ANALYSIS OF SERVICE FAILURES

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ABSTRACT

When a component fails prematurely, it is most important that an *engineering evaluation* be made of the loss. If one is alert enough to learn from past problems then "Experience gained is directly proportional to equipment ruined," provided the true cause is determined. A comprehensive failure analysis will enable the engineer to predict future problems, establish inspection criteria and intervals, improve safety, refine operating procedures and correct equipment specifications. The ultimate goal of all of this effort should be a reduction in maintenance expense and improvement in equipment on-stream time.

In most cases, only the materials oriented engineer is involved in the analysis of service failures, since it is always presumed that the material of construction is "guilty until proven innocent." Unfortunately, this approach can lead to a somewhat biased and incomplete result, and in many cases, does not find either the true cause or an acceptable long term fix. The necessary requirements of a comprehensive failure analysis using "real world" examples are presented.

INTRODUCTION

Fracture of engineering materials (predominantly metals, but including wood, concrete, ceramics, plastics and elastomers) was estimated in 1983 to cost U.S. industries alone $119 billion, annually. The same group also estimated that this amount could be halved if currently understood materials selection and preventative techniques were employed. Although failures occur in an extremely small percentage of the billions of tons of materials in service, they can cause wide publicity and attention.

Service failure of equipment including machinery are in reality "people failures." Man produces the designs, makes the materials and fabricates the materials into the equipment he designs. Other people may install and operate the equipment, but all are still people of one background and experience or another.

Materials have the unique ability to leave behind telltale signs of discrepancies from the norm and indicate how they have been abused. The problem is developing the background and experience necessary to read these signs and *properly* interpret the failures.

In addition to metallurgy, the failure analyst must also be familiar with such other disciplines as corrosion mechanisms, non-destructive testing, stress analysis, machinery design, lubrication technology, steel mill practices, fabrication techniques and welding engineering.

What Constitutes a Failure

The term *failure* may mean different things to different people. Herein, failure will be defined in terms of usefulness. A part or assembly is considered to have failed under one of the following three conditions:

- When it becomes inoperative.
- When it is still operable, but is no longer able to perform its intended function satisfactorily.
- When serious deterioration has made it unreliable or unsafe for continued use, causing repair or replacement.

Sources of Failures

Failure can be categorized into several distinct groups. Extensive study and research had led to the identification of the most common conditions which can cause failures. These fundamental factors that lead to failures of mechanical equipment are:

- Inadequate design.
- Inadequate selection of materials.
- Imperfections in materials.
- Deficiencies in processing.
- Errors in assembly.
- Improper service conditions (startup and shutdown).
- Inadequate maintenance.

Do Not Destroy the Evidence

Since failure analysis is predominantly systematic "detective work," destruction of important evidence is of major concern. As in any autopsy of the deceased, it can mean the difference between an accurate determination of the sequence of prior events that lead to the failure or an educated guess at best. As an example, the section of a large gearbox shaft that had undergone a torsional failure (Figure 1) was received for evaluation. Unfortunately, someone had ground all of the edges to remove the sharp corners, thinking he was doing us a favor. All of the initiating evidence was destroyed in the process. Therefore, the following rules should be adhered to in preventing the destruction of evidence:

- Do not fit fractures together.
- Do not sandblast, wirebrush or acid clean failed parts.
- Do not flame-cut within six inches of a fracture or failure.
- Do not store failed parts out-of-doors.
- Immediately record, through photographs and written documents, the position of all fragments, surface conditions and eyewitness accounts.

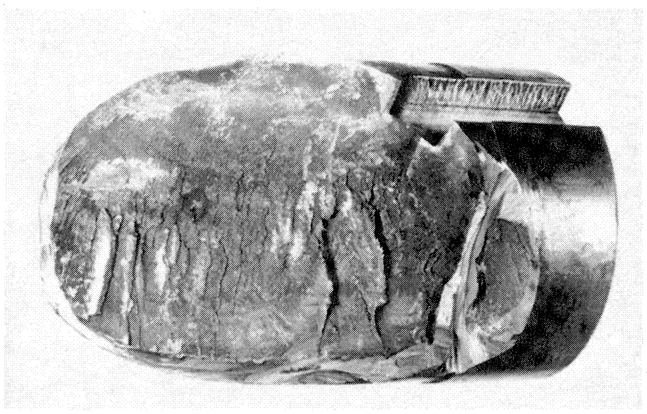

Figure 1. As Received Torsional Failure of a Large Diameter Gearbox Shaft with Most of the Initiation Point Evidence Destroyed by a Mechanic's Removal of the Sharp Corners.

TECHNIQUES AND TOOLS USED IN FAILURE ANALYSES

The failure analyst has a number of tools available to aid in the search for the correct cause of a service failure. Some of the more commonly used are:

1. Visual
2. Photography (preferably color)
3. Nondestructive Testing
   - Liquid Penetrant
   - Magnetic Particles
   - Radiography
   - Ultrasonics
4. Indentation Hardness Testing
5. Chemical Analyses
   - Bulk
   - Stratified
6. Mechanical Testing
   - Tensile
   - Impact
   - Fatigue
   - Creep
   - Stress to Rupture
7. Fracture Mechanics
   - Mathematical Analysis
   - Testing
8. Metallography
   - Macro
   - Micro
9. Electron Microscopy
   - Transmission
   - Scanning
10. Electron Microprobe
11. Electron Spectroscopy for Chemical Analysis (ESCA)-Auger
12. Energy Dispersive X-ray Analysis

Identification of Types of Failures

Failure analysis is separated into two distinct parts, the first being the *mode* of failure, and secondly, the *cause* of failure. The mode is the failure process, and the cause is the part that can be altered or changed to prevent future occurrence. Some commonly recognized failure modes are:

- Fatigue (mechanical and thermal)
- Ductile Fracture (stress overload)
- Brittle Fracture
- Stress Corrosion
- Hydrogen Damage
- Corrosion
- Wear and Erosion

The next sections will describe each mode of failure, including examples of actual field failures.

Fatigue Fracture

All structures and parts, regardless of their material of construction, can experience fatigue failure when subjected to cyclic loading. Fatigue is truly insidious, in that it develops so gradually that it is almost always well established before becoming apparent. Even though the fatigue mechanism is becoming well understood, parts still fail, due to the engineer's unfamiliarity with all the aspects of fatigue failure.

The fatigue life of a material is very sensitive to small changes in loading conditions, local stress concentrations and variations in the metallurgical characteristics of the material (i.e., chemistry, chemical segregation, grain size, heat treatment effects, hardenability, etc.).

Fatigue by definition is the progressive localized permanent structural change that occurs in a material subjected to repeated or fluctuating strains at stresses less than the tensile strength of the material. The result is progressive cracking that eventually causes complete fracture, if a sufficient number of fluctuations occur. Fatigue fractures are the result of the simultaneous application of tensile stress, cyclic stress and plastic strain. The absence of any one of these three components prevents both crack initiation and progression. Cracking is initiated by the cyclic stress and propagated by the tensile stress, causing localized plastic deformation. The fatigue mode of failure occurs in three stages:

- Crack initiation.
- Crack progression until the remaining cross sectional area is too small to support the applied load.
- Sudden fracture of the remaining cross section.

As stated earlier, fatigue resistance is affected by a number of *controllable* factors:

- The chemistry of the material and its resultant microstructure have a profound effect on fatigue strength. In fact, they can equally influence on mechanical strength (tensile and yield). Alloying elements, such as chromium, nickel and moly, have the greatest effect on the iron base system. Solid solution alloys show the maximum increase in fatigue strength.
- Grain size appears to be a strong determining factor in inhibiting the plastic deformation process that occurs with crack propagation.
- Environmental factors such as cyclic temperature, temperature gradient and corrosion pitting that result in stress concentrations. The thermal fatigue failure shown in Figure 2 was due to the temperature gradient across the thickwall section.
- Reduction of localized surface stress concentrations by such techniques as case hardening, shot peening, autofrettage and thread rolling.
- Proper heat treatment can markedly improve fatigue resistance. As an example, for steels, a tempered martensitic

structure produces the highest fatigue strength. Deviation from this with increased mixtures of pearlite, free ferrite and retained austenite result in inherent metallurgical notches. This effect on the endurance limit of American Iron and Steel Institute (AISI) 4340 at various hardness levels is shown in Figure 3.

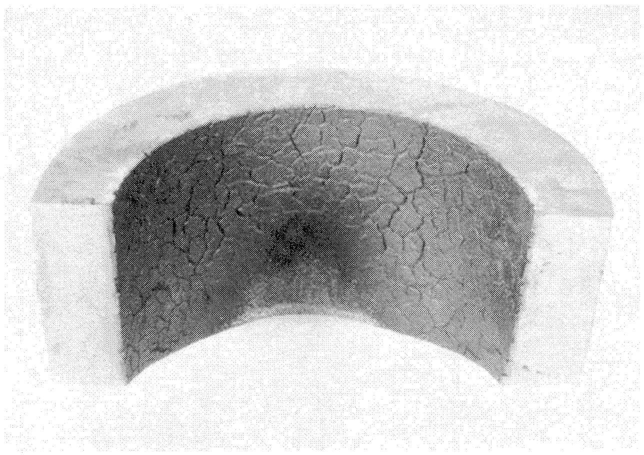

Figure 2. Surface Cracking of the Inside Surface of an American Casting Institute (ACI) Grade Hk-40 Furnace Component from Thermal Fatigue.

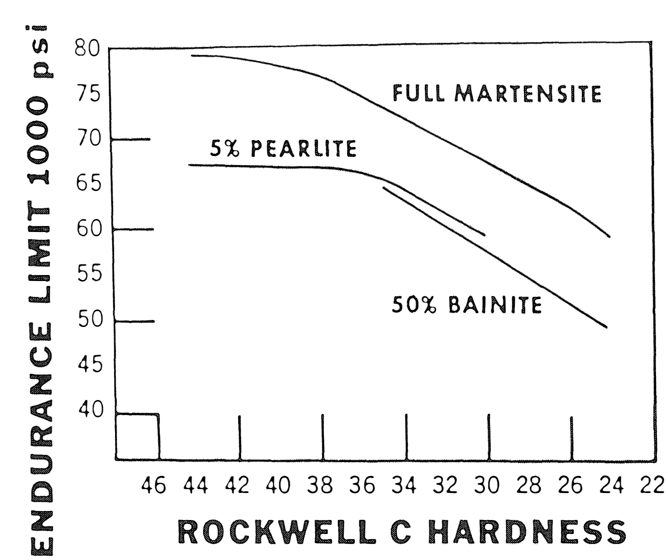

Figure 3. Effect of Non-Martensitic Transformation Products on the Rotating Beam Endurance Limit of an AISI-4340 Low Alloy Steel.

• Manufacturing techniques can greatly influence the fatigue performance of a component. For instance, large multi-throw crackshafts are fabricated by twisting their individual crank sections at the main journals. Two methods of laying out forged slabs prior to rough machining and twisting are shown in Figure 4. The old technique placed the web section, containing the crank pin to main overlap, on the center line of the slab, which inherently contains the maximum shrinkage, segregation and nonmetallic inclusions. This is also the section that is subjected to the highest bending stress during operation. A typical bending fatigue failure of a large crankshaft is shown in Figure 5. An improved method places the less desirable slab or ingot centerline at the center of rotation, which is the lowest stress area. Surface irregularities at section changes act as stress raisers. A machining notch initiated the failure of the connecting rod bolt shown in Figure 6. Failure to properly pre-tension the bolt during assembly allowed it to cycle in axial tension. The introduction of residual stresses in surface layers are also detrimental. Alteration of the metallurgical condition can be caused by heavy grinding due to overheating (tempering, formation of untempered martensite or burning). Structural discontinuations introduced during manufacture can also lead to failure by fatigue. A rolling lap that acted as the initiation point for a fatigue failure of a large diameter spring is shown in Figure 7. Electroplating, high strength, high hardness, low alloy steels can cause hydrogen induced crack initiation, as illustrated by the failure of the reciprocating pump crankshaft shown in Figure 8.

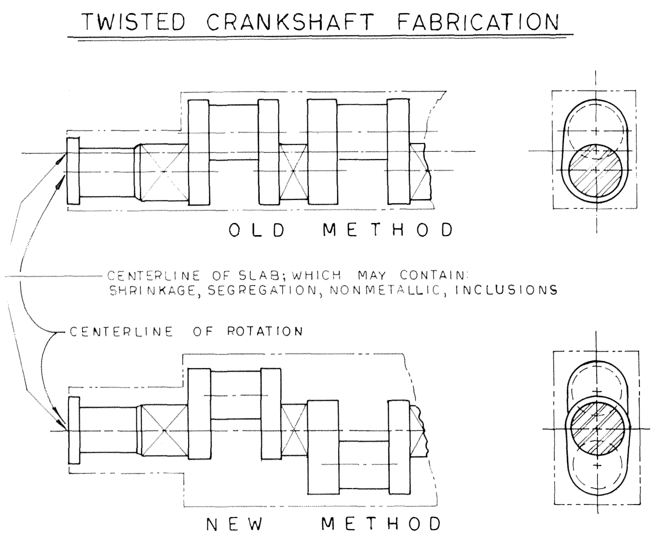

Figure 4. Two Methods of Forged Slab Layout Used in Fabricating Large Twisted Crankshafts.

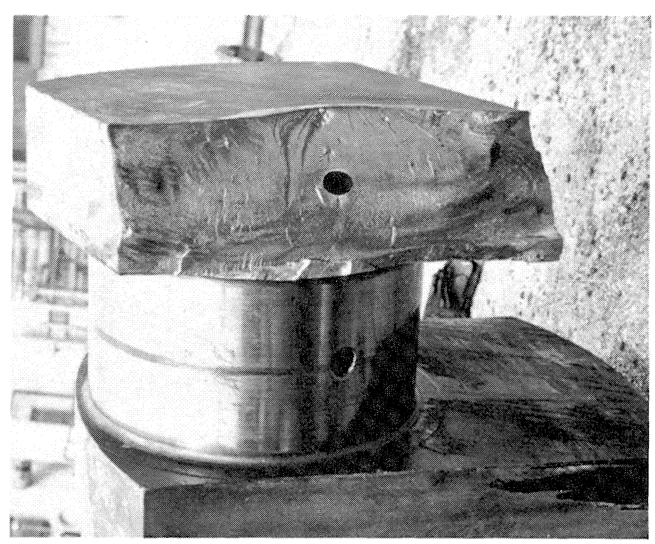

Figure 5. Failure of a Large 12 Inch Diameter Journal Reciprocating Engine/Compressor Crankshaft. The failure mode was fatigue in bending caused by main bearing misalignment.

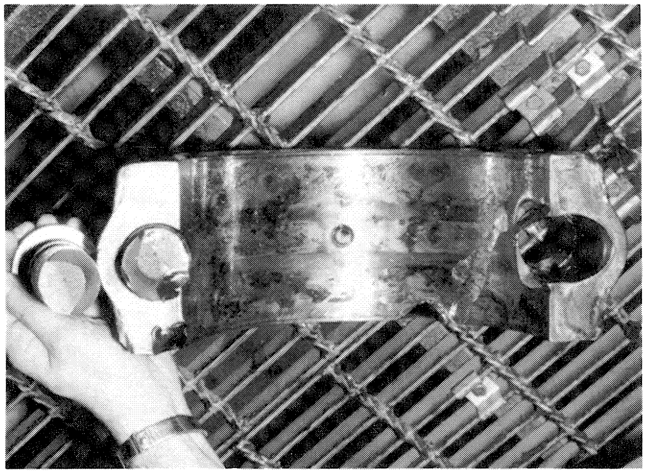

Figure 6. Fatigue Failure of an Upper Connecting Rod Bolt in a Large Reciprocating Engine. Two step fracture propagation initiated at the surface notch. The bolt was not pre-tensioned when installed, allowing it to cycle in axial tension.

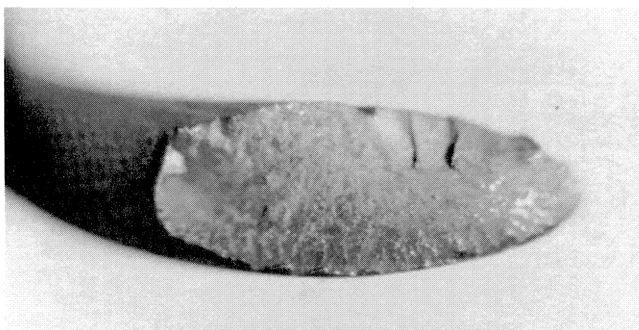

Figure 7. Large Diameter Relief Valve Spring Failed in Fatigue Initiating at a Rolling Lap Shown at the Center Top of the Photograph.

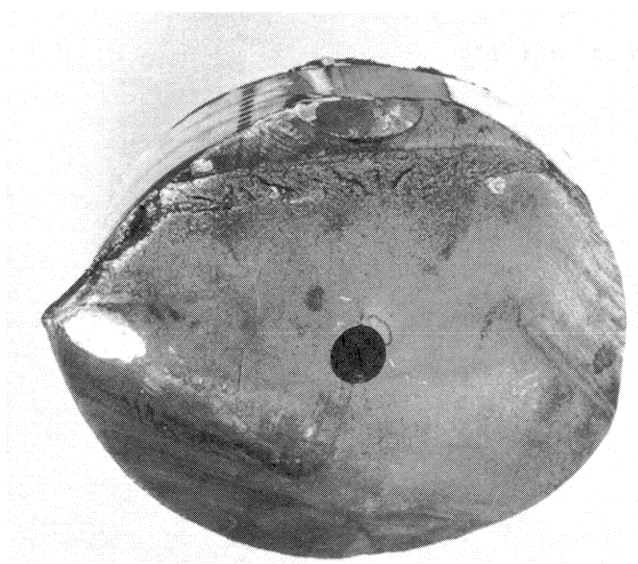

Figure 8. Hydrogen Induced Fatigue Fracture of Reciprocating Pump Crank Shaft. The failure plane is located at the undercut step on the journal end. Note the spalled chromplating on the journal surface.

Fatigue fractures exhibit a number of characteristic features which are recognizable to the experienced failure analyst. Every failure is slightly different and, in most cases, does not contain all of the characteristic signs. Fatigue failures show a general lack of ductility (no elongation or reduction of area) as exhibited by their smooth surfaces in the fatigue area. Most fatigue fractures are flat and straight, while some may be stepped and branched (Figures 9 and 10). These differences are a function of the applied load. The final area of failure is normally coarse in texture, compared to the fatigue zone, as shown in the failure of a connecting rod in Figure 11.

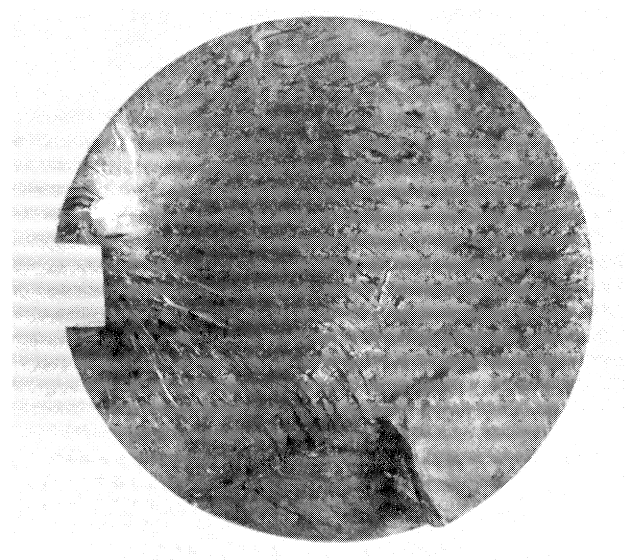

Figure 9. Bending Fatigue Failure of a Zirconium Alloy 705 Pump Shaft Initiating in the Keyway.

Figure 10. Combination Torsional and Bending Fatigue Failure of a Zirconium Alloy 705 Pump Shaft Due to a Loose Impeller.

In general, the smoother the fatigue cracked surface, the lower the applied stress and the longer period of time during which the crack has been propagating. If the fatigue zone is large, compared to the coarse zone, the applied stress was very low. Conversely, if the fatigue zone is small, as shown in Figure 12, and the coarse final fast fracture is large, then the applied stress is high.

Figure 11. Failure of the Wrist Pin End of a Reciprocating Compressor Connecting Rod Showing Two-Step Fatigue Fracture.

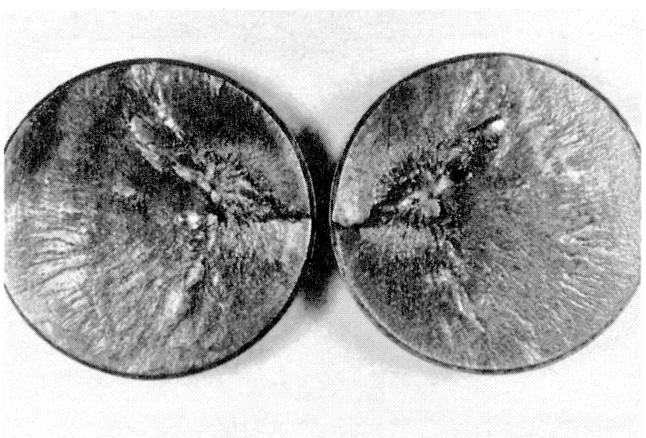

Figure 12. Four Inch Diameter Crankshaft Failure at a Snap Ring Groove by Bending Fatigue with Severe Stress Concentration.

Fatigue fracture faces are generally characterized by *beach markings*, which are curved, parallel, radial lines concentric to the failure initiation point or points (Figures 13 and 14). These are sometimes referred to as oyster or clam shell markings. This is an indication that the crack propagation occurred in steps or stages, with arrest between the steps, as opposed to continuous propagation. This condition suggests that crack propagation occurred at maximum loading or only during overload.

Not all fatigue fractures exhibit definite recognizable beach markings. In these situations, cracking probably occurred by uninterrupted growth and there was little or no load variation. Therefore, the appearance of a fatigue fracture is almost totally influenced by the loading cycle (bending, torsion, tension or combination). A schematic diagram of the various fatigue patterns and how they are influenced by loading and stress concentrations is shown in Figure 15.

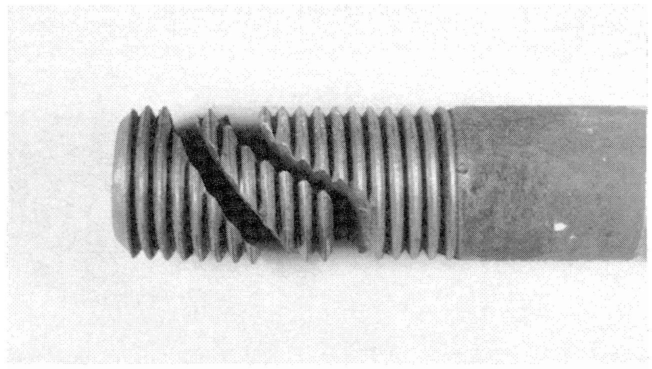

Figure 13. Multi-Fracture Failure of a Two Inch Diameter Cylinder Head Stub.

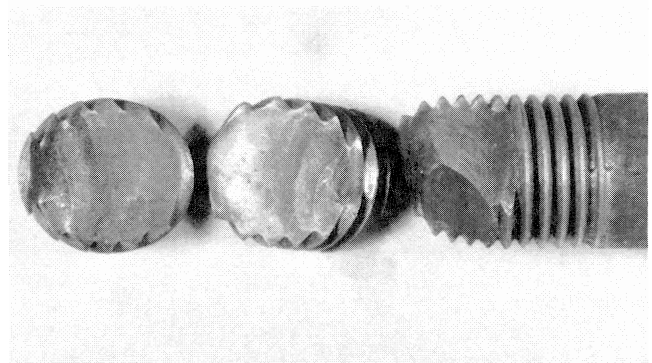

Figure 14. Multi-Plane Fatigue Failure Caused from the Thread Being Tapered Resulting in Non-Uniform Loading.

Ratchet markings are peripheral steps on a fatigue fracture surface caused by multiple crack initiations. This type of fatigue generally occurs in shafts subjected to rotational bending. An example of ratcheting is shown in the fatigue failure of thick wall high pressure tubing, shown in Figure 16, containing four distinct initiation points, each starting in the root of the attachment thread at the outside diameter. Markings point in the direction of the fatigue crack propagation. They are at

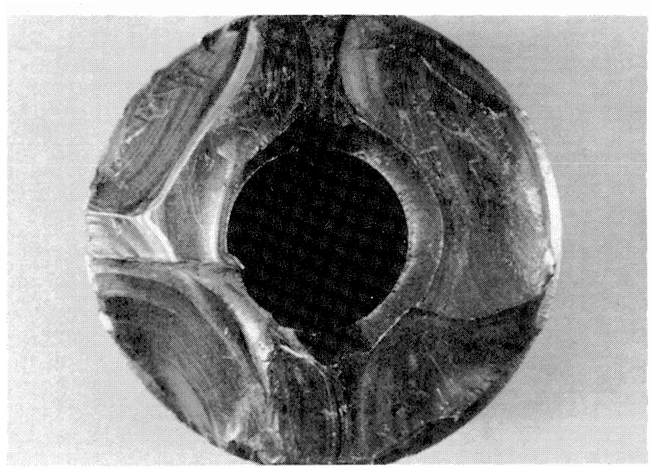

Figure 16. Fatigue Ratcheting Failure of a Thick Wall High Pressure Tube Containing Four Distinct Initiation Points.

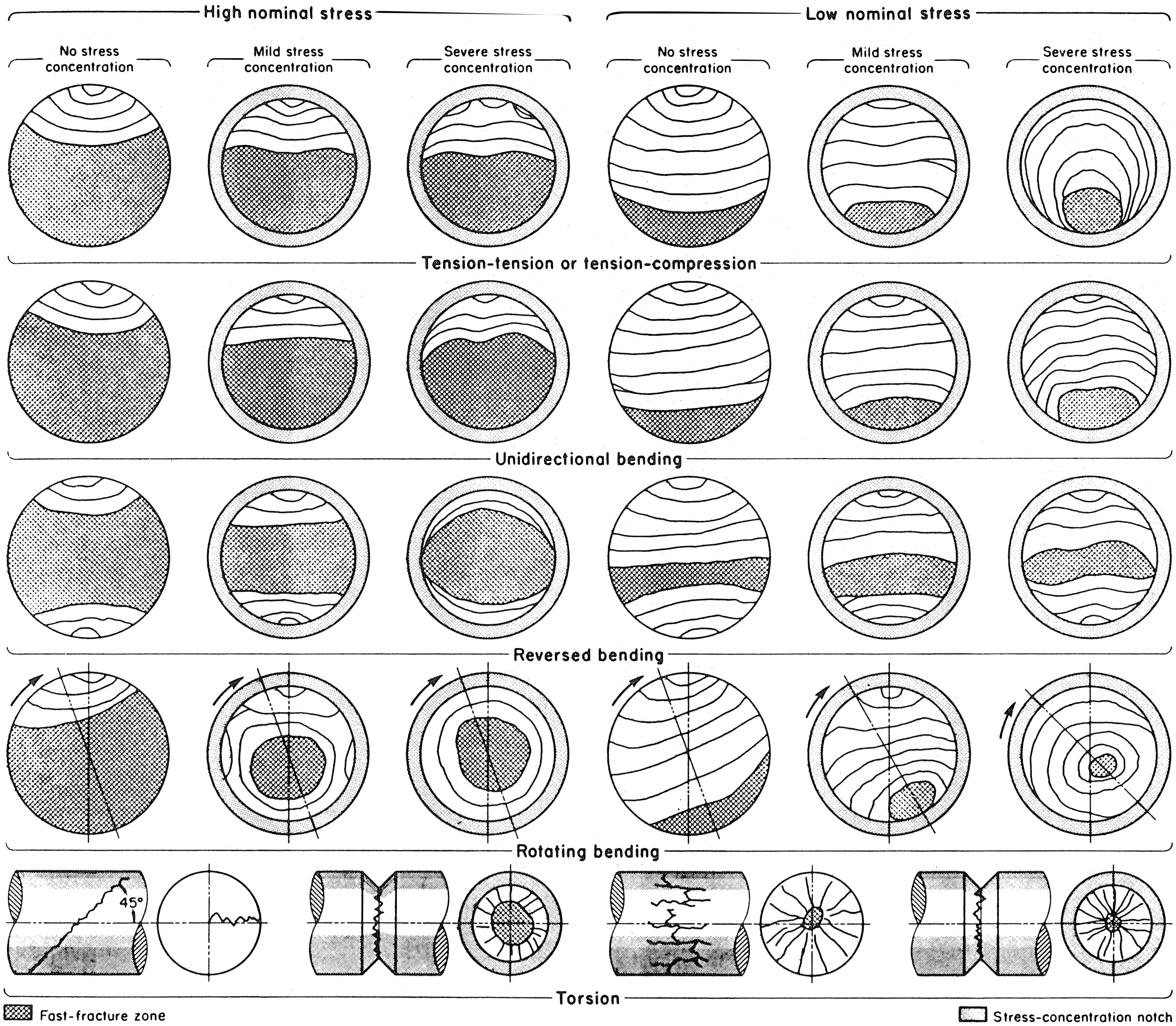

Figure 15. Schematic Representation of Circular Cross Section Fatigue Failures in Bending (C. Lipson).

slightly different levels and join together to create one major crack. This condition normally is an indication of high stress concentration at the crack origins.

Fatigue striations are finely spaced parallel fracture surface markings that can only be found by an electron microscope. These are considered as positive indications of fatigue. It is believed that each striation represents a single load cycle. A scanning electron micrograph of fatigue striations found in a type 304 stainless steel member in low cycle fatigue is featured in Figure 17. Fatigue striations may be found on fractures that exhibited no evidence of the classical beach markings. For this reason, the electron microscope has become an almost invaluable tool in evaluating the fatigue mechanism.

Ductile Fracture (stress overload)

Ductile or stress overload failures represent a large percentage of those reported by failure analysts. They all exhibit classic plastic deformation in the form of elongation or reduction of area as found in the typical tensile test. Frequently, the final fracture area contains the 45° shear lip of a cup and cone

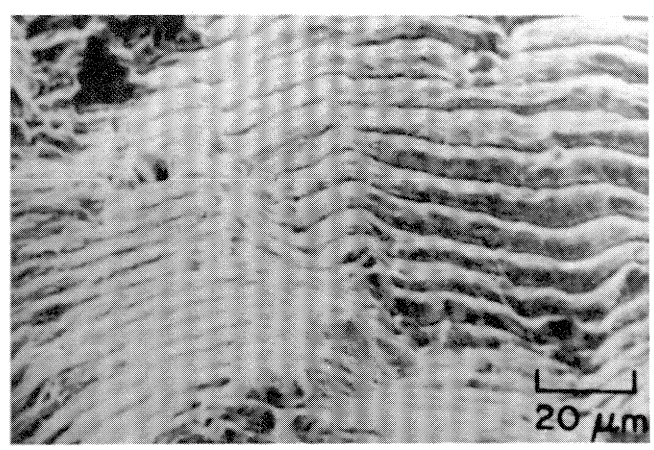

Figure 17. Scanning Electron Microscope (SEM) Fractograph of a Type 304 Stainless Steel Fatigue Failure Showing Clearly Defined Ductile Fatigue Striations.

separation. Electron micrographs of this type of failure mode with typical void coalescence are shown in Figures 18 and 19.

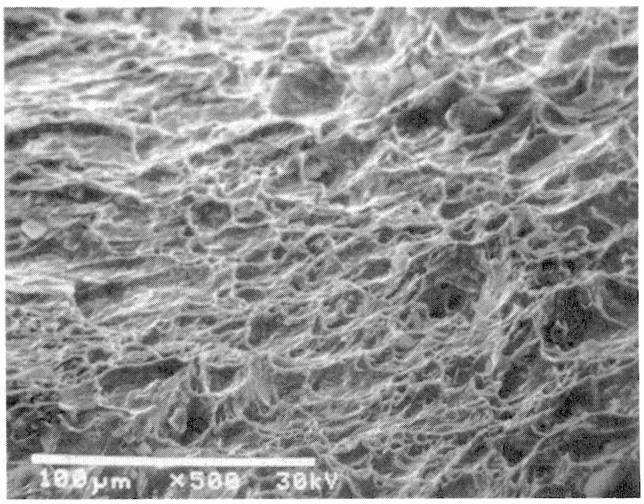

Figure 18. SEM Fractograph of a Tensile Overload Failure Showing Normal Cup and Dimple Failure.

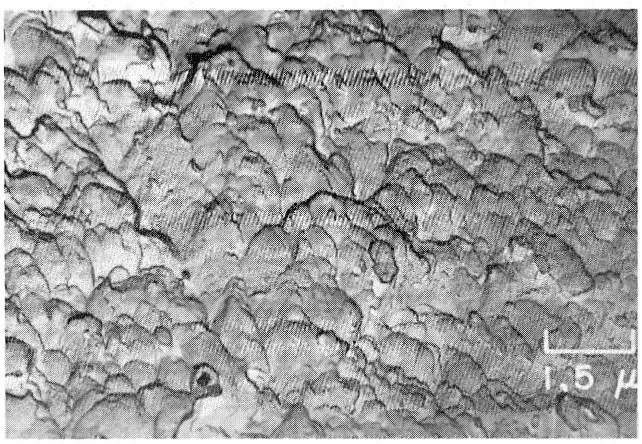

Figure 19. Transmission Electron Microscope (TEM) Fractograph of a Torsion-Overload Failure Showing Elongated Shear Dimpling.

Stress overload failures are generally the result of inadequate design, operating error, incorrect selection of material, improper heat treatment or insufficient quality assurance during manufacture.

Two examples of stress overload failures caused by improper manufacturing techniques are shown in Figures 20, 21, 22 and 23. The first involved a compressor secondary cross head requiring a casting with a minimum tensile strength of 55,000 psi. The manufacturer specified a grade of ductile (nodular) cast iron that met the minimum strength. No quality assurance was performed on the casting to verify that it was fully nodular. The failure analysis was performed after the cross head had failed and had caused extensive damage to the machine. The analysis found a mixed structure of ductile and gray cast iron with an average ultimate tensile strength of 30,000 psi. The straight flat fracture shown in Figure 21 is typical of gray cast iron.

The second failure is of a cast standard "T" hook refractory brick hanger used to support roof tile in a process furnace. A shrinkage void, shown in Figure 23, reduced the effective cross-sectional area causing failure by stress overload. The shrinkage void was due to inadequate casting feeding practice by the foundry.

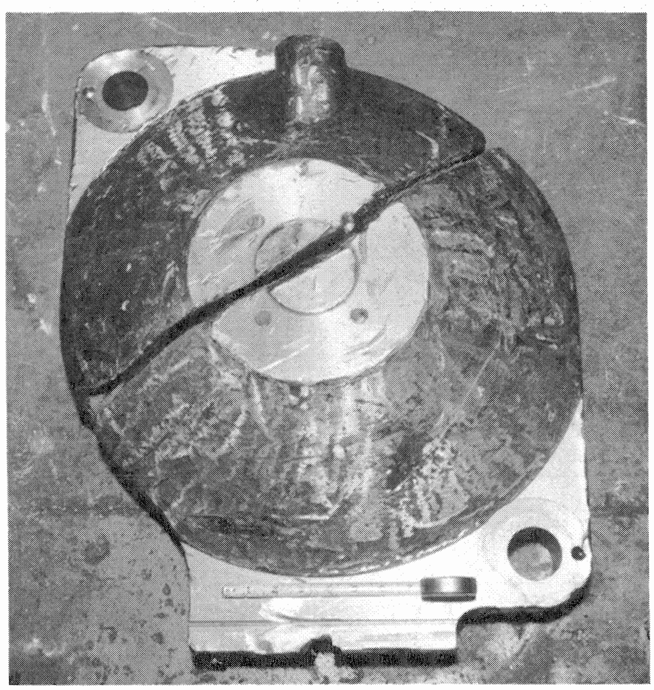

Figure 20. Overload Failure of Secondary Crosshead from High Pressure Compressor.

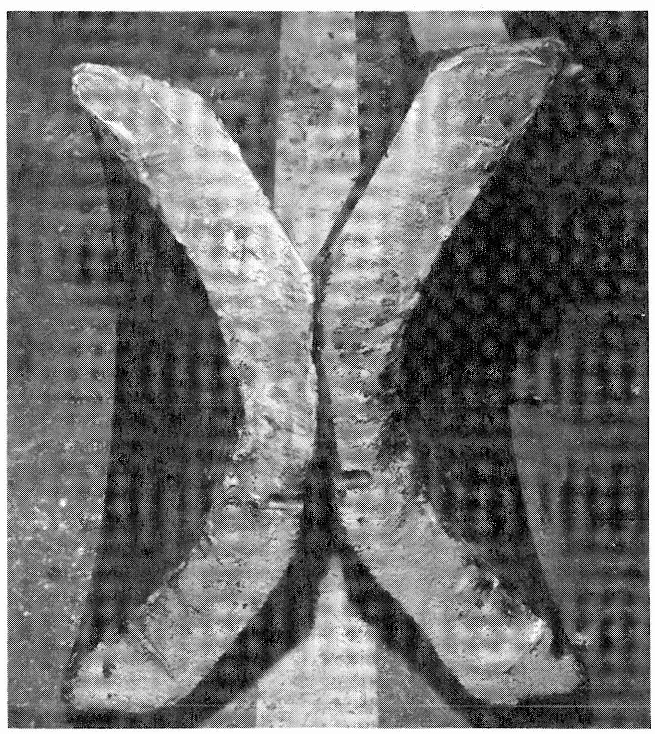

Figure 21. Fracture Surfaces of a Crosshead Failure Showing the Initiation Point on the Concave Surface at the Upper End. The material was specified to be ductile cast iron, but was determined to be mixed ductile-gray iron with reduced mechanical properties.

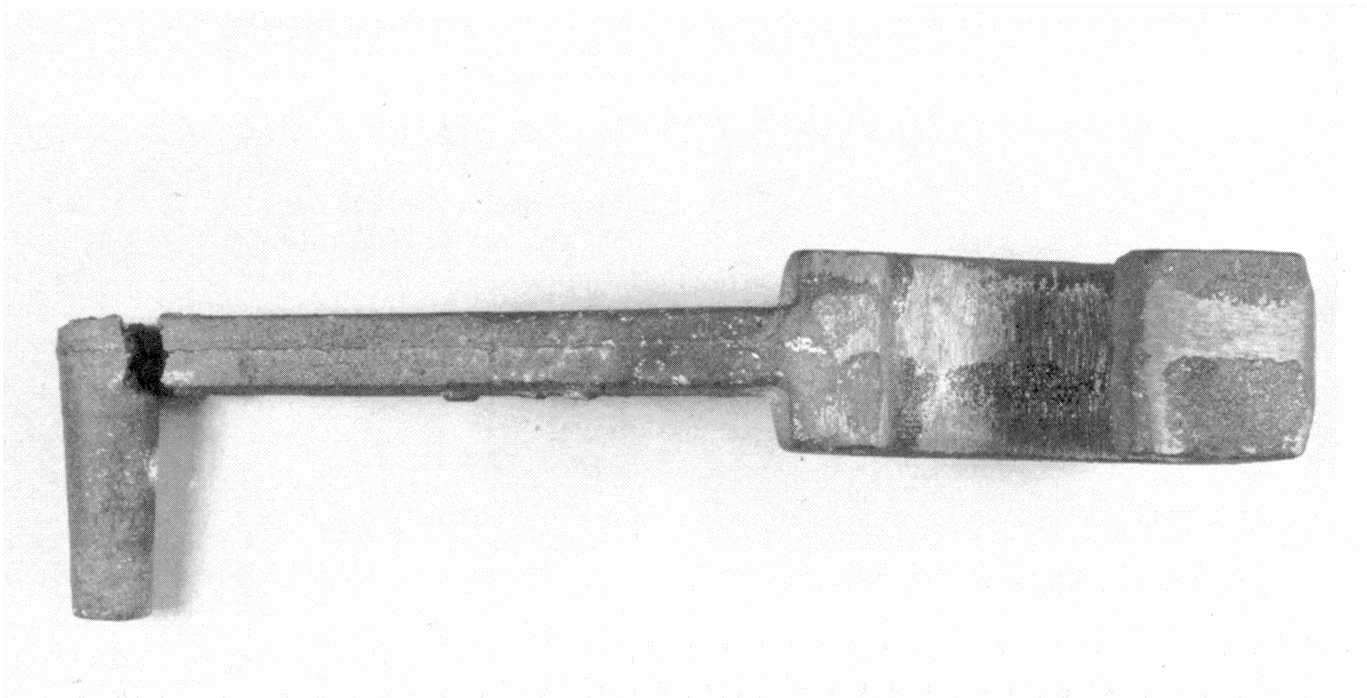

Figure 22. "T" Bar Refractory Hanger Casting Failure.

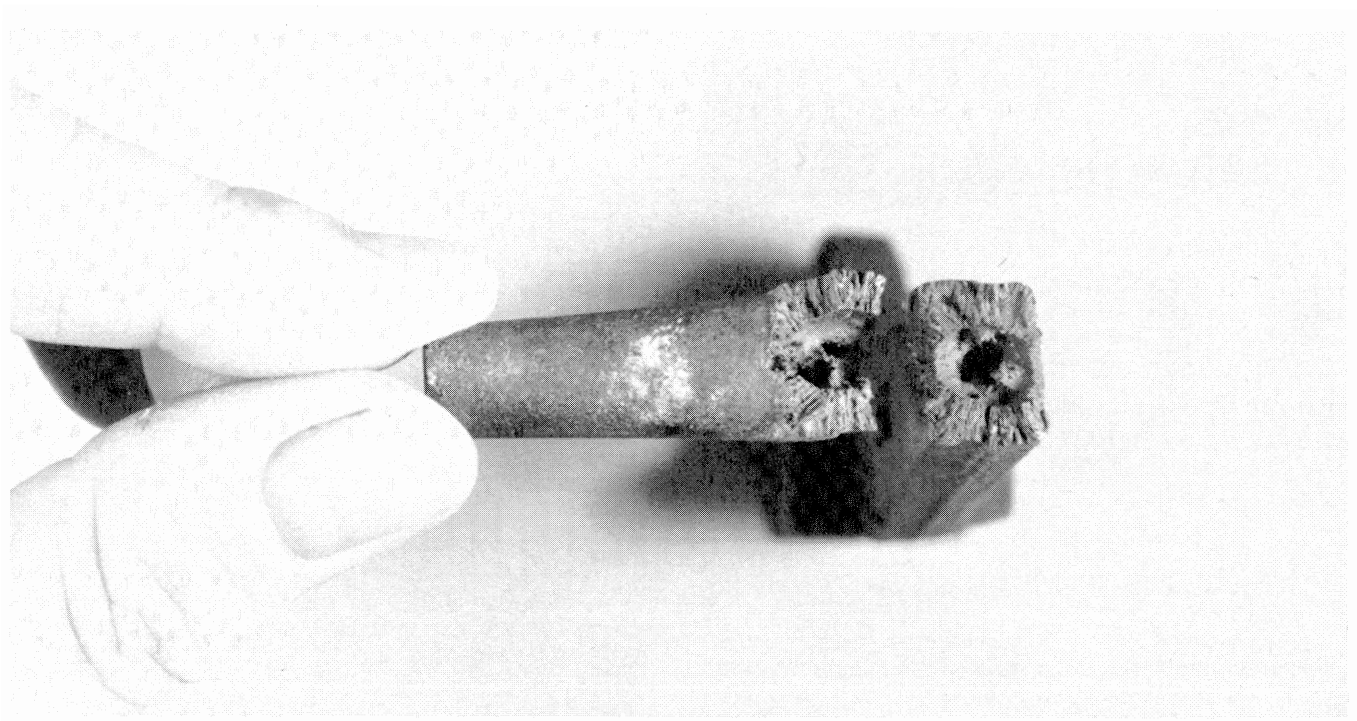

Figure 23. Fracture Surfaces of Figure 22 Showing Large Shrinkage Void at Intersection of the "T" to the Main Shaft Causing a Reduction in the Effective Cross Sectional Area.

Brittle Fracture

Fatigue fracture is sometimes called "brittle," due to the absence of definite signs of ductility. However, in the true metallurgical sense, it is not a brittle mode of failure.

Most body-centered cubic metals, including steels, change their resistance to dynamically applied load with temperature. This ductile to brittle transition, as measured by the ability to absorb impact energy, is referred to as the brittle range or transition temperature. The most widely publicized occurrences of brittle fractures are the Liberty ship failures at dockside, but other examples are seen in the form of piping systems, structural bridges and automobile components. An example of a typical brittle fracture of a pressure vessel component is shown in Figure 24.

Brittle fracture resistance of engineering materials is primarily controlled by metallurgical properties, such as chem-

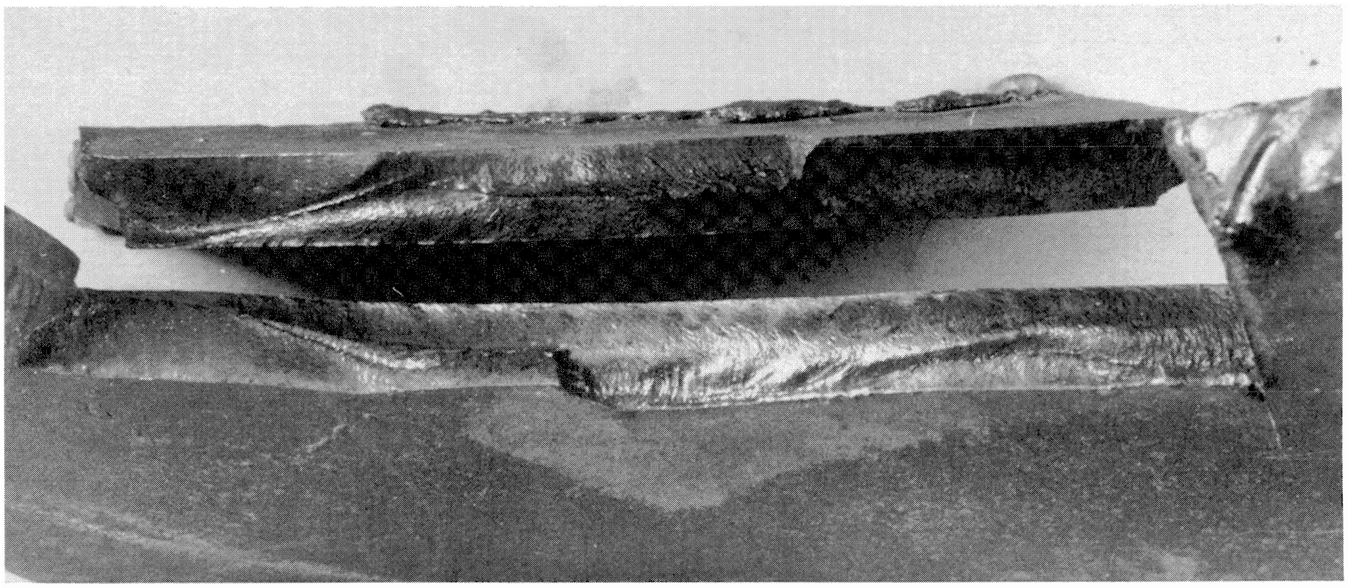

Figure 24. Brittle Fracture of Cryogenic Pulsation Bottle Baffle.

ical composition, grain size and microstructure. Processing of these materials also largely affects their toughness. For example, many low alloy steels are subject to brittle fracture if their thermal heat treatment cycle is not performed correctly. Specifically, if tempered between 550°F and 1100°F for extended periods or cooled slowly from the tempering temperature, these materials show an increase in the transition temperature and a reduction in the toughness, as measured by energy absorption.

Overheating for forging produces large grains and incipient melting resulting in brittle fracture. Also, incomplete solution of the carbite structure during the thermal heat treatment of carbon and low alloy steels can lead to a loss of ductility.

Stress Corrosion

Stress corrosion cracking is brittle appearing failure which can occur in ductile materials and exhibits no plastic deformation in or near the cracking. Stress corrosion results when a metal is subjected to electrochemical corrosion while being stressed. This mode of failure can be either transgranular, intergranular, or a combination of both. The intergranular mode is shown in Figure 25. The fracture type is a function of *metal and environment*. It is generally considered to be catastrophic since the crack propagation is very rapid. For stress corrosion to occur the following four parameters must be present simultaneously. The exact percent of contribution of each is the subject of much speculation.

- Steady State Stress
- Promotor
- Electrolyte
- Temperature

Hydrogen Damage

The presence of atomic hydrogen can affect metals, namely steels, in two primary ways. The first is by concentrating at sites, primarily non-metallic inclusions, causing the equilibrium pressure between the molecular hydrogen in the voids and the atomic hydrogen surrounding microstructure to be sufficient to cause delamination and blistering. This mode of failure is shown in a section of ¼ in steel plate from a pressure vessel in Figures 26 and 27.

Figure 25. TEM Fractograph of an Intergranular Failure from Stress Corrosion Cracking.

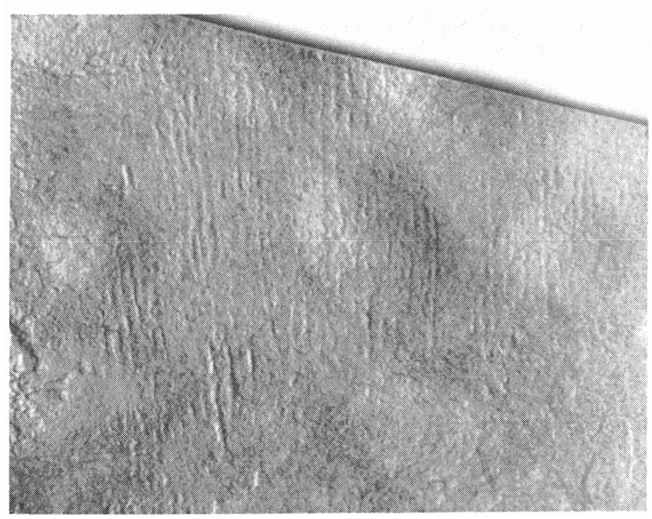

Figure 26. Hydrogen Blistering of Carbon Steel Reactor Vessel from Long Term Exposure to a Hydrogen Generating Environment at Elevated Temperature.

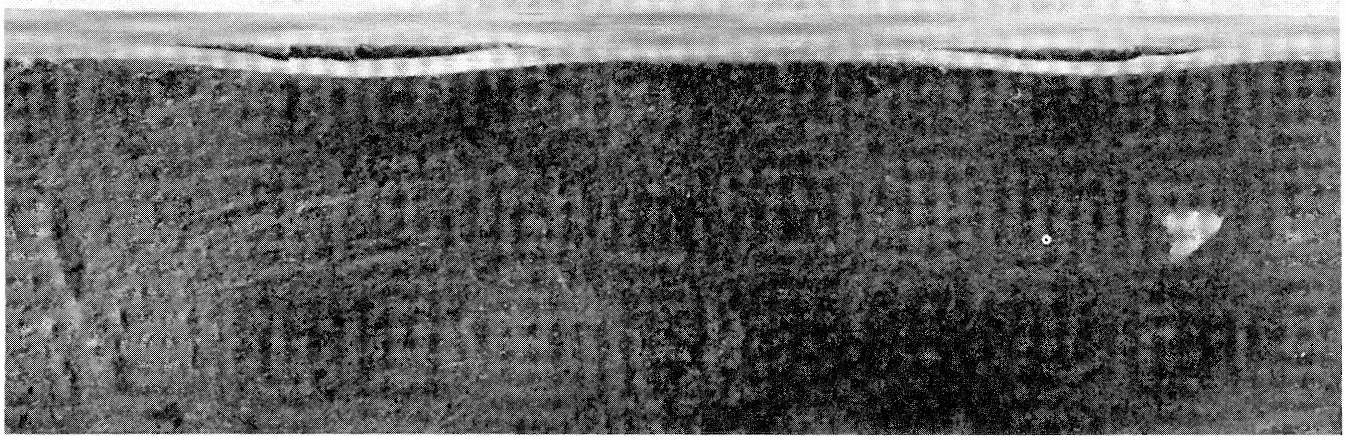

Figure 27. Cross Section of Plate in Figure 26 through Blisters Showing Delamination of Plate at Defects from Hydrogen Diffusion Combining to Molecular Form and Expanding.

Secondly, hydrogen can have a pronounced affect on the ductility (hydrogen embrittlement) of high strength steels and other alloys. Critical levels of hydrogen can be introduced into the metal in a number of ways, such as during the steel making process, heat treatment, electroplating, exposure to molecular H_2 gas/hydrogen sulfide and surface corrosion in aqueous solutions. An example of hydrogen diffusion during chromium plating and its initiation of a bending fatigue failure is shown in Figure 8. The reciprocating pump crankshaft was plated for restoration, but not baked after plating. Hydrogen induced fracture started at the edge of the plating undercut step and then progressed in fatigue.

Embrittlement by hydrogen causes a decrease in tensile ductility and a reduction in the notched tensile strength of a material. The result is a *delayed* fracture under static load.

Corrosion

Corrosion can be described as the chemical and/or electrochemical reaction of a material with its environment. It depends on the electrochemical operation of cells at the metal surface. Corrosion may be the primary failure mode leading to direct degradation of metal parts or create a condition that makes it a contributor to failure by another mechanism, such as corrosion pits forming the nucleus of a fatigue fracture. The specific application of a component part governs when its deterioration has reached the failure stage.

Frequently, the design engineer, because of his lack of corrosion experience, overlooks many of the parameters controlling the rate and type of corrosion that can lead to later service failures. Some of these parameters and their cause-effect are:

Residual stresses—which can be caused by forming, cold work, shearing, localized thermal treatment, welding and machining with heavy cuts can contribute to increases in the local corrosion rate in some environments, such as acidic solutions. They can also cause stress corrosion checking.

Applied stress—can cause corrosion fatigue or stress corrosion cracking in some environments.

Temperature—increases accelerate the corrosion rate of many materials (for every 10°F increase, the rate may double).

Crevices—can cause concentration cell corrosion resulting in failure from hydrogen embrittlement or nucleation for fatigue fracture.

Dissimilar metals—If the metals are in *electrical contact* and in an *electrolyte*, then galvanic corrosion of the less noble metal can occur, resulting in either localized pitting or corrosion.

Velocity—Velocity accelerated corrosion (relative motion between the environment and the metal surface) causes removal of the protective film of materials that may otherwise have low corrosion rates under stagnant condition.

Welding—Deposited weld metal may have a higher corrosion rate in an environment than the same wrought material. Welds cause a degree of residual stress due to their shrinkage-volume change. This can cause stress corrosion of the weld and adjacent material in certain metal-environment combinations. The welding process can cause sensitization of austentic stainless steels with normal carbon levels, resulting in intergranular corrosion in some environments.

Heat treatment—Thermally induced residual stress gradients can occur in components subjected to either local heat treatment or drastic quenching after heat treatment. These can lead to both general and stress corrosion failures.

A specialized corrosion failure is shown in Figure 28 involving the inner and outer races of a ball bearing from a 1000 hp electric motor. The severe fluting shown is characteristic of stray current passing through the bearing and electrolytically machining (oxidizing) the races. Metallographically, the structure under the ridges is untempered martensite typical of the structure found adjacent to an Electrical Discharge Machining (EDM) machined surface.

Wear

Wear is generally defined as a surface phenomenon that occurs by displacement and detachment of material by the mechanical action of contacting solid, liquid or gas. Wear normally causes a dimensional change with time and, therefore, differs from other failure modes which cause sudden

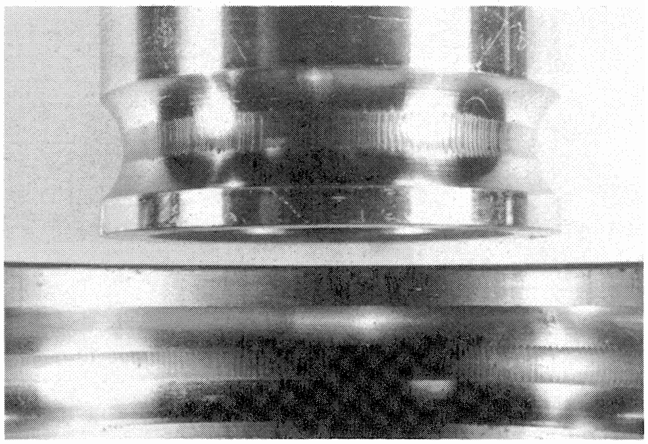

Figure 28. Ball Bearing Inner and Outer Race from a 1000 HP Electric Motor Showing Fluted Surface Caused by Stray Currents.

fracture. Like the dimensional changes from a general corrosion mode of failure, wear is considered as the cause of failure only when it makes the component unsuitable for service.

Wear is not always purely mechanical, but may include chemical corrosion as a strong factor. In all cases, stress is the major component involved in wear. Most experts agree that wear failure can be divided into six types:

Abrasive—wear is the removal of material from the surface by contact with hard projections on mating surfaces or with hard suspended particles moving relative to the wearing surface.

Adhesive—wear occurs when two metallic surfaces slide against each other under pressure. The result is scoring, seizing, galling or scuffing. Local bonding of the two surfaces occurs due to the high pressure followed by shearing of these projections resulting in displacement of one metal surface to the other.

Fretting—is an adhesive wear mechanism caused by vibration or cyclic relative motion of small amplitude. It generally occurs on contact surfaces that were not intended to move relative to each other. Corrosion may or may not be associated with the fretting mechanism. An example of a fretting induced fatigue failure is shown in Figures 29, 30 and 31.

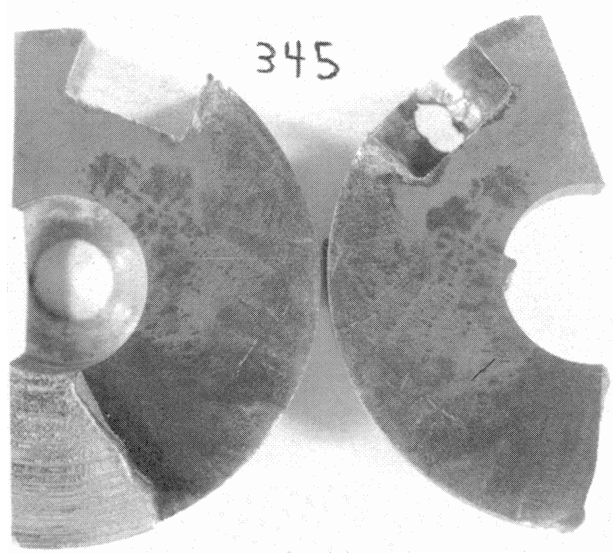

Figure 30. Fracture Surface of the Turbine Shaft (Figure 29) Showing Fatigue Extending about 60% across the Section.

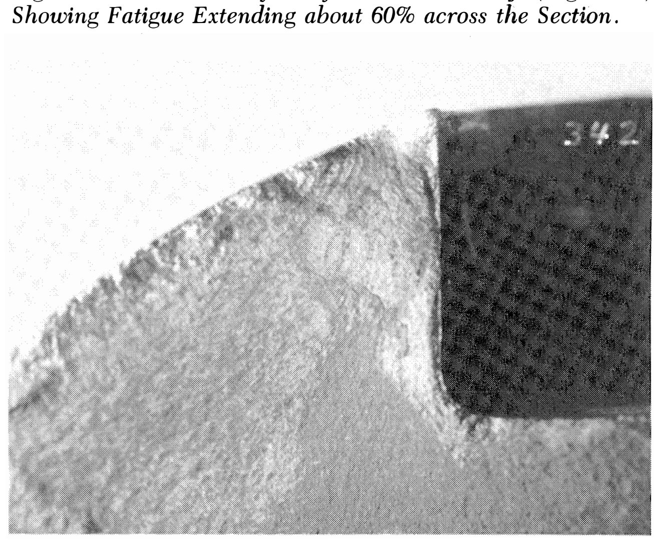

Figure 31. Fatigue Nucleation at Fretting Line and Keyway Corner on Turbine Shaft (Figure 29).

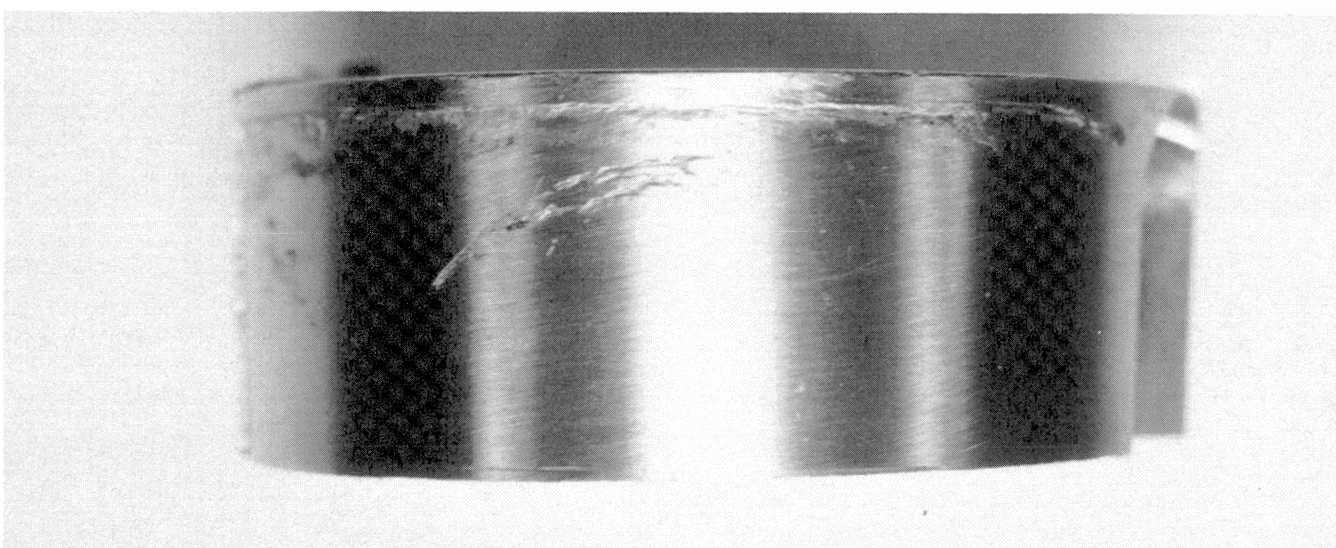

Figure 29. Section of Failed Tapered Turbine Shaft Showing Continuous Line of Fretting Wear at Edge of Coupling Land.

Corrosive—wear is an abrasive wear in a chemical environment that accelerates the removal of the corrosive products by mechanical action. However, mechanical action may produce chemical attack by removing the protective passive film.

Erosion-corrosion—or velocity accelerated corrosion, occurs due to the relative motion between the fluid and the metal surface. This condition may occur in the absence of abrasive particles. Most metal attacking environments have critical maximum velocities in which erosion-corrosion will not occur. An example of erosion-corrosion involving abrasive practices is shown in Figure 32. This closure flange was grooved by the action of catalyst particles and gas leakage. Cavitation is a special form of this failure mode. A cavitation induced fatigue failure of a high speed rotor due to incorrect material selection and hardness is shown in Figures 33 and 34.

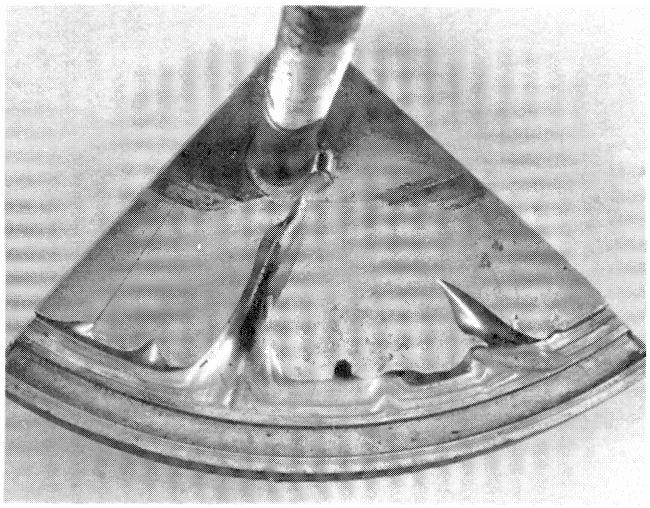

Figure 32. Erosion-Corrosion Failure of a Type 316 Stainless Steel End Closure from a Combination of Catalyst Particle and Corrosive Gas Leakage.

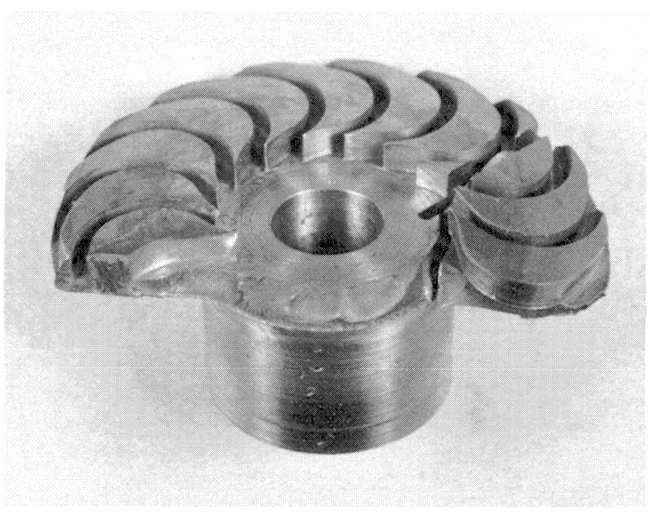

Figure 33. Failure of an Oil Dynamometer (Brake) from a Cryogenic Expander.

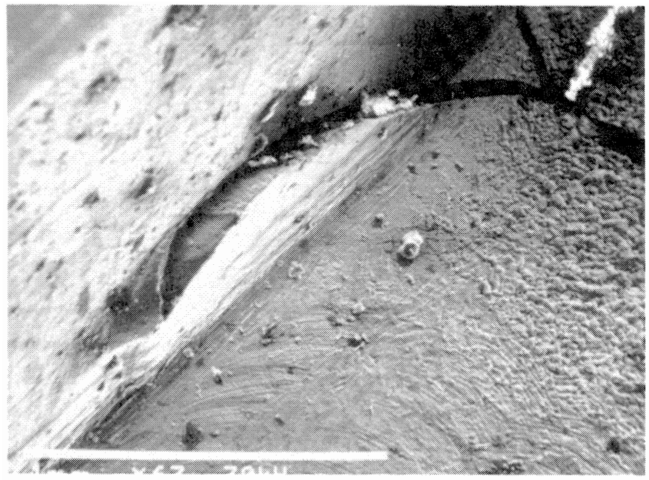

Figure 34. SEM Fractograph of the Dynamometer Wheel in Figure 33 Showing Cavitation Pitting Nucleation for Fatigue Failure of the Blading.

Surface fatigue—is localized surface damage from metallic particles becoming disloged from the surface due to very high cyclic contact loading. The result is pitting and spalling of the surface. Ball and roller bearings frequently fail by this mechanism.

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