.

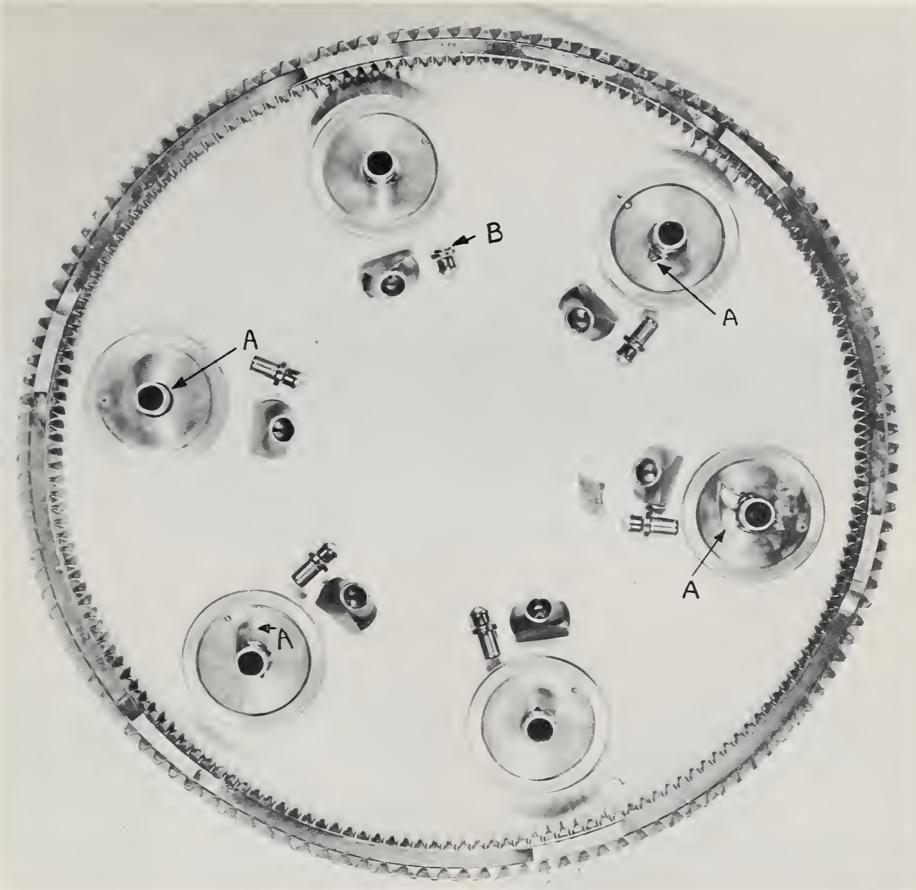

FIGURE 30.1. *Failed torquemeter parts.*

Arrows A indicate fatigue fractures in several of the pistons. The original fracture was thought to be in the ball end B. × ⅓.

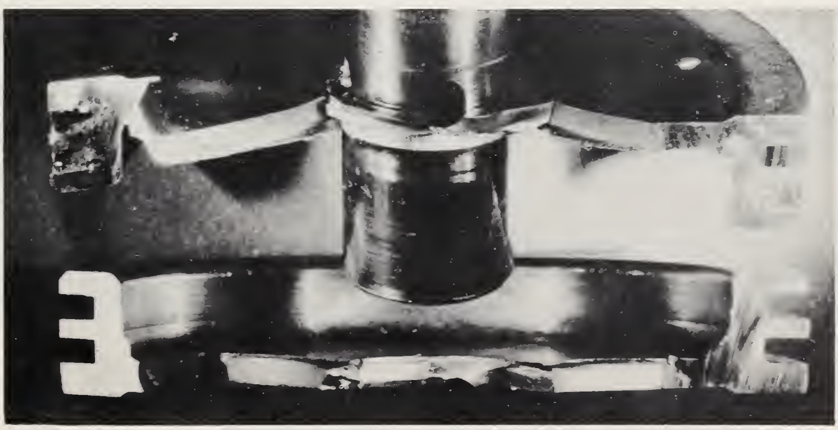

FIGURE 30.2. *Fatigue cracks in one of the pistons.*

The piston was cut in from each edge to reveal the fracture surface. × 1.

Case 31: Boiler feedwater pump plunger (17% chromium stainless steel AISI type 440C). When the plunger was removed for resurfacing a crack was found. The plunger was then broken apart in the shop. The failure was due to the combined action of corrosion and fluctuating stress. It was found that there was extensive precipitation of carbides at the grain boundaries in this part. This is not a normal condition in this steel, and resulted in making it susceptible to intergranular corrosion. This corrosion occurred chiefly in narrow bands around the plunger, probably at lines of contact between the plunger and the packing around it during periods when the pump was not operating. The areas of intergranular corrosion reduced the resistance of the material to fatigue to such an extent that a crack was initiated at numerous points around the periphery, and had progressed to a depth of about one-third of the radius when discovered.

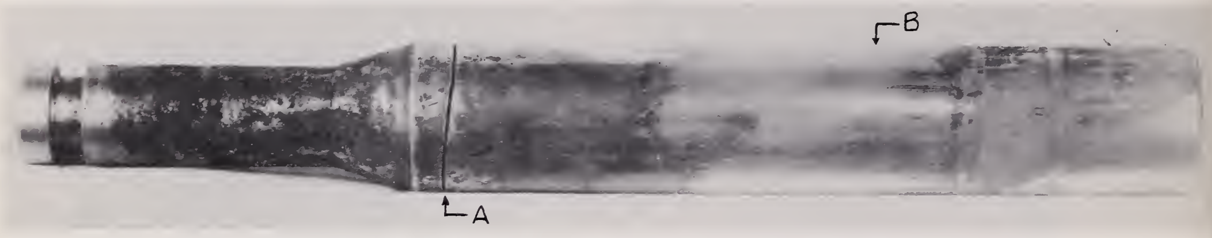

FIGURE 31.1. *Pump plunger broken at A, where a crack had been found.*

A—B marks a line of corrosion having a contour similar to that of the crack. × ½.

FIGURE 31.2. *Surface of the fracture.*

The dark outer portion was a fatigue crack that occurred in service; the light portion was broken in the shop after the plunger had been removed. The area of the crack was more than half that of the cross section of the plunger. × 1.

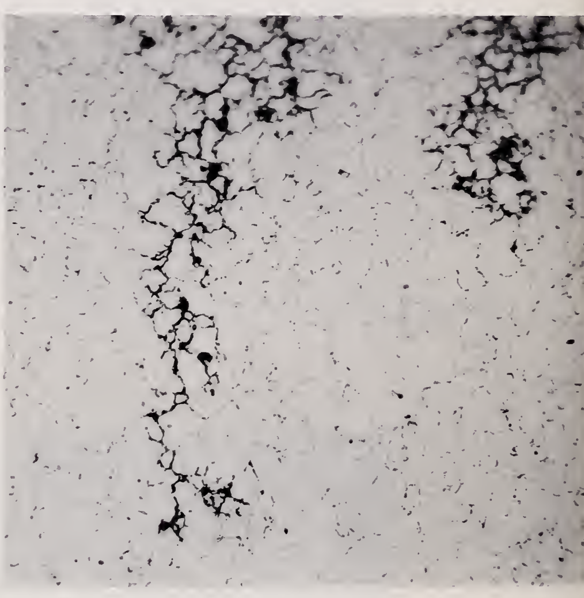

FIGURE 31.3. *Transverse section of the plunger near the fatigue fracture.*

Intergranular corrosion had occurred at numerous places such as this on the periphery of the plunger, and this resulted in the initiation of the fatigue crack. The precipitation of carbides at the grain boundaries which can be seen in this photomicrograph, is not normal in this steel. Etched with nitric acid in alcohol. × 300.

FIGURE 31.4. *Corrosion on the surface of the plunger remote from the fatigue crack.*

The upper line of corrosion pits is the same as that shown by B in figure 31.1. Metallographic examination of this area showed intergranular corrosion similar, but not as deep as that in figure 31.3. × 3.

Case 32: Structural tubing from aircraft (aluminum alloy). Cracks were found in several spar caps and other structural parts made from square aluminum tubing in planes that had been in transoceanic service. In some cases it was possible to stop the growth of the cracks by drilling holes in the tubing at the ends of the cracks. Some of the parts showing the most severe cracking were removed from the planes in order to determine the cause and the effect of the cracking on the strength of the part. No fractures of any of these parts occurred. The stress-corrosion cracking resulted from a combination of very high internal stress and mildly corrosive conditions encountered in flying over the ocean. The internal stress apparently resulted from the method of fabricating the tubing.

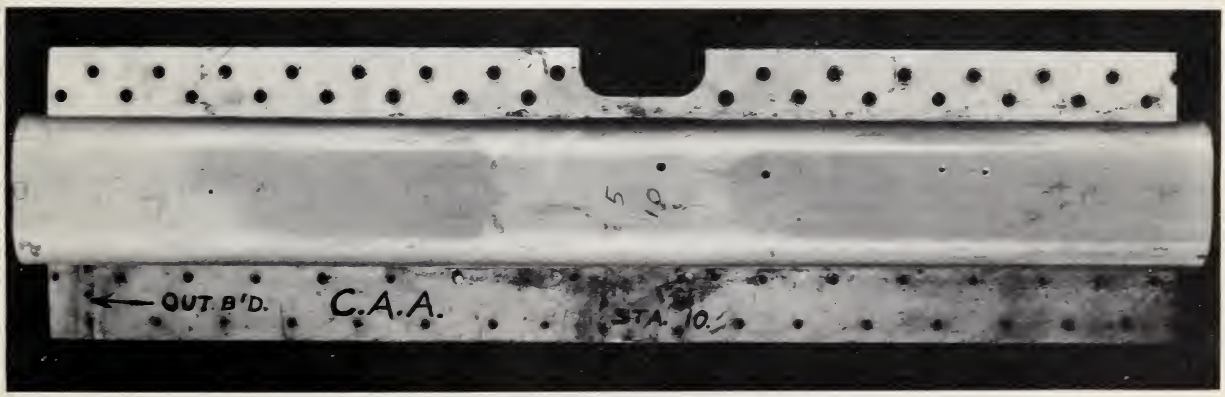

FIGURE 32.1. *One of the pieces of cracked spar cap removed from a plane which had been in transoceanic service.*

Cracks can be seen between pairs of holes in the tubular portion of the cap in the right-hand part of the figure; additional cracks at the left are circled. × ¼.

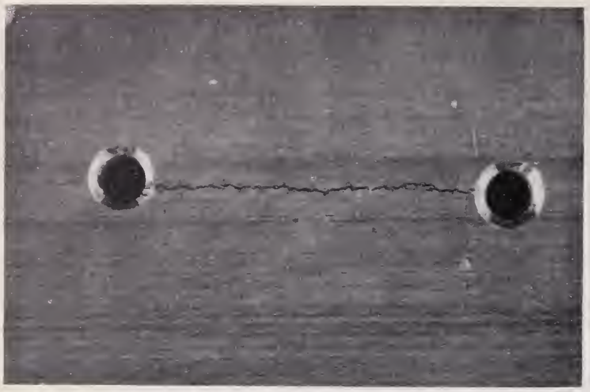

Figure 32.2. *Crack at right of figure 32.1.*

The crack had progressed beyond hole at left, which had been drilled in an effort to stop its progress. The "meandering" nature of the crack is characteristic of stress-corrosion cracking in aluminum alloys. Note the absence of corrosion on the surface. × 1.

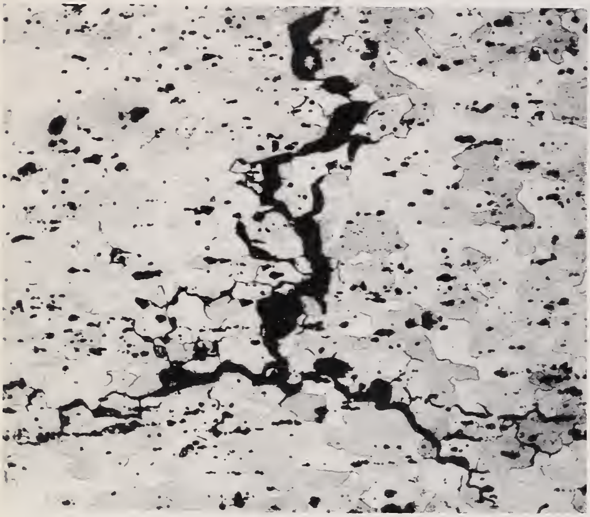

Figure 32.4. *Photomicrograph showing the intercrystalline path of a crack.*

Etched with HF, HCl, and HNO_3 in water. × 100.

Figure 32.6. *Three sections cut from one of the tubes to show the presence of internal stress.*

In the section on the left the outside half of the wall thickness was first milled off, then the wall was sawed on the opposite side. No change in the width of the saw cut was observed. Tube expanded on being cut when no milling had been done, (center) and expanded still more when the inner half of the wall was removed prior to sawing (right). This indicates that there was a tangential tensile stress in the outer half of the tubes and accounts for the failure of the cracks to penetrate completely through the walls (fig. 32.3). × ⅓.

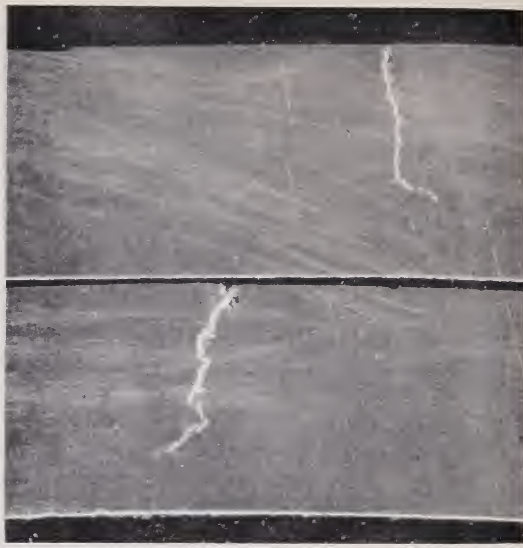

Figure 32.3. *Cross sections of the tube wall, showing the depth of penetration of the cracks.* × 7.

Figure 32.5. *Specimen that curved when cut from the tube wall as a result of the high internal stress in the part.*

The upper side of the specimen is the outer surface of the tube, so the direction of curvature indicates that there was a longitudinal tensile stress in the outer surface of the tube. × ⅓.

Case 33: Aircraft hinge fitting (24S aluminum alloy). The fitting failed because of stress-corrosion cracking. The stress causing this failure was apparently produced by forcing an oversized bearing into a hole in the fitting. It has been shown that such a force fit can cause tensile stress of sufficient magnitude to cause stress corrosion cracking in material that is susceptible to intercrystalline corrosion. It is possible to heat treat 24S aluminum alloy in such a way that it is not susceptible to intergranular corrosion, and if this had been done, it is unlikely that the part would have failed. However, this heat treatment requires a rapid cooling rate, which could not have been obtained in this part unless the holes had been machined prior to heat treatment, and perhaps not then. The stress in the part could have been reduced by decreasing the tightness of the force fit.

FIGURE 33.1. *Fractured fittings as received.*

The bearing had been lost from the fitting on the left, while that on the right had merely cracked (arrow). × ¾.

FIGURE 33.2. *Typical intercrystalline corrosion in one of the fittings. Unetched.* × 100.

Case 34: Window washer's anchor (copper-aluminum-silicon alloy). The anchor failed under the load normally applied when a man leans on his safety belt. Fortunately, the anchor on the other side of the window did not fail, so no injury resulted. The failure was due to stress-corrosion cracking. The principal stress in the bolt was that due to tightening the nuts on the inside of the wall in order to draw the surface plate up against the frame. Several corroding media may have influenced the failure; soluble materials washed out of the air or out of the masonry by the rain may have collected behind the surface plate where the moisture would evaporate slowly. Also any window washing fluid containing ammonia would be very damaging.

FIGURE 34.2. *Longitudinal section near the fracture, showing the intercrystalline cracks typical of stress-corrosion failures.*

Etched with ferric chloride. × 500.

FIGURE 34.1. *Window washer's anchor with one bolt broken at arrow A.*

The anchor was held in place by drawing up the nuts against the inside of the window frame; plate B was against the outside. Consequently, there was a tensile stress in the bolt between the nut and the plate. Corrosive solutions collected behind the plate and caused the stress-corrosion failure. × ⅓.

Case 35: Aircraft wing attach angle (75S aluminum alloy). The part was removed from the airplane when cracks were found on inspection. This case illustrates the care that must be taken to avoid the possibility of stress-corrosion cracking. The service loads would not be expected to cause much stress in a transverse direction in the angle, and extrusions of this alloy are not normally susceptible to stress-corrosion cracking in the longitudinal direction. However, this assembly was bolted to a surface that was probably slightly concave, so that the clamping action of the bolts caused a bending moment in the short leg of the angle. The resultant stress in the transverse direction, combined with atmospheric corrosion, was sufficient to cause cracking.

FIGURE 35.1. *Cracks in the lower angle as revealed by a dye penetrant inspection method.*
The longitudinal cracks were caused by a tensile stress in the transverse direction. × ⅕.

FIGURE 35.2. *Portion of one of the cracks shown in figure 35.1 opened to show the fracture surfaces.*
Note the flakes which were raised when the surfaces were separated. This is indicative of the typically branching nature of a stress-corrosion crack. × 2.

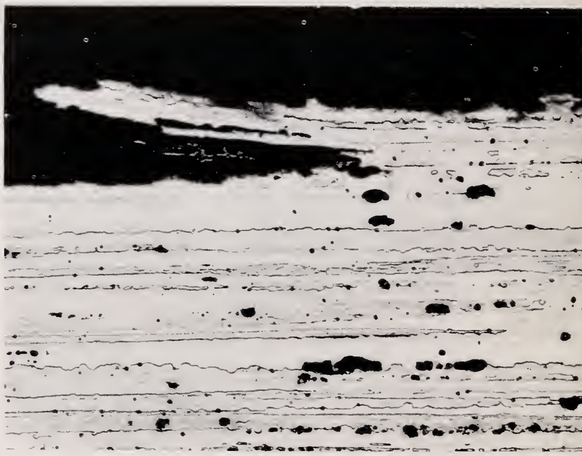

FIGURE 35.3. *Longitudinal section perpendicular to the fracture shown in figure 35.2.*
It can be seen that the fracture tends to follow the boundaries of the elongated grains. Etched with HNO_3, HCl, and HF in water. × 100.

4. Precautions for Avoiding Failures

The above cases were chosen in order to provide examples of most of the common causes of mechanical failure of metals. They were selected after reviewing all of the several hundred cases that have been studied in the Metallurgy Division of the National Bureau of Standards during the 12-year period covered by the Circular. Consideration of the distribution of all of these cases brought out several points of interest in regard to the over-all problem of prevention of metal failures in service. These are necessarily based to some extent on personal opinion and on the assumption that the cases submitted are representative of those encountered generally.

Fatigue is by far the most common cause of mechanical failure of metals in service. This is to be expected, as the causes for failures due to static overload would normally be eliminated before the equipment was put into service. It is generally agreed among persons concerned with the examination of service failures that the primary factor responsible for the fatigue failure of a part is much more often its geometry than the material of which it is made. A large percentage of the failures examined probably could have been avoided by improved design to eliminate points of high stress concentration.

In view of the number of failures attributable to design, there does not seem to be sufficient emphasis on fatigue in educational and training programs dealing with mechanical design. This is particularly true with respect to the damaging effect of notches, holes, threads, change of section, tool marks, and other stress raisers. This statement is based in part on the number of "repeaters" that are submitted. For example, in reference [1] there is shown (figs. 32 and 33, p. 21) an aircraft cylinder that failed because of a fatigue crack originating at the inadequate fillet between the clearance cut for the hold-down nut and the cylinder wall. Similar failures have occurred almost every year (see case 19), the latest having been received in June 1953.

Fretting between closely fitting members is a frequent source of fatigue fractures that does not seem to be properly appreciated. This provides another instance of "repeat offenders." In reference [1] figures 22 to 25, on pages 16 and 17, show propellers that failed because of fretting between the hub and the blade under the clamping ring. An almost identical failure is discussed as case 16, and another was submitted for examination in March 1953. When fretting is severe between steel members it may often be detected by the presence of a fine brown powder. This should always be regarded as a danger sign, and corrective action should be taken if the parts are subjected to fluctuating stress. A powder, usually black, is formed by fretting between aluminum members.

As most fatigue fractures start on the surface, the condition of the surface is of primary importance if fatigue failures are to be avoided. Decarburization of the surface of a steel member, for example, reduces the fatigue strength to that of a similar member having low carbon content throughout. Defects of the surface, such as tool marks, scratches, corrosion pits, etc., are far more damaging to the fatigue strength of a part than to its static strength.

Brittle fractures probably rank second to fatigue failures in frequency of occurrence in service. Large structures such as ships and storage tanks are particularly subject to this type of failure and the results are often catastrophic. It is generally not possible to test such structures under all conditions to which they may be subjected, and failure may be caused by a critical combination of high stress, low temperature, or shock loading. The design of large structures should therefore be conservative, and care should be taken to use materials having good resistance to brittle fracture over the range of temperature expected in service. Every effort should be made to avoid defects in fabrication or damage in service that would serve as stress raisers.

While it is beyond the scope of this circular to consider failures of metals due to corrosion, it is frequently a contributing factor in mechanical failures, as noted in some of the examples above. Even a small corrosion pit will serve to concentrate the stress in the surface of a part, and is therefore potentially dangerous if the part is subjected to fluctuating load. Even corrosive agents that do not appreciably corrode the metal in the unstressed condition may greatly reduce its fatigue strength. Similarly, some metals are subject to cracking under a combination of static stress and mildly corrosive conditions. Some light metals and copper alloys are most often found to give trouble in this way, and care should be taken to avoid the possibility of stress corrosion in using these materials. Preventive measures include the proper selection of alloys, the use of metal with a corrosion-resistant cladding, avoiding designs that apply stresses in the transverse direction in extrusions, and the elimination of residual stress by proper heat treatment.

5. Summary

As stated in the introduction, the cases shown in section 3 demonstrate that the cause of a service fracture may have its origin in the design, fabrication, or use of metal structures or machine elements. Some of the precautions that appear to be the most important in each category are listed below:

1. *Design.* Elimination of sharp reentrant angles at fillets, keyways, and other changes of section. Accurate stress analysis at points of stress concentration and verification of the analysis by experiment or by fatigue testing of sample parts. Selection of material and fabricating methods to produce parts having adequate transverse strength if significant stresses are to be applied in that direction. Proper combination of material and static design stress to eliminate the possibility of stress corrosion cracking in the environments to be encountered. Specification of materials that will provide adequate resistance to brittle fracture, particularly under shock loading and low ambient temperatures.

2. *Fabrication.* Careful workmanship to avoid points of stress concentration due to welding defects, tool marks, improperly formed fillets, grinding cracks, quenching cracks, etc. Control of forging practice to avoid folds, seams, and internal fissures. Protective atmospheres during heat treatment to avoid decarburization. Proper control or elimination of residual stress due to press fits or cold-working in parts subject to corrosive environment. Rigid inspection of highly stressed parts to eliminate surface imperfections.

3. *Use.* Control of operations to restrict the loads to those for which the machine or structure was designed. Protection of parts from corrosion

that may be damaging. Periodic inspection of highly stressed members by personnel acquainted with the nature of fatigue failures. Prompt repair or replacement of parts damaged by unusual conditions, such as fire, collision, overloading, or unusual corrosion. Periodic disassembly of clamped members to inspect for evidence of fretting.

Service failures are far more frequent than is necessary in view of the present status of our knowledge of the properties of metals and of design against stress concentration. It is hoped that this review of past errors will aid in decreasing future ones. Several other excellent references are listed at the end of the Circular.

The authors are indebted to the following agencies for permission to use material in reports submitted to them. Office of Aviation Safety, Civil Aeronautics Administration; Bureau of Safety Investigation, Civil Aeronautics Board; Minimum Wage and Industrial Safety Board, Government of the District of Columbia; Bureau of Ordnance, Department of the Navy; Office of the Surgeon General, Department of the Army; Bureau of Aeronautics, Department of the Navy; Bureau of Motor Carriers, Interstate Commerce Commission, and U. S. Coast Guard.

As the reports cited above cover a period of 12 years, they represent the work of many members and past members of the Metallurgy Division. Up to 1942 the examinations were supervised by the late W. H. Swanger, and from 1942 to 1950 by W. F. Roeser. We acknowledge the work of Hugh L. Logan, Samuel J. Rosenberg, and Harold Hessing, who performed some of the examinations included in section 3. Of the many persons who assisted with these examinations, we thank particularly Irene C. Minor, who did much of the photographic and metallographic work.

6. References

[1] Staff of Battelle Memorial Institute under the direction of H. W. Gillett, Prevention of the failure of metals under repeated stress (John Wiley & Sons, Inc., New York, N. Y., 1941).

[2] Charles Lipson, Why machine parts fail, Machine Design (May to December 1950).

[3] R. E. Peterson, Interpretation of service fractures, Handbook of Experimental Stress Analysis, chap. XIII (John Wiley & Sons, Inc., New York, N. Y., 1950).

[4] Aircraft design through service experience, Civil Aeronautics Administration Manual No. 103 (Sept. 1953).

[5] M. L. Williams and G. A. Ellinger, Investigations of structural failures in welded ships, Welding J. **32**, 498s (Oct. 1953).

[6] The tool steel trouble-shooter, Bethlehem Steel Co. Handbook 322 (1952).

Washington, January 8, 1954.

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Related Publications of the National Bureau of Standards

Hydrogen Embrittlement of Steel, Review of the Literature — Circular 511

Considerable disagreement has existed concerning the effect of hydrogen in steel embrittlement. *Hydrogen Embrittlement of Steel*, by R. W. Buzzard and H. E. Cleaves, a recent review (1951) of the literature in this field, now establishes that certain undesirable effects generally ascribed to hydrogen can be lessened or eliminated by maintaining the hydrogen content at a minimum.

Classifying defects according to the probable source of hydrogen in the metal, the paper discusses defects that may be induced by hydrogen retained after solidification of molten steel, introduced into steel at elevated temperatures, or acquired by steel during chemical or electrochemical treatments. Such defects include the tendency to cause porosity and blowholes in cast metal, flaking, pickling embrittlement, shatter cracks, hairline cracks, weldment failures, and numerous other service failures. The paper organizes references to laboratory experiments which show that hydrogen can cause brittleness and which demonstrate an apparent relationship between brittleness and hydrogen content.

In addition to presenting a study of embrittlement in relation to the presence of hydrogen from different sources, the paper contains a brief review of available information on the chemistry of the hydrogen-iron system and on the effect of hydrogen on the structure and properties of iron. The selected bibliography lists 1,191 items of literature in this field published during the last century and a half.

National Bureau of Standards Circular 511, 29 pages, 20 cents.

Heat Treatment and Properties of Iron and Steel — Circular 495

The basic theoretical and practical principles involved in the heat treatment of ferrous metals are presented in this Circular. The authors, S. J. Rosenberg and T. G. Digges, have prepared the material in simplified form principally to give an understanding of heat treatment to those unacquainted with the subject.

The effects of various treatments on the structural and mechanical properties of iron and steel are thoroughly discussed although many theoretical aspects and technical details have been omitted for the sake of simplicity. Subjects presented include properties of iron, alloys of iron and carbon, decomposition of austenite, heat treatment of steels, hardenability, heat treatment of cast iron, nomenclature of steels, recommended heat treatments, and properties and uses of steels. A list of selected references is also given, and a large number of graphs, tables, and photographs illustrate the text.

National Bureau of Standards Circular 495, 33 pages, 30 cents.

Nickel and Its Alloys — Circular 485

This Circular combines information obtained by the Bureau in its own investigations with that available in published records of work done elsewhere. Particular attention is given to the physical and mechanical properties of nickel and its ferrous and nonferrous applications.

Information on nickel in this publication includes sources; extraction, recovery, and refining processes; metallography; chemical properties; physical properties; mechanical properties at different temperatures; and casting, fabrication, and miscellaneous processes. Many ferrous and nonferrous alloys are listed, and their properties such as density, thermal conductivity, tensile strength, magnetic properties, and corrosion resistance are discussed. The text is adequately illustrated with curves and tables.

National Bureau of Standards Circular 485, 72 pages, 50 cents.

Publications of the National Bureau of Standards — Circular 460

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This Circular and its supplement lists all Bureau publications from 1901 through June 1952, including Applied Mathematics Series, Building Materials and Structures Reports, Circulars, Handbooks, Research Papers, and Miscellaneous Publications. Brief abstracts for the publications issued after January 1, 1942 are also included.

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