FCP REPORT NO. 1

ANALYSIS OF FAILURES IN METAL COMPONENTS

by

Thomas J. Dolan

FRACTURE CONTROL PROGRAM

College of Engineering
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Abstract

Valuable knowledge is available in the literature from documentation on prior failures that may be used to develop a logical analysis of the causes of failures that occur in service. Careful investigation, detailed observations, and sorting of a wide variety of information is important in analyzing how and why a part failed. The material selection, design, processing and fabrication, maintenance and service environment must all be given careful study. All possible modes of failure should be considered to assure against a recurrence from unknown factors. A variety of failures are discussed to emphasize the necessity of foreseeing the influence of the design and processing on response of the metal to the service environment.

A Report of the
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Introduction

In modern equipment operating under severe environmental conditions, a designer is confronted with many complex problems in the selection and evaluation of the optimum material, processing, expected loadings, and design stresses. Components such as turbines, reactors, missiles, submarines, and cryogenic equipment may be subjected to extremely high or low temperature, corrosive liquids, high vacuum, progressive deterioration due to radiation damage, surface wear, etc. From the many "standard" mechanical tests available today, one finds confusion in the interpretation of existing data as far as its application to a particular design is concerned. No wonder we have failures! Materials selection must often be confined to a small group of metals for outstanding resistance in one characteristic, such as inertness to the environment in chemical processing equipment. However, many other factors must be considered such as strength, toughness, fabricability, wear resistance, etc., before selection and design can be finalized for prevention of failure.

Detailed analysis of failures encountered in developing a prototype (or in a service component) is vital before appropriate changes can be made to assure a reliable product. I will discuss some of the causes of failure with techniques of investigation and illustrate by typical examples some of the interactions that must be considered in arriving at an accurate and consistent analysis.

Failure Modes

In general, the service failures to be avoided may arise from many causes. For mechanical equipment, these causes might be broken down roughly into three categories; about one-third of the failures occur in each category, as follows:

I. Design inadequacies (sharp corners or abnormal stress-raisers, inadequate fasteners, wrong material or heat treatment, unforeseen conditions of service, lack of accurate stress analysis, etc.);

II. Processing and fabrication (about half of these may be due to metallurgical factors such as quench cracks, improper heat treatment, forging or casting defects, non-metallic inclusions, etc., and the other half due to misalignments, weld flaws, improper machining or assembly, grinding cracks, cold straightening, etc.).

III. Environmental and service deterioration (including overloads, chemical attack, wear, corrosion, diffusion, improper maintenance, etc.);

(A more detailed breakdown of these three categories is included at the end of this paper.)

A "failure" simply implies that a member fails to fulfill its intended function satisfactorily. It usually occurs as: (a) fracture, (b) excess deformation, or (c) deterioration. The failure mechanism is usually a material failure that is controlled by the entire environment and history, but all parameters of the specific component must be included to determine the conditions which combined to cause failure.

For example, the relation between the load and the peak stress is not linear in a riveted joint in an aircraft wing. Hence, a fatigue failure of the wing (while it is a material failure) is largely dependent upon design and fabrication rather than solely upon material selection. Slight changes in design and fabrication details may prevent failure whereas selection of a new material for the same design may result in duplication of previous failures.

Failures of Category I above (design considerations) result from mistakes or incompetency of the designer. For example, Fig. 1 illustrates flexural fatigue failure due to a sharp fillet and sharp keyway which are known to be poor design, since they develop large stress concentrations. In other instances press fits, bolted joints, etc., may result in fretting fatigue failures (such as Fig. 2) that cannot readily be avoided by selecting an alternate metal or design detail. The solution here is to seek alternate processing (such as cold rolling or nitriding) to induce favorable residual compressive stresses to inhibit crack growth.

The variables of processing and fabrication are major factors in determining the flaw sizes and metallurgical changes that will be built into the structure; these contribute to the potential danger of failure from fatigue or from brittle fracture as these flaws approach critical size.(2, 3)* Figures 3 and 4 illustrate failures due to flaws initiated during processing that developed to critical size in service. The complexity of the contour of the component and the influence of processing operations must be considered as portions of the environmental conditions; their influence in altering the mechanical properties must be evaluated (sometimes by a simulated service test) to assure reliability and safety of operation.

For those failures due to flaws developed by processing or fabrication (Category II), there are few, if any, standard tests that can be used to cover all of the possible inherent defects that may be induced by such operations as: casting, forging, welding, machining, grinding, heat treating, plating, chemical diffusion, or careless assembly operations. It is sometimes difficult to avoid mistakes such as illustrated in Fig. 5.

As is outlined in Table I each processing operation may induce residual stresses, modify the mechanical properties by severe cold work in local zones, or develop a multitude of other localized effects such as underbead cracking,

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*Numbers in brackets refer to references in the bibliography.

local heating, porosity, hydrogen embrittlement, non-metallic inclusions, which may be categorized as "defects or flaws". In many applications it is the presence of these small defects (that may later develop to critical flaw sizes) which drastically affect the resistance of the member and determine the nearness to failure such as shown in Fig. 6. Conversely, some "flaws" of the type in Fig. 7, have not materially affected the satisfactory performance of the component because the service life was limited by erosion of the bore of the gun rather than by crack propagation. It is important that one analyze the influence of every step in the manufacturing process as it relates to the final mechanical properties required in the finished component.

In developing a design philosophy or a procedure for nondestructive inspection or testing, it is well to assume that all engineering materials contain "defects" (that is, they are not homogeneous and isotropic). A defect in this sense may be regarded as any lack of perfection: poor or striated metallographic structure, stringers or laminated inclusions, micro-voids around welds, residual stresses, etc.; on the macro scale, machining defects, laps, seams, casting voids, and underbead cracking in welds, are obvious types of flaws encountered. Many such "flaws" may be too small to be detected by currently available methods of nondestructive examination.

For given stresses a critical flaw size exists for the metal; larger flaws will stimulate sudden catastrophic brittle appearing fracture. In adverse environments* flaws may continue to grow if stresses are maintained above a threshold value. Also, micro size defects may grow progressively under repeated stressing and develop "fatigue" failure. In some applications a member may fail by corrosion-

*While chemical and corrosive attack provide aggressive or harmful conditions of operation, many of the higher strength metals are quite susceptible to slow flaw growth in neutral water.

fatigue as in Fig. 8, or by stress corrosion cracking because of environmental conditions and the unknown residual, or shakedown stresses developed by fabrication procedures, or by service loads.

In view of the statistical nature of the sizes, types, and locations of defects, the probability of finding a potentially dangerous triggering defect is difficult to estimate on a quantitative basis. Many parts may contain undesirable flaws which are located in zones of low service stress and hence, do not cause problems. On the other hand, the detection of flaws that lead to an average life that is satisfactory gives no guarantee against premature or catastrophic failure of some small percentage of the components produced.

Table II forms the basis for relating standard failure modes in structural applications to service conditions, and the desired mechanical characteristics for resistance to each mode of failure. The table needs expansion to include all of the altered strength characteristics due to faulty processing or to unusual service conditions. Many designers do not understand the significant changes in material from processing or environment that may cause failure. Material or component evaluation should include samples that have been processed by the method intended in final production to include normal processing "defects" or "flaws" in the determination of the mechanical resistance. Figures 9 and 10 show a catastrophic failure that developed from "minor" surface defects in processing that became critical when exposed to the unique service environment.

Some processing operations result in localized alteration of the mechanical strength characteristics that may be vital in determining future performance of the part. One type of degradation is illustrated by the failure of the tie-bar of the crane shown in Fig. 11. Brittle fracture would not have been expected on the basis of the original mechanical properties of this low-carbon steel. Castings frequently have variable properties and unknown residual stresses depending upon thickness of sections and cooling rates. The failure of blades on the cast fan in Fig. 12 is probably related to this factor in design, plus the fact that as-cast surfaces and undesirable vibrations of the blades all contributed to fatigue failure.

Deterioration

For failures of Category III (deterioration), there are no standard tests that can be used at the present time to evaluate materials. In some instances (as illustrated in Fig. 13) unforeseen vibrations or overload conditions may develop to cause failure; in others such as Fig. 14, a service induced damage may develop fatigue failure. Many service conditions involve extremely rapid rates of heating or include radiation damage, ablation, corrosion, or the various types of wear. Specialized testing is necessary to evaluate material for a specific application involving one of these deleterious effects as the controlling variable. Figure 15 shows a special type of deterioration from the service environment that cannot be appraised from "standard" laboratory tests. For these types of severe service, every effort should be made before selecting the material to simulate the expected temperature, time, dosage, etc., as nearly as possible in the laboratory testing program.

Deterioration during service in an aggressive environment needs to be given special consideration. There are many types of surface disintegration, chemical activity, or metal transfer that affect stability of the component; these are influenced by the time, temperature, and dosage of the critical factors in the service environment. Because of the complexity of interaction of the factors outlined in Table I, careful detective work is often necessary to determine the cause of a specific failure with a high degree of certainty. Not only must the failed part itself be examined in great detail, but background information on its chemistry, processing and fabrication, service history, and environment, etc., need to be correlated as is indicated by the failures in Fig. 16, and in Figs. 17 and 18. A rational and complete analysis of the failure mode must be based on positive supporting evidence (rather than the absence of contrary evidence).

Analysis of Failure

In studying resonance of sound in pipes and cavities, Lord Rayleigh in his book, "Theory of Sound" remarks: "When the theoretical result is known, it is almost impossible to arrive at an independent opinion by experiment." One must heed this warning when developing the failure analysis of a component: do not approach the analysis of a given failure by preconceiving an answer before making the detailed investigation.

Carefully documented case histories of failures of the past often illustrate the synthesis and detective work necessary to prevent similar recurrences in the future. A wealth of information on a variety of failures is available in the References listed in the bibliography. The documentation of the British Comet airplane failures[10] represents an outstanding example of the tremendous amount of study and experimentation sometimes necessary to track down the initial cause of failure when the interaction of several modes of failure occur during the course of the accident. The Comet failures also illustrate the occasional complexity developed by interactions between materials selection, design details, new types of service loadings, and a final failure consisting of a rapidly running crack initiated from a very small fatigue crack which developed to critical flaw size. A complex interaction of several modes developing to final fracture is illustrated by the case shown in Fig. 19.

In investigation of a failure great care must be used in detailed visual, optical, or metallurgical examination, chemical and hardness tests, etc., to prevent careless handling that may destroy important evidence. Subtle cases of embrittlement, diffusion, localized corrosion, etc., often require careful documentation of the service history (time, temperature, loadings, and environment) supplemented by chemical analysis, electron micrographs, etc. Further study of the sequence of events during the failure, plus knowledge of the location markings and condition of all adjacent parts after the incident, is necessary to confirm the analysis beyond reasonable doubt. Of course, there is always the possibility of an unforeseen loading, unreported collision, or unanticipated vibration that may develop to cause premature failure as in Fig. 20. These factors may usually be diagnosed by careful examination and gathering of facts.

As supplementary information, I have appended a list of classifications as to cause of failure and general guidelines to be following in determining the major cause or causes. Only an engineer with broad background and experience can be trusted to synthesize the many contributing factors to arrive at a correct analysis in some of the more complex modes of failure.

The Investigation

Use care in the nature and sequence of the procedures of examination, so that evidence required in certain types of analysis (such as surface contaminants) will not be lost or contaminated in the early stages by improper handling. A combination of several factors may be responsible for the failure to perform satisfactorily.

When failures occur it is vital that complete analyses be made for proper corrective action. Five operations areas are available for the determination of failure causes and the interplay of factors that were involved in the failure. In chronological order these areas are as follows:

1. Initial Observations. Detailed study by visual inspection of the actual component that failed, preferably at the failure site as soon after the fact of failure as possible. Profuse color photographs are essential to record every detail for later review. An experienced investigator can usually indicate the predominate failure modes of the various components and permit concentration on the acquisition of all available background data. Detailed interpretation must be made of deformations, markings, fracture texture appearance, deterioration, contaminants, final location of components and debris, etc.

2. Background Data. A large amount of pre-failure data concerned with specifications and drawings, component design, fabrication, repairs, maintenance, and service use must be gathered. (Sometimes only limited data are available.) Concentration on obtaining facts pertinent to all possible failure modes is essential. Particular attention to environmental details, including normal service loads (as well as accidental overloads and cyclic loading) and resulting stress, temperature variations, and gradients is desirable.

3. Supplementary Laboratory Studies. Tests are desirable to verify that the material in the component actually possesses the chemistry, dimensions, processing, and physical properties specified in the design. Special supplementary studies may be needed; for example, chemistry of corrosion products, simulated service or environmental tests, determination of microstructure and development of cracks, dynamic strain measurements, elevated or low temperature tests, surface replicas, etc., to define the factors which contributed to the failure. A new or more refined stress analysis may be required. Electron probe X-ray analysis can be useful in examining inclusions, micro-segregation, or the composition of oxide, or surface contaminants.

Each failed part should be regarded as a storehouse of information if the investigator will take the time and care necessary to "read" the evidence it contains. Fractures include many surface artifacts and distinguishing features that can be read by an experienced observer; the textures, and surface irregularities are characteristics of the material and its processing, as well as of the loadings and environment which caused the fracture.

Frequently, examination of a fracture face with a low power binocular microscope (say 20X) can give a fairly complete answer as to the type and cause of failure. However, the observer must be one familiar with a wide variety of fracture textures, and one who can approach the examination without a preconceived idea of what caused the fracture. Further confirmation can often be obtained by studies of cracks, structures, etc., at higher magnification, using small mounted samples from the regions of failure.

Electron microscope studies (17) are sometimes useful in complex cases, but suffer from difficulties with surface contamination and micro-corrosion if the fracture is not new and clean. At high magnification one also has to select small zones for study, and interpretation becomes difficult. The artifacts one studies may be likened to mushrooms in the forest; the observer may fail to see the trees by concentrating on the small objects made visible by this powerful tool. The scanning electron microscope has the advantage of allowing a "zoom" from low to high magnification of a specific area to aid in interpretation of the textures being examined. However, it is somewhat limited in the size of specimen that can be examined. Because of the wide variety of metals and modes of fracture, interpretation by an experienced observer is necessary whether at magnifications of 20X or 6000X for either optical or electron microscope studies of fracture surfaces.

4. Synthesis of Failure. It is necessary to list not only all positive facts and evidence, but also to list all the negative responses to the questions that may be asked about who, what, where, when, and why before deciding "how" it failed. Sometimes it is important to know that specific things "did not" happen or certain evidence "did not" appear, and include these "facts" in deciding what could have happened. From a tabulation of these data, the actual failure should be synthesized to include all items of the evidence available. Frequently, it may be necessary to develop additional data from (2) or (3) above for completeness or for further verification.

The final solution must give full consideration to the interplay of design, fabrication, materials properties, environment, and service loads. The classification as to the cause will usually fall into one of the categories outlined in the following list, and corrective action or applied research guidance can be recommended. Appropriate solutions may involve re-design, change of alloy and/or processing, quality control, protection against environment, changes in maintenance schedules, or restrictions on service loads or service life.

"Classification as to Cause of Failure"

I. Failures due to faulty processing

1. Flaws due to faulty composition (inclusions, embrittling impurities, wrong material)
2. Defects originating in ingot making and casting (segregation, unsoundness, porosity, pipes, non-metallic inclusions)
3. Defects due to working (laps, seams, shatter cracks, "hot-short" splits, delamination, and excess local plastic deformation)
4. Irregularities and mistakes due to machining, grinding, or stamping (gouges, burns, tearing, fins, cracks, embrittlement)
5. Defects due to welding (porosity, undercuts, cracks, residual stress, lack of penetration, underbead cracking, heat affected zone)
6. Abnormalities due to heat treating (overheating, burning, quench cracking grain growth, excessive retained austenite, decarburization, precipitation)
7. Flaws due to case hardening (intergranular carbides, soft core, wrong heat cycles)
8. Defects due to surface treatments (cleaning, plating, coating, chemical diffusion, hydrogen embrittlement)
9. Careless assembly (mismatch of mating parts, entrained dirt or abrasive, residual stress, gouges or injury to parts, etc.)
10. Parting line failures in forging due to poor transverse properties

II. Failures due to faulty design considerations or misapplication of material

11. Ductile failure
    a. Excess deformation (elastic or plastic)
    b. Tearing or shear fracture
12. Brittle fracture (from flaw or stress-raiser of critical size)

13. Fatigue failure
    - a. Load cycling
    - b. Strain cycling
    - c. Thermal cycling
    - d. Corrosion fatigue
    - e. Rolling contact fatigue
    - f. Fretting fatigue
14. High-temperature failure (creep, oxidation, local melting, warping)
15. Static delayed fractures; hydrogen embrittlement, caustic embrittlement, environmentally stimulated slow flaw growth
16. Excessively severe stress-raisers inherent in the design
17. Inadequate stress analysis, or impossibility of a rational stress calculation in a complex part
18. Mistake in designing on basis of static tensile properties instead of the significant material properties that measure the resistance of the material to each possible failure mode

III. <u>Failure due to unusual or unexpected deterioration during service conditions</u> (partial history of operation is necessary for analysis)

19. Overload or unforeseen loading conditions
20. Wear (erosion, galling, seizing, gouging, cavitation)
21. Corrosion (including chemical attack, stress corrosion, corrosion fatigue) Dezincification, graphitization of cast iron, contamination by atmosphere. Preserve corrosion product until carefully analyzed. Determine whether intergranular, galvanic, type of pitting, etc.
22. Inadequate or misdirected maintenance or improper repair (welding, grinding, punching holes, cold straightening, etc.)
23. Disintegration due to chemical attack or attack by liquid metals or platings at elevated temperatures
24. Radiation damage (sometimes must decontaminate for examination: this may destroy vital evidence of cause of failure) susceptible to time, temperature, environment, and dosage
25. Accidental conditions: abnormal operating temperatures, severe vibration, sonic vibrations, impact or unforeseen collisions, ablation, thermal shock, etc.

Acknowledgment

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TABLE I.

FAILURE DUE TO PROCESSING METHODS OR TO DETERIORATION

	Processing and Fabrication		
1.	Mechanical	Cold forming, stretching, bending machining, polishing, grinding, etc.	Each of the processing operations will alter gross or local mechanical properties and may result in micro or macro cracks, or depletion of ductility in localized zones. Surface effects and metallurgical changes from processing may have significant influence on fatigue strength, brittle fracture resistance, and corrosion resistance. Anisotropic properties, zones of dissimilar material, and orientation of principal stresses with respect to unfavorable structural characteristics should be given detailed study in evaluating the resistance to failure in the final product. This will require detailed research to appraise the changes in resistance caused by each specific processing or fabrication operation. (applies to items 1–3)
2.	Thermal	Heat treating Welding, brazing, etc.	
3.	Chemical	Processing base material Cleaning Plating Chemical coatings	
	Deterioration:	Each specific environment or operation needs unique analysis of the significant structural action that limits the usefulness in the service interded.	
1.	Mechanical	Specialized abrasion, galling, cavitation, wear, cyclic or slow flaw growth, etc.	
2.	Chemical	Stability and activity dependent upon temperature and severity of environment. Oxidation, intergranular attack, diffusion and alloying from foreign elements uniquely determined by the chemical agents, time, and temperatures of operation.	
3.	Thermal	Metallurgical changes, grain growth, ablation, melting, etc. dependent upon melting point and stability in the time and temperature for prescribed service.	
4.	Corrosion	Time, temperature, simultaneous stressing, frequency of wetting and composition of the corrosive agent as well as the chemical composition and processing of the structural member and its mating parts.	
5.	Radiation Damage	Influenced by time, temperature, and intensity of the dosage.	

TABLE II.

RELATION OF FAILURE TO OPERATING CONDITIONS AND MECHANICAL PROPERTIES OF THE MATERIAL

MODE OF FAILURE	LOADING MODE			STRESS TYPE			OPERATING TEMPERATURE			MATERIAL TYPE		SIGNIFICANT MECHANICAL RESISTANCE OF THE MATERIAL MEASURED BY:
	Static	Repeated	Impact	Tension	Compression	Shear	Low	Room Temp.	High	Brittle	Ductile	
Brittle Fracture	X	X	X	X			X	X		X	X	Charpy "V"-notch transition temperature. Notch toughness. K_{IC} toughness measurements.
Ductile Fracture	X			X		X		X	X		X	Tensile strength. Shearing yield strength.
Fatigue (millions of cycles)		X		X		X	X	X	X	X	X	Fatigue strength for expected life, with typical stress raisers present.
Low Cycle Fatigue		X		X		X	X	X	X	X	X	Static ductility available and the peak cyclic plastic strain expected at stress raisers during prescribed life.
Corrosion Fatigue		X		X		X		X	X	X	X	*Corrosion fatigue strength for the metal and contaminant and for similar time.
Buckling	X		X		X		X	X	X	X	X	Modulus of elasticity and compressive yield strength.
Gross Yielding	X			X	X	X	X	X	X		X	Yield strength.
Creep	X			X	X	X			X	X	X	*Creep rate or sustained stress-rupture strength for the temperature and expected life.
Caustic or Hydrogen Embrittlement	X			X				X	X	X	X	*Stability under simultaneous stress and H_2 or other chemical environment.
Stress Corrosion Cracking	X			X		X		X	X	X	X	*Residual or imposed stress and corrosion resistance to the environment. K_{Iscc} measurements.

* Items strongly dependent upon elapsed time.

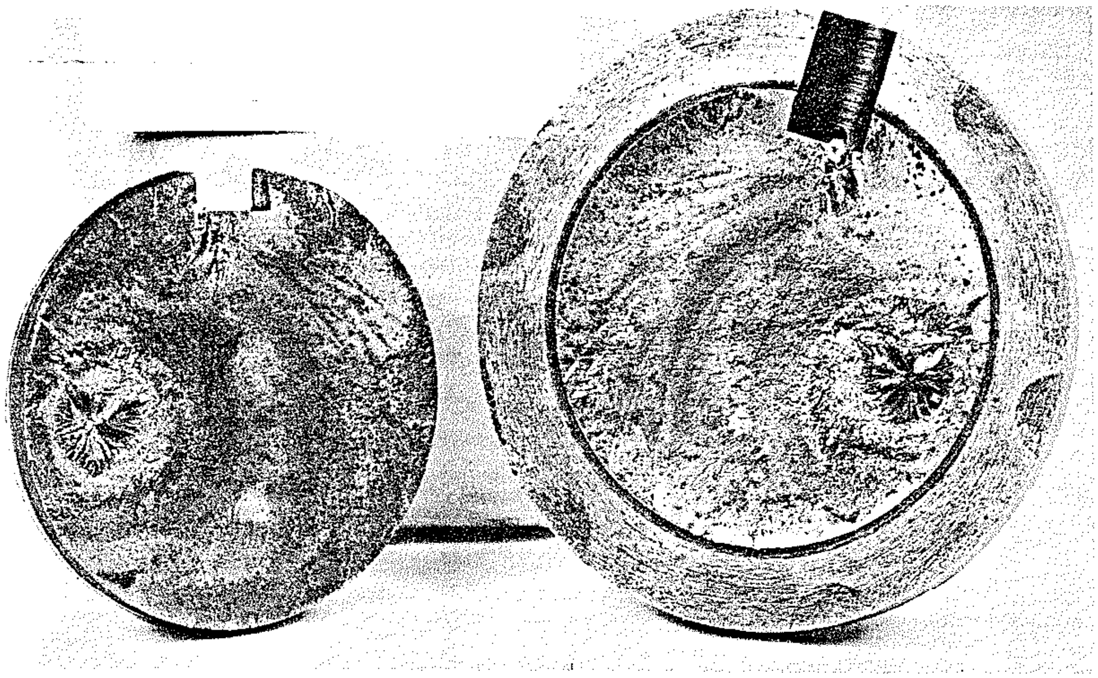


Fig. 1 Fracture Surfaces of Shaft in Rotating Bending Resulting from Poor Design Detail. (AISI 1046 Heat Treated to Rockwell C25)

Note that failure initiated from the interaction of the two stress concentration factors at the keyway and fillet; these effectively multiply each other. Extensive fatigue crack propagation before the final brittle fracture of a small "off center" zone indicates that the part was subjected to relatively small bending stresses during its service life.

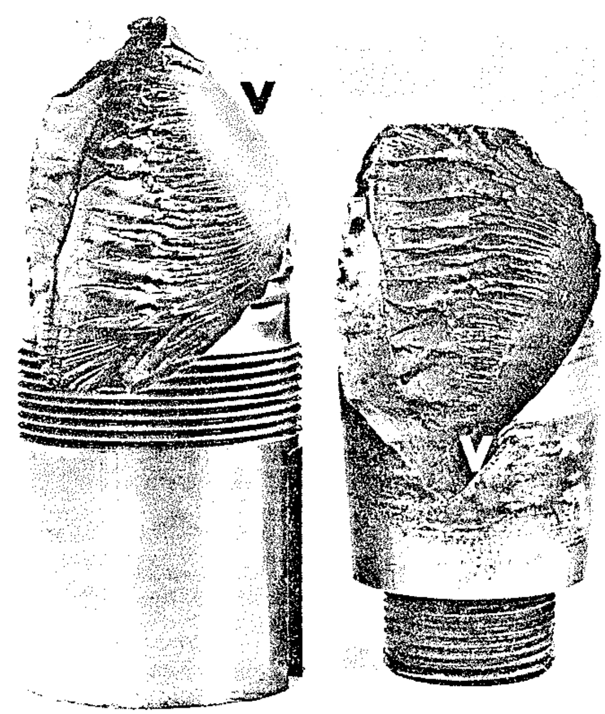


Fig. 2 Torsional Fatigue Failure at Front End of Crank Shaft.

This failure started in an area of fretting corrosion which occurred under a hub which was assembled at "V." In spite of the many other stress raisers (fillet, keyway, threads, grooves) the failure initiated from the discolored zone on the hub due to the microscopic rubbing action from cyclic elastic deformations. (Hardness R_c 25)

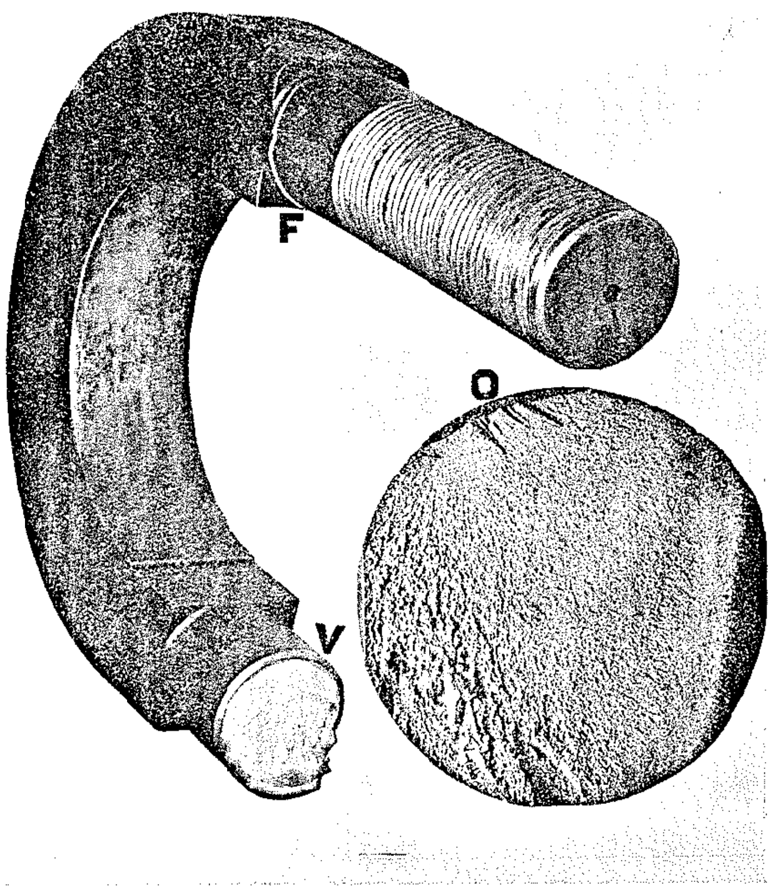


Fig. 3 Pulling Yoke of High Strength SAE 4340 Steel Fractured at a Stress of Only 30,000 psi.

Fracture initiated at F; fracture at V resulted from eccentric loading after initial failure. The dark area on the cross section near O contained oxide scale indicating a prior crack that occurred during fabrication or heat treatment and caused the brittle fracture during static load.

(Courtesy of J.A. Bennett)

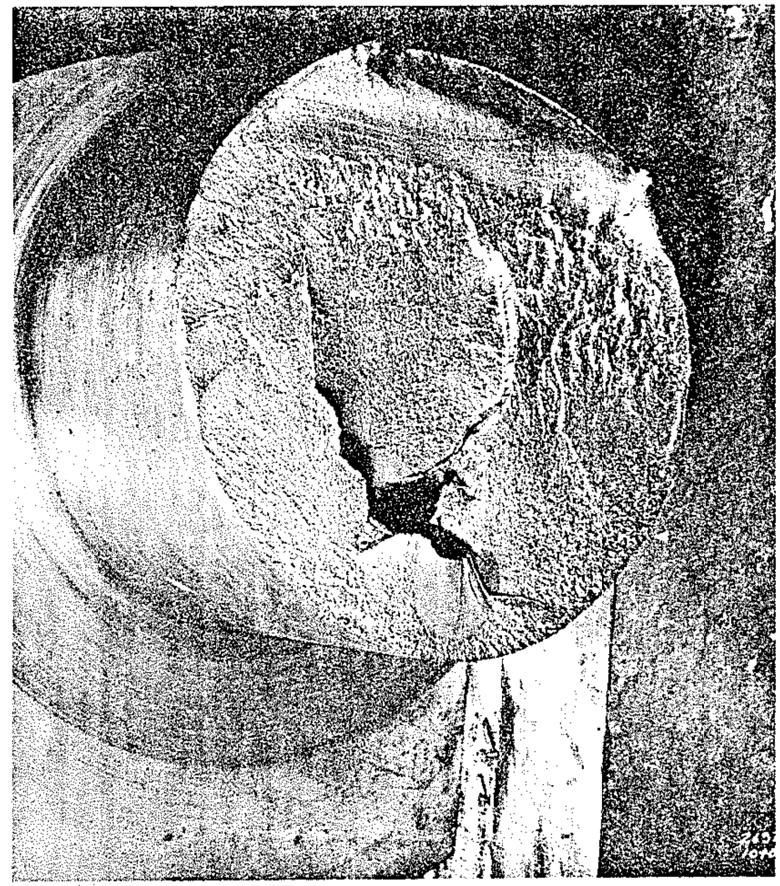


Fig. 4 Fracture of Large Diameter Crank Pin on 800 Ton Mechanical Press.

The smooth circular areas surrounding the star-shaped crack are characteristic of fatigue as is also the smooth fracture near the upper portion of the crank pin. The "star" fracture developed from a longitudinal pipe cavity or forging burst that initiated the transverse circular fatigue zones which led to final brittle fracture.

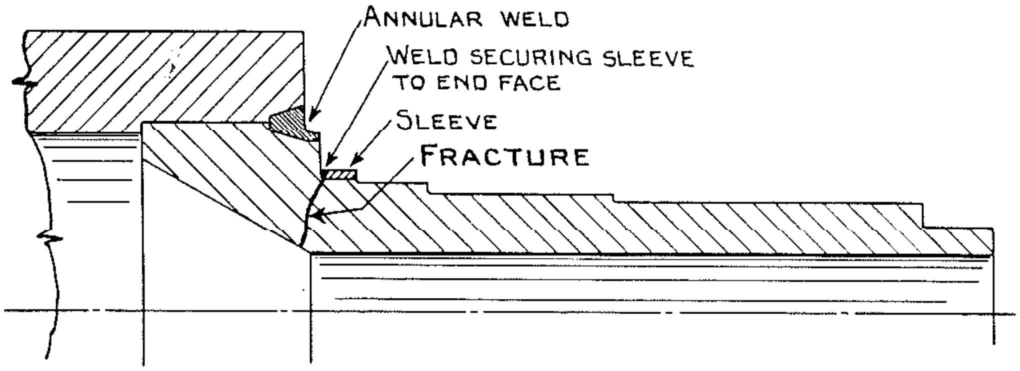


Fig. 5 Failure of a Steam Heated Roll Caused by Welding on Repair Sleeve.

Improper weld procedures in fastening on a small sleeve that was used to patch over a machining defect developed hairline cracks adjacent to the weld which propagated in fatigue to cause rupture. The large annular weld also present was done at an earlier stage with proper preheating and slow cooling. The repair weld placed in a zone of high stress concentration was improperly applied in fabrication and was not subsequently stress relieved.

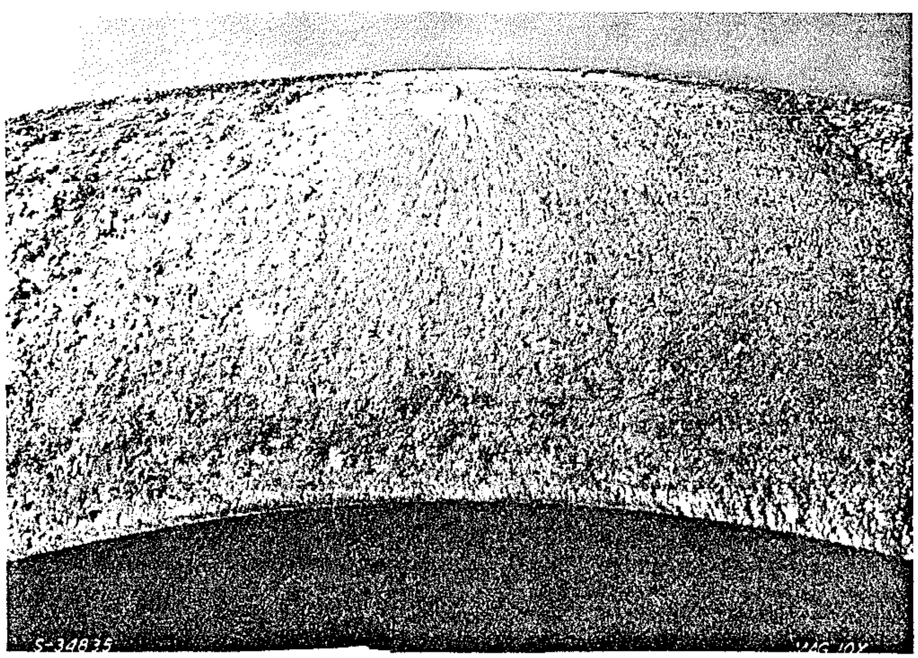


Fig. 6 Fracture Surface of Special Shaft of AISI 4350 at Rockwell C-38. Outer Surface Cold Rolled in Final Processing.

Fracture combines fatigue origin at subsurface inclusion below compressively stressed cold rolled layer; final propagation as brittle fracture after fatigue crack reached critical size.

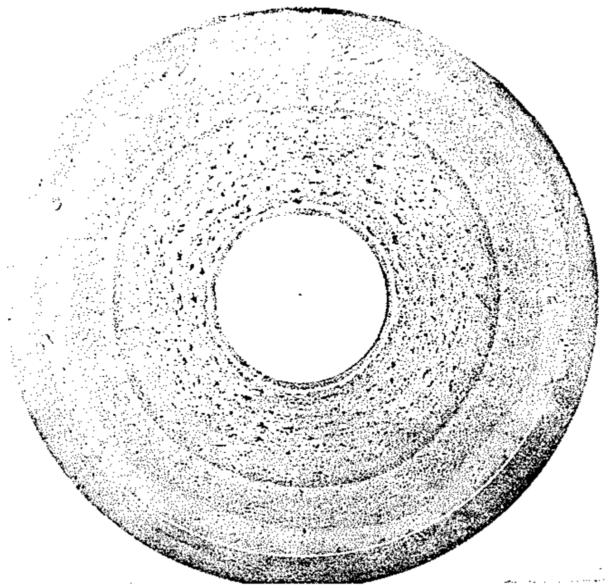


Fig. 7 Macro-etched Section of Centrifugal Casting for Gun Tube. (Obvious segregation present)

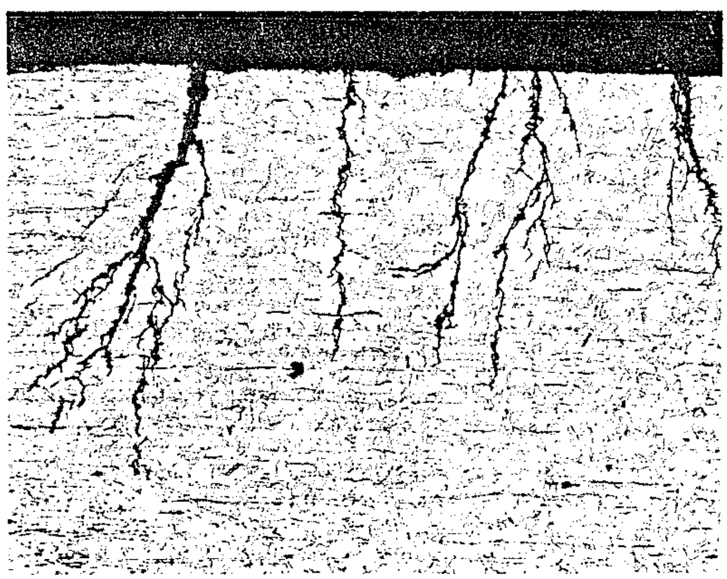


Fig. 8 Expansion Joint in a Steam Distribution Line. Failure was traced to corrosion fatigue resulting from stresses caused by thermal cycling and a hostile environment due to dripping condensate. Photomicrograph at 100 X of type 304 stainless sheet steel.

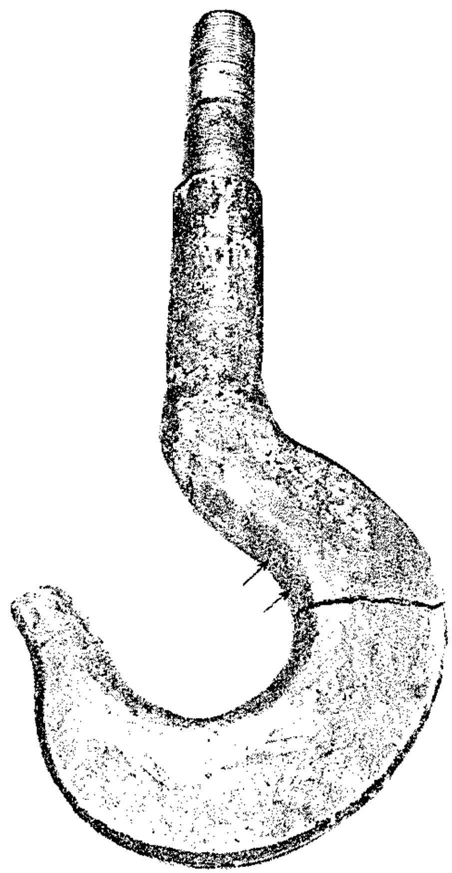


Fig. 9 Brittle Failure of a Crane Hook Initiated at a Pre-Existing Defect.
(See Fig. 10)

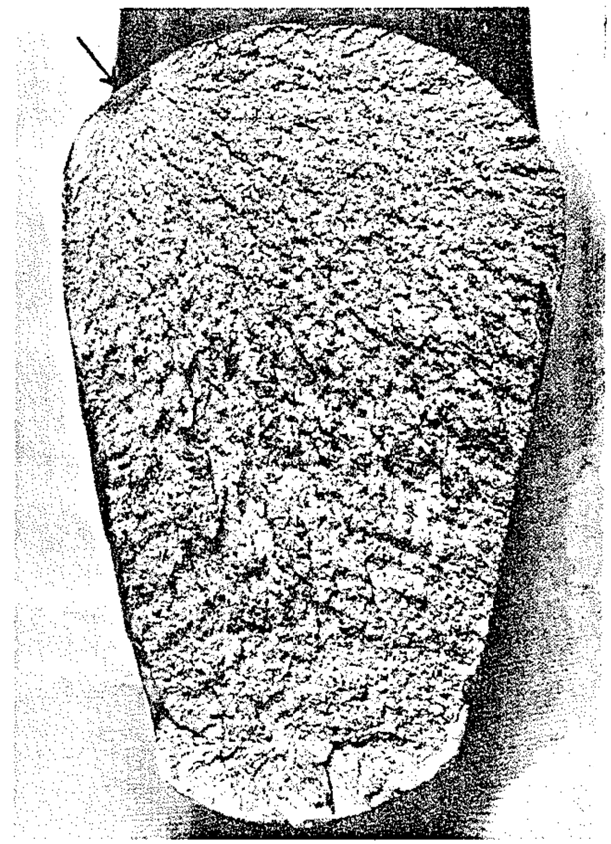


Fig. 10 Fracture Surface of Crane Hook Showing Defect at Origin.
Small folds or laps in surface material during rolling and forging of the hook developed critical size after the hook had been subjected to slight amounts of cold work in service and aging by exposure to radiant energy from hot metal ladles.

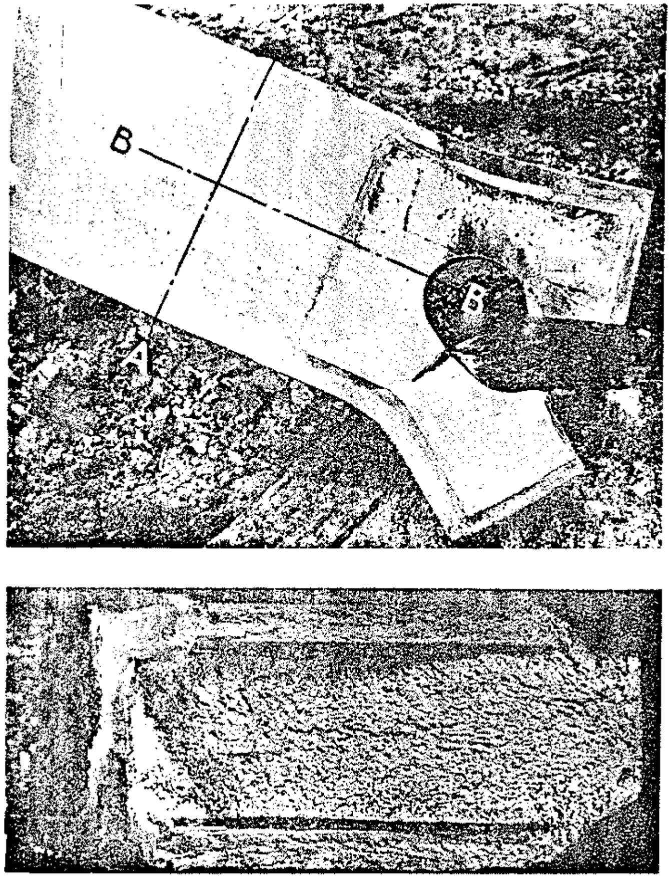


Fig. 11 Failure of Jib Tie-Bar of Tower Crane

Brittle fracture originated at the end of the bar which had been cold sheared in fabrication. The material was of low carbon "rimmed steel" which results in substantial internal segregation of inclusions of phosphorous, sulphur, manganese, etc. Cold working of these rimmed steels followed by aging (which can be substantially accelerated by elevated temperatures from welding in the area) results in severe embrittlement as evident in this failure. The local cold working from shearing and subsequent heating from adjacent welding led to strain age embrittlement of the deformed steel. Lower picture shows fracture face.

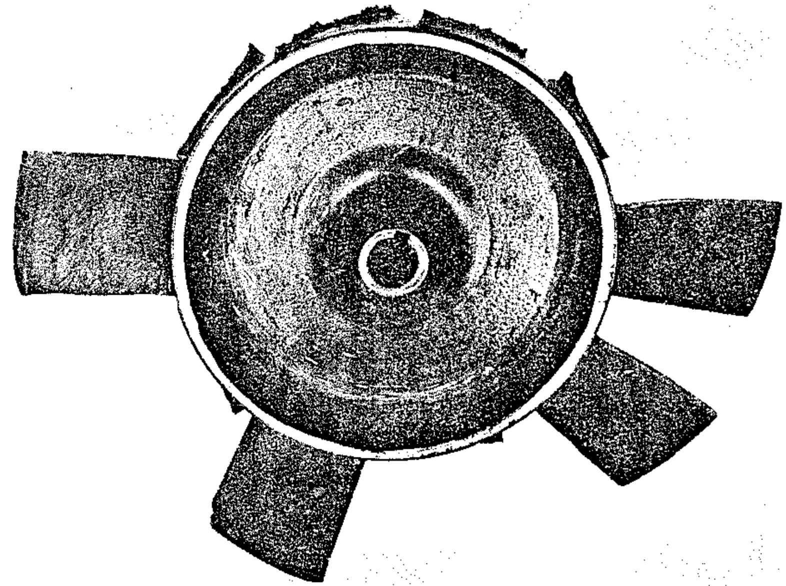


Fig. 12 Fatigue Failures of Blades on Cast Magnesium Fan.

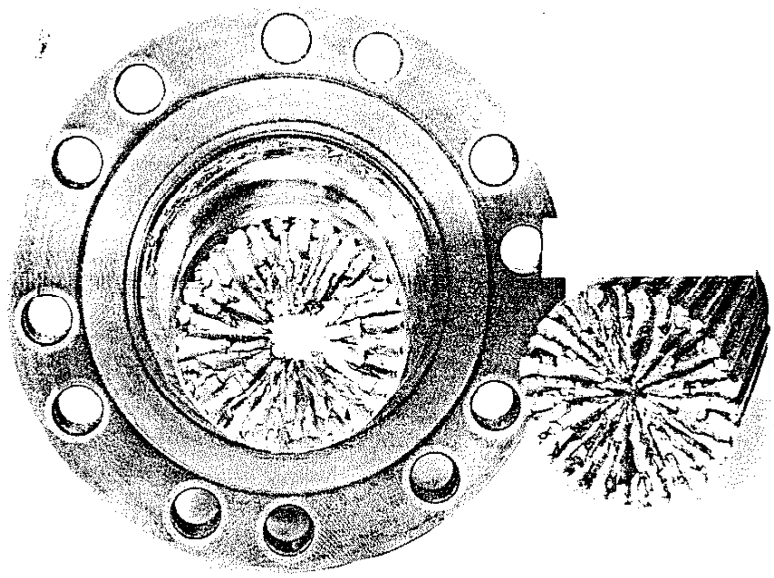


Fig. 13 Ductile Shear Failure from Severe Cyclic Torsional Overload on Splined Shaft.

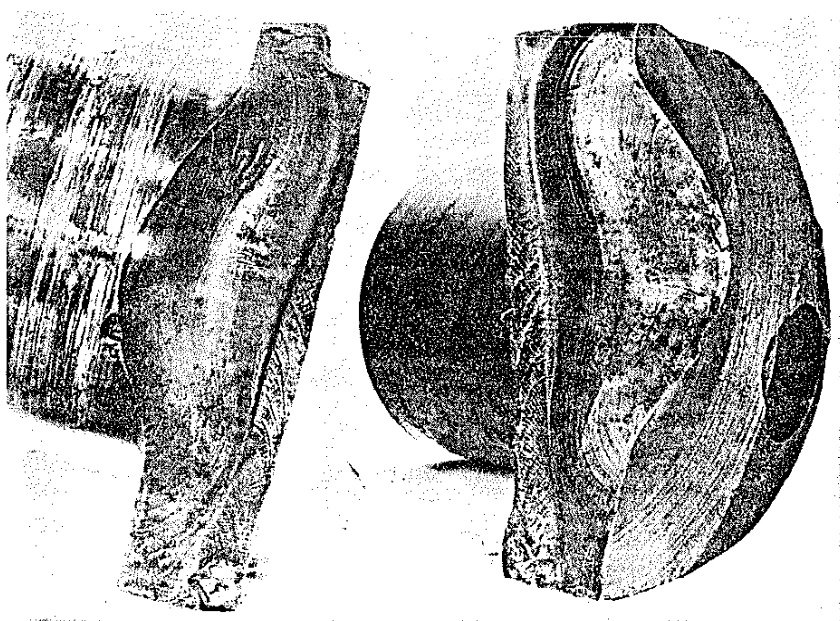


Fig. 14 Bending Fatigue Failure of Diesel Engine Crankshaft Resulting from Service Induced Damage.

Note that failure initiated at deep score or seizing marks in the crank pin and propagated across crank cheek.

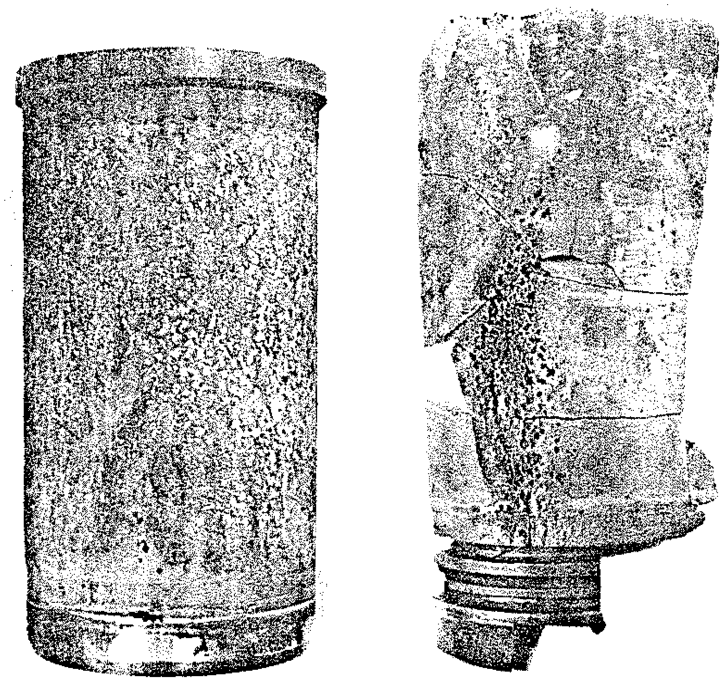


Fig. 15 Typical Examples of Cavitation Damage to Diesel Engine Cylinder Liners.

Caused by high frequency vibration of the cylinder wall in contact with the liquid coolant.

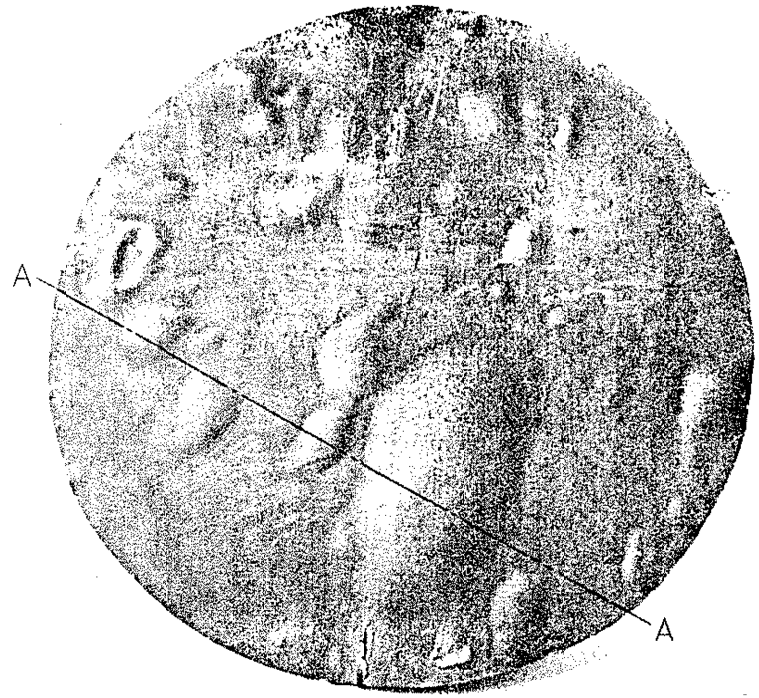


Fig. 16 Blistering Due to Hydrogen Occlusion in Tank for Transport of Concentrated Sulphuric Acid.

Though low carbon steel is not attacked by concentrated sulphuric acid, condensation of water vapor on acid wetted surfaces led to corrosion of the hydrogen evolution type that penetrated the plate by diffusion. Defects in the form of laminations, slag film, and stringers formed nuclei at which the hydrogen combined to molecular form building up pressure and forming blisters.

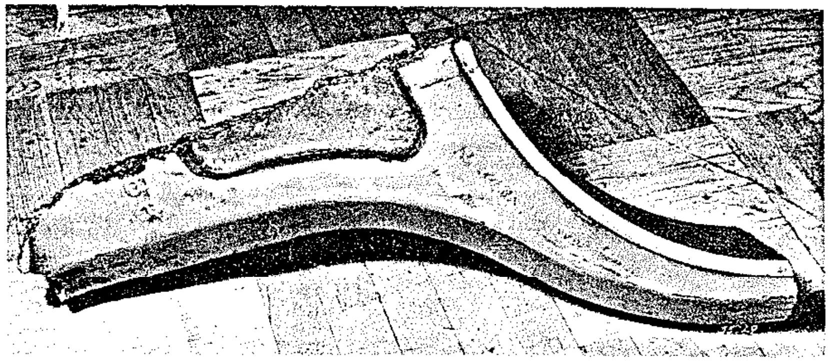


Fig. 17 Fracture in Cast Connecting Rod for Large Press. Numerous small cracks developed in the bushing seat after 2 years of service. (See Fig. 18 also)

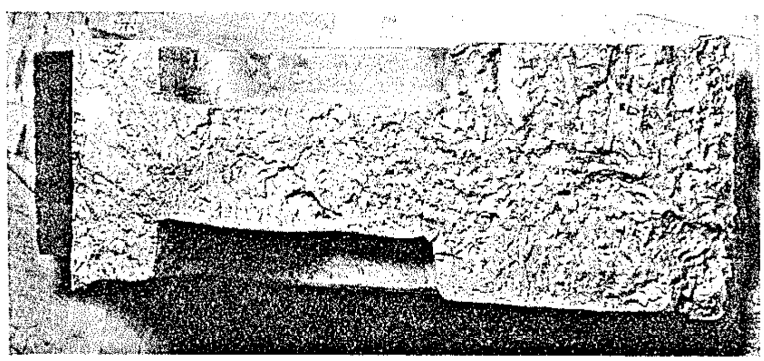
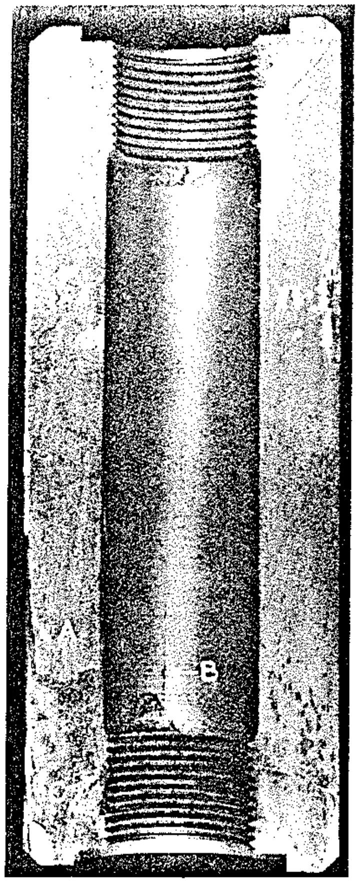


Fig. 18 Fracture Face of Part Shown in Fig. 17. Failure initiated at top left in dendritic pattern probably due to mistake in steel-making with low carbon content. Brittle fracture accompanied low Charpy impact properties.



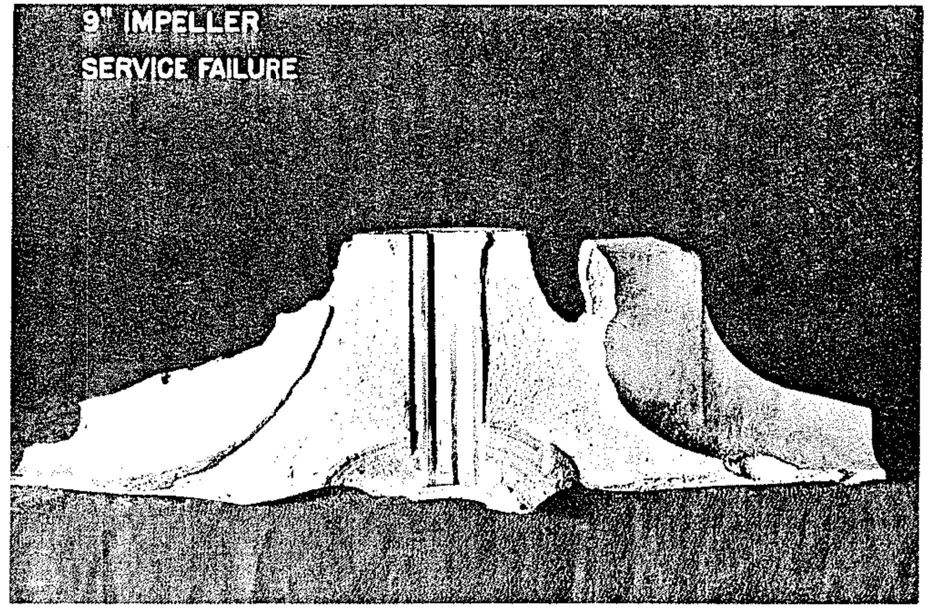


Fig. 20 Failure of Die-Forged Super Charger Driven Through a Splined Shaft.
Exhaust impulses led to torsional vibrations causing fatigue crack which developed to critical size for brittle fracture of the rest of the impeller.

Fig. 19 Brittle Fracture of Stainless Steel Pressure Vessel.
Corrosion and intergranular cracking initiated at thread root "C" due to contact with bronze nut. After some 400 pressurizations to 9000 ps a small fatigue crack initiated from zone C and failure then occurred in a brittle manner across the diameter. Several other cracks also existed. This martensitic stainless steel was treated to a Brinnell hardness of 321 giving a higher tensile strength than desired. Initial failure was probably due to the susceptibility of the martensitic stainless steels to the embrittling effect of hydrogen released by local corrosion developed at the threaded ends. For a replacement vessel, heat treatment to a lower tensile strength and stainless steel end plugs were combined with an attempt to eliminate moisture from the vessel.