PRECLUDE FAILURE: A PHILOSOPHY FOR MATERIALS SELECTION AND SIMULATED SERVICE TESTING

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ABSTRACT

Failure of products in service under foreseeable conditions often subject manufacturers to legal liability when personal injuries occur; hence, the care used (or the philosophy employed) in material selection, design, analyses, fabrication, and maintenance must be sufficient to preclude failure. Failure analysis requires careful sorting of a wide variety of information to determine how and why a metal part failed in service or testing and to determine what can be done to prevent a recurrence. Valuable knowledge is available in the literature from documentation of prior failures that may be used to develop logical approaches to the design and development of new components. A philosophy of design and prototype evaluation based on the prevention of failure is more sound and workable than the stereo typed application of empiricisms, codes, specifications, and factors of safety now commonly used. Reliance on design for static loadings and for factors of safety based on tensile strength as a criterion are frequently erroneous and dangerous. If a part does not fulfill its intended function satisfactorily, it "fails" by: a) excessive deformation, b) fracture, c) surface disintegration, d) deterioration of properties. A variety of failures will be discussed to emphasize the factors that must be considered in selection of an optimum material and in prescribing an effective method of simulated service testing. Considerable latitude in use and misuse of equipment must be foreseen in order to predict possible modes of failure. A broad consideration of service environment is necessary for correcting faulty design and selecting proper materials which will withstand modifications due to processing, fabrication, maintenance, or repair operations that lead to failure.

Preclude Failure: A Philosophy for Materials Selection and Simulated Service Testing

INTRODUCTION

The prevention of failure and procedures for failure analysis are topics receiving increased emphasis because of the large number of product liability suits arising in the courts against manufacturers of almost every type of product. In assuring the quality of a product, it is not enough to predict, interpret, and verify failures in various types of laboratory and proving ground testing; the manufacturer must develop procedures to prevent all foreseeable types of failure. During the past few years there has been a rapid increase in the number of law suits against manufacturers because of accidents resulting in injuries; plaintiffs accuse the manufacturer of negligence, fraud, improper design, inadequate materials, implied warranty, etc. Legal implications imply that every person owes a duty to all others to exercise due care to guard against any injury which may follow as a reasonable, probable, or foreseeable consequence in the use of his product.

When a product causes an injury, the accident itself affords a degree of circumstantial evidence against the manufacturer. These cases can only be combatted by strong factual and tangible evidence that the design, manufacturing, inspection, and quality control exceeded the requirements set by the standards, codes, and specifications of today's best practices of the industry.(1)* Furthermore, careful analysis of the evidence must prove that the failure was caused by an abnormal operating condition or by improper maintenance or faulty repair and thus that the cause of the accident was not under the control of the manufacturer. Any factual uncertainties must be submitted to a jury to be resolved as to whether the accident resulted from gross misuse of the product or was due to mistake or negligence on the part of the manufacturer. Thus, the detailed analysis for all foreseeable conditions and the

*Numbers in parentheses refer to articles listed in the Bibliography.

presentation of the manufacturer's design considerations, processing, and quality control procedures adopted to prevent failure are important evidence. One cannot emphasize too strongly that the whole philosophy of design must be based upon safety of operation and "prevention of failure." All foreseeable failures (such as that in Fig. 1) must be avoided.

SOURCES OF FAILURE

In the development of equipment to operate under unique and severe environmental conditions, a designer is confronted with many problems in the selection and evaluation of the optimum material from the wide variety available. Components such as gas turbines, nuclear reactors, space missiles, submarines, and cryogenic equipment are subjected to combinations of severe environments which may involve extremely high or low temperature, corrosive liquids, high vacuum, progressive deterioration due to radiation, surface wear, etc. In spite of the many "standard" mechanical tests available today and the large number of simulated service experiments being conducted, there is great confusion in the interpretation of existing data as far as its application to a particular design is concerned. For severe conditions the selection must often be confined to a small group of candidate materials due to a necessity to design for outstanding resistance in one characteristic, (for example, high temperature resistance in the case of a gas turbine blade, or inertness to the chemical environment in some forms of chemical processing equipment). However, there are many other factors which must be considered such as resistance to brittle fracture, fabricability, wear resistance, ductility, etc. before optimum selection can be made of the most suitable material. Confusion often results because of the lack of significance attributable to many "standard" mechanical properties obtained in laboratory tests or listed in handbooks.

An engineer should design a structural component to preclude failure; hence, we must understand: "What are the causes leading to failure" and "what are the modes of failure that might be anticipated" in the proposed service environment. The reasons for failure may be classified into three categories:

I. Faulty processing or fabrication

II. Faulty design considerations or misapplication of material because of unforeseen conditions in loading, temperature, localized stresses, etc.

III. Deterioration in unique or unusual service conditions which may involve very specialized characteristics such as wear, radiation damage, ablation, improper maintenance, etc.

In general, "failure" implies that a member fails to fulfill its intended function satisfactorily. 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 lead to failure.*

For example, the relation between load and 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 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. Conversely, this same member may fail by stress corrosion cracking because of environmental conditions and the unknown residual or shakedown stresses developed in fabrication and service that are not inherent in the material. A shaft such as that in Fig. 2 may fail by fretting fatigue because of the design details; thus, the selection of an alternate material would not materially improve the situation.

For a railway car hopper or a rock truck, large plastic deformations and even cracks may develop from impact with heavy loads dumped into the container, but the component continues to fulfill its function satisfactorily. This does not constitute a failure even though the material has failed locally. Nuclear reactors often have wall

*References 19 to 30 inclusive illustrate a wide variety of failures and the combination of circumstances which lead to failure in fatigue, brittle fracture, etc.

thicknesses of 3 to 4 inches, but attempts are now being made to develop materials and fabrication methods for wall thicknesses up to 12 inches. This does not mean that a material satisfactory in a four inch wall will be satisfactory in a 12 inch wall. The variables of processing and fabrication and the overall size of the component are major factors in determining the flaw sizes that will be built into the structure and the potential danger of failure from fatigue or from brittle fracture as these flaws approach critical size.[2, 3] In the brittle fracture field it is important to note that the "critical" flaw size for rapid propagation of fracture is dependent upon the overall size of the component in which it is located. In these instances the material selection will be largely dependent upon the ability to roll, heat treat, cold form, machine, weld, etc. as a vital part of the material selection because of the procedures needed to process and fabricate this type of component. Figs. 3 and 4 illustrate failures due to flaws developed during processing that developed to critical size in service.

This means that size effect, stress gradients, notch sizes, slow flaw growth, critical crack size, and residual stresses are variables that must be considered in determining the mode of failure that might take place in the material. The complexity of the contour of the component and the influence of processing operations must be considered as a part of the environmental conditions that must be appraised as major factors that alter the mechanical properties and may lead to failure. Thus, strong emphasis must be placed on critically examining every operation done on the material as comprising the vital parameters in the environmental and service conditions that must be included in selecting the material for a given component.

RATIONAL APPROACH TO MATERIALS SELECTION

For failures of Category II above (design considerations) we can start with modes of failure, relate these to the service conditions under which the part must operate and determine specific types of mechanical resistance required in the material.

For materials evaluation we would then select those methods of mechanical test that most nearly measure the specific resistance desired in this particular service condition. There are, of course, some gaps in which new test methods need to be evolved for better determination of quantitative values that can be used for final design purposes. Table I presents in outline form an organized approach for selection of material and design stresses. More detail, of course, needs to be added in the last column to arrive at quantitative values.

For those failures due to faulty processing or fabrication (Category I) there are few, if any, standard tests that can be used for evaluation 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 II each processing operation may induce residual stresses and modify the mechanical properties by severe cold work in local zones, under-bead cracking, local heating, porosity, hydrogen embrittlement, non-metallic inclusions, and a multitude of other localized effects which may be categorized as "defects or flaws." In many applications it is the presence of these small defects or critical flaw sizes which drastically affect the resistance of the member and determine the nearness to failure such as shown in Fig. 6. Thus, when running typical laboratory tests to determine the mechanical resistance of the material, care must be taken to select samples which include the kinds of defects and localized effects that are expected to occur from the processing operations. It is important that one analyze the influence of every step in the manufacturing process as it relates to the final mechanical properties expected in the finished component. This can only be done by tests of samples that have been subjected to the same processing operations as would be expected for the finished component.

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. 7) unforeseen conditions may develop to cause failure. Many service conditions involve extremely rapid rates of heating or include radiation damage, ablation, corrosion, or the various types of wear. A broad range of factors must be considered as outlined in Table II. These are examples of conditions for which specialized testing is necessary to evaluate material for a specific application involving one of these deleterious effects as the controlling variable. Fig. 8 shows a special type of deterioration that cannot be appraised from "standard" laboratory tests. The only thing that can be said of these types of severe service conditions is that every effort should be made to simulate the expected temperature, time, dosage, etc. as nearly as possible in the laboratory.

The major emphasis at the present time on the evaluation of materials is that of relating the structural applications to failure based on design considerations (Category II). Table I forms the basis for a workable start in relating standard failure modes to service conditions and determination of mechanical parameters or characteristics for resistance to this mode of failure. The table can be expanded somewhat but we can never hope to include all of the altered characteristics due to faulty processing or to unusual service conditions in a table such as this. What is important, however, is that the material evaluation include samples that have been processed by the method intended in the final structural component so as to include normally expected processing "defects" or "flaws" in the determination of the mechanical resistance. Figs. 9 and 10 show catastrophic failure developed from "minor" surface defects in processing that become critical when exposed to the service environment.

From the structural viewpoint the modes of failure are few in number, namely: (a) excessive deformation, (b) fracture, (c) surface disintegration, (d) deterioration of properties. Some of these modes may be characterized as shown in the first column of Table I. The subtle influencing factors that occur during processing result in localized alteration of the mechanical strength characteristics of the material that sometimes seem trivial but may be vital in determining the satisfactory performance of the part. This is well 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 the steel.

Deterioration during service in a specific 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 II, careful detective work is often necessary to determine the cause of a specific failure (or to design a component for satisfactory performance) 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 in the failure in Fig. 12. A rational and complete analysis must be based on positive supporting evidence (rather than the absence of contrary evidence).

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 the answer before making the detailed investigation.

Carefully documented case histories of failures of the past* form a valuable textbook from the university of hard knocks and often illustrate the synthesis and detective work necessary to prevent similar recurrences in the future. The documentation of the British Comet airplane failures (22) represents an outstanding example of

*See, for example, the appended references 5, 8, 12, and 19 through 28.

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 size.

In making an analysis of a failed part it is imperative that great care be used in detailed visual, optical, metallurgical examination, chemical and hardness tests, etc. without 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 and condition of all adjacent parts after the incident, is necessary to confirm the analysis beyond reasonable doubt. The complex interaction of several modes developing to final fracture is well illustrated by the case shown in Fig. 13.

DESIGN CODES

Most of the aircraft and missile industry in the past has been committed to design on the basis of a series of static loadings involving: (a) "design load" as the nominal load for which the component is designed to operate, (b) "limit load factor" applied to the design load to compensate for uncertainty regarding exact conditions of peak loading, and (c) "factor of safety" as a ratio of the ultimate load or yield load to the limit load (that is, the yield load may be specified as 1.1 x limit load or the ultimate load 1.5 x limit load). The "ultimate load" is specified as the load which will induce a stress equal to the "minimum guaranteed" ultimate strength of the material. In general, this policy is intimately related to static load carrying capacity of a component that is loaded in tension. It leaves wide gaps for the designer to determine factors such as "ultimate load" when the mode of failure as outlined in Table I is other than ductile yielding or tensile fracture. It is embarrassing to have fatigue cracks develop in an airplane wing that was designed with a "factor of safety" of, say, 1.5. Realistically, everything built has a small, though significant, probability of failure.

For each mode of failure a different mechanical resistance or "property" of the material is involved in measuring the nearness to structural damage. One observes that the tensile strength is not a significant or reasonable criterion to measure the nearness to failure (or the "ultimate load" in the failure mode) except in a few very limited cases. Similarly, a so-called "factor of safety" based on tensile strength is meaningless in measuring the nearness to failure by brittle fracture, fatigue, buckling, stress corrosion cracking, etc. Aircraft and missile people put great emphasis on "strength-to-weight ratio" as a criterion for selection of material. In the vast majority of cases this is taken to be synonymous with tensile strength divided by weight per unit volume. Except for those few cases in which ductile fracture or gross yielding may be the limiting condition for failure, the tensile strength and yield strength are not useful criteria and may, in fact, lead to the selection of an unsatisfactory material. Increased tensile strength is usually detrimental where the potential mode of failure may be brittle fracture, low cycle fatigue, stress corrosion cracking, etc.

In view of the statistical variability and chance effects involved in material behavior, engineering judgment must be included in the final decision making process and proportioning of members for a particular application. Furthermore, it is inconsistent to talk in terms of a "factor of safety" in view of the statistical variability involved. If one could determine the mean values and standard deviations for the load and strength parameters, he could then analyze the problem in some detail and come up with a "probability of failure." Philosophically, the idea of a probability of failure is diametrically opposed to the idea of a factor of safety but is a more realistic approach when one recognizes all the uncertainties involved in any structural design. Many codes or specifications infer so called factors of safety of 1.2 or 1.5 in selection of design stresses; these are factors of ignorance and do not define "safety," but only specify an intent to develop a design method which keeps the probability of failure to a relatively low value.

Though most standard specifications require tensile test data, the properties measured are not generally indicative of an inherent mechanical resistance for the specific service condition. The widespread use of standard tensile tests is useful only as a routine check of the relative quality of different lots of a given material; the test data serve as an index of batch to batch variability of the material. One can only determine whether the data for the batch received is approximately the same as those for previous batches that performed more or less satisfactory in service. There is no assurance that a new material having the same (or even better) tensile strength than that satisfactory in the past will guarantee satisfactory service performance. A striking example was evident in the drastic failure of the heat treated wire used some years ago for construction of the Mount Hope and Ambassador suspension bridges. By all standard laboratory tension tests the heat treated wire showed tensile strength and routine qualities somewhat better than those of cold drawn wire that was the standard type previously used. During erection of these two bridges many wire strands had broken in each bridge before the service loads were applied; it became necessary to dismantle and replace the suspension cables with the old type cold drawn wire (30).

For each foreseeable mode of failure there are only a few significant material parameters of technical interest that must be determined for selection of an optimum material; these are the specific material strength characteristics that quantitatively measure the nearness to structural damage in the failure mode. In some instances a trade-off will need to be made between characteristics such as cost, fabricability, availability, weight, etc. before the final selection is made. The problem then becomes one of securing additional information on the variability of material properties that control the significant behavior (that is, to evaluate these quantitatively to appraise the batch to batch variation and minimum acceptable values for purposes of setting design stresses). In applications where deterioration may be a major factor, additional simulated service testing is necessary as insurance against occurrences of failures such as hydrogen embrittlement, corrosion fatigue failure, diffusion of foreign atoms at high temperature, etc. For example, Fig. 14 suggests that "stainless" steel may not be immune to stress corrosion cracking. The most troublesome areas of material selection are those related to mechanical behavior in which the properties and resistance are influenced by the effect of time of application such as in resistance to creep, corrosion, wear, etc. These applications still require a great deal of judgment in the interpretation of laboratory test data and their extrapolation to long periods of time in service. Unexpected environmental conditions may arise to cause failure as shown in Figs. 16 and 17. Caution must be used to recognize that in some environmental conditions the material properties may change and the specific material resistance be altered by the time and the relative dosage of exposure in service.

SIMULATED SERVICE TESTING

Many of the so-called "standard properties" (such as tensile strength, fatigue limit, etc.) reported from laboratory tests or handbooks do not of themselves have real significance in measuring the fundamental resistance of the material in an actual complex component in service. For this reason simulated service testing has become an important facet of industrial development of all kinds of mechanical equipment. Investigations may be conducted on individual parts or assemblies and frequently service performance measurements are made in an actual field operation. In either event, it is particularly important to include all factors of service loadings: time, temperature, environment, prior processing operations, strain history in critical zones, interface effects at surfaces of the component, and other conditions that may affect its functional operation in actual service. Since this is difficult (if not impossible in some instances) the results must be interpreted with caution particularly in those instances where service induced defects and deterioration with time may become a major cause of failure. For example, if creep at high temperatures or corrosion are expected in service, the lifetime performance cannot be simulated quantitatively by any simple accelerated testing technique. Furthermore, if simultaneous repeated loading is a factor the interactions affecting the fatigue strength must be taken into consideration. Acceleration of the testing procedure by higher frequencies of load application will accelerate the cyclic fatigue effects but do not give sufficient time for true representation of creep or corrosion effects which are time dependent. Conversely, if one accelerates the creep effects by increasing the temperature, there is danger of induced metallurgical changes and over-emphasis on creep that will not give a true representation of the interplay between creep, fatigue, and corrosive effects that occur during the normal service life of the component.

Even without the complicating effects of corrosion or high temperatures, it is known that overload testing is frequently misleading. Overloading may disperse or readjust residual stresses by yielding or redistributing the peak stresses in a complex redundant structure. The beneficial effect of shot peening on leaf springs is well known; but in a reversed bending test it would not show up as well because the compressive residual stresses would be reduced by yielding when subjected to high reversed stresses. As indicated in Fig. 15 no improvement in fatigue life was caused by shot peening when heavy overloads were employed but substantial increases in fatigue life were obtained when tested at nominal operating stresses.

In general, accelerated testing of a part is frequently found necessary to produce failure within a limited period of time. This usually requires the application of excessive loads not usually expected to be encountered in service. Such tests are open to suspicion since the relative trends observed in comparing two materials (or two alternate designs) might be reversed if tests are repeated at lower load levels. For example, in fatigue the S-N curves may cross at levels just above the normal operating stress levels. Thus, wherever feasible, it is desirable to retain loading conditions as near as possible to those expected in service.

As a guide in deciding whether a specific group of simulated service studies should be conducted, the following might be set up as a preliminary criteria:

1. Are the data to be obtained from the experiment going to be significant and interpretable in terms of real physical behavior?

2. Will the results and knowledge gained be useful in terms of interpreting the significant structural resistance in engineering application of the part?

While these questions seem obvious, there are many subtle factors that make it difficult to give a yes or no answer. For example, since the methods used in processing the specimen have a vital influence in controlling the mechanical resistance, the data obtained need to be carefully interpreted in terms of these variables. Any change in production and operating conditions from those existing in the laboratory sample would be expected to give a different performance in a machine component in service. These differences often cannot be quantitatively predicted. If the experiment can faithfully reproduce service conditions of the finished part, data of engineering significance are obtainable. This is difficult in complex parts of the type shown in Fig. 18. The failures obtained must closely simulate the failures observed or expected in service before true simulation of the service condition is achieved.

Intelligent use of experimental methods may enable the engineer to improve the design or to settle other important questions within the following general scope:

1. To evaluate important unknown quantities such as service load, pressures, temperatures, dynamic behavior, or fatigue life in cases for which only limited data are available.

2. To appraise the adequacy of a design by performance testing or to study alternate design details to decrease fabrication, material, or production costs while maintaining optimum structural integrity.

3. To check assumptions used in the design procedure by measurements of actual behavior (such as vibrations, localized strains, temperature gradients, buckling strength, etc.) in the actual physical structure.

That is, tests of full size parts are particularly useful for the following purposes: (a) revealing serious stress concentrations; (b) comparing alternate designs; (c) appraising different fabrication procedures, or locating fabrication defects; (d) accumulating service data for predicting safe or economic life; or (e) obtaining information on actual structural behavior in service for redesign of individual parts.

It is impossible to build a practical machine without the presence of some stress raisers. On the other hand, the localized recesses, notches, fillets, holes, crack-like flaws, etc. become the significant controlling factors in brittle fracture or in strength of parts subjected to repeated loading. It is certainly undesirable to design parts with unnecessary stress-raisers as shown in Fig. 19. Even at elevated temperatures (for which creep is the predominant mode of failure) stress raisers may still play an important part in localizing the fracture to narrow zones of high strain.

All too frequently, the failure of a part in service is taken as evidence of the necessity for a "test" without sufficient information (or a detailed failure analysis) regarding the immediate conditions which led to the failure. A hastily planned series of tests usually results in the discovery that the data obtained do not contribute any significant knowledge of the factors which led to the failure. As a requisite for success, one must decide in advance what he wants to know and plan the instrumentation and observations to measure the significant structural action associated with the service condition.

In contemplating the history of a component in service one must be alert to possible modifications to the material due to wear, abnormal operation or improper maintenance and repair. For example, Fig. 24 shows a fatigue failure initiated by inadequate lubrication and Fig. 21 a fracture due to a minor gouge developed during routine maintenance. Some types of rebuilding after excess wear may also lead to fracture as shown by the fatigue failure in Fig. 25.

"PROOF" TESTING

Various procedures of proof testing of pressure vessels, piping, etc. are widely used throughout industry, but the interpretation and significance of these "overloads" are little understood. A proof test is not really a quality assurance test; rather, it is an overall inspection test to determine whether gross defects exist that might cause failure on the first loading or which may cause flaws to be enlarged to permit detection. It gives inspectors the opportunity of searching for flaws that have extended to detectable size during the overloading. The fact that the component withstood an overload needs to be carefully interpreted and regarded with skepticism. The significance depends upon the type of intended service condition; whether the loads are to be static or repeated, the temperatures of operation, the time in service, and the relative ductility and toughness of the material.

Every structure contains small flaws whose size and distribution are dependent upon the material and its processing (see, for example, Figs. 4, 6, 19, 20, and 23). These may range from non-metallic inclusions and microvoids to weld defects, grinding cracks, quench cracks, surface laps, etc. Because of high local concentration of stress, a proof test will extend existing flaws and develop plastically deformed microscopic zones of metal surrounding the tips of the more serious flaws (providing the material has sufficient toughness to resist catastrophic fracture). When dealing with high strength steels,[2, 3] brittle fracture will occur if the flaws are extended to a sufficient or "critical" size as illustrated in Fig. 20. For tougher materials or higher temperatures, the tendency is for flaw extension and blunting of the flaw without catstrophic fracture. In either case, the lack of obvious fracture in the proof test gives only partial assurance that it would withstand the same load a second time. In some instances a service induced defect may provide a flaw and embrittle metal to cause failure (see Fig. 21).

Unfortunately, the plastic deformations that occur in localized zones of peak strain during proof testing use up some of the (local) available ductility that is necessary to resist failure in low-cycle (high-strain range) fatigue conditions. Any repetitions of the proof testing cycle will reduce the normal cyclic operational life of the vessel because of this depletion of available local ductility. Proof testing more than once provides no additional useful information and thus has a deleterious effect on flaw growth and on the impact strength or fatigue life. The localized extension of flaws is accelerated on each subsequent proof cycle, though the gross amount of plastic strain that might be observed with the usual strain gage instrumentation might actually decrease in a cyclic strain-hardening material for each subsequent load repetition.[14] What is significant, however, is that micro-extension by slow and cyclic flaw growth is occurring on a scale that cannot readily be measured with the use of conventional instrumentation.

Since the critical flaw size will decrease at low temperatures, proof testing at room temperature does not guarantee against catastrophic brittle fracture for parts that must operate at low temperatures. Also, proof testing at or below the "nil-ductility temperature" invites a catastrophic fracture initiating from very small (but critical size) flaws. Prescribing proof pressures by the use of ratios of tensile strength or of yield strength at the proof temperature versus the operating temperature is not an appropriate method of giving any assurance against brittle fracture at a lower operating temperature. For members subjected to severe repeated loading, the assumption must be made that every repetition of loading will extend existing flaws; a proof test does not correlate with or give any assurance against failure in this type of service. Agglomerations of inclusions are "flaws" that can be propagated to failure as illustrated in Figs. 22 and 23.

Care must be taken in setting a proof pressure at a value which will not cause excessive plastic deformation.[2, 3] The material ductility and toughness are reduced by large localized deformations, and the resulting distortions may change functional behavior of the component as well as increase existing flaw sizes. The determination of what is excessive deformation depends upon the material ductility, the function of the component, and the types of loading cycles expected in normal service. Localized plastic deformations in a highly ductile material develop favorable redistribution of stress but prove harmful if the material has limited ductility or if it cyclically strain-softens, thus concentrating further localized cyclic strains in the critical zone.

SUMMARY

The emphasis in recent years in the aircraft and missile industry has been placed upon a continuing search for structural materials with high static strength in order to achieve minimum weight. The premature adoption of some of these exotic materials, however, has resulted in a number of embarrassing failures because high static strength does not necessarily insure improved performance and, in fact, may make a part more susceptible to brittle fracture, stress corrosion cracking, and other modes of failure. For this reason a philosophy of design based on concepts presented in Table I needs to be considered with added emphasis on better methods of analysis of performance in fatigue, widespread adoption of fracture mechanics methods of prescribing toughness characteristics and maximum tolerable sizes of flaws. There will continue to be a need for simulated service testing and lengthy prototype evaluations after completion of final fabrication operations on early production models. I hope I have re-emphasized to each of you the necessity of careful evaluation of changes in mechanical properties caused by fabrication processes and the needs for improvement in design concepts. Great care and better methods are needed for appraising the resistance of materials to the environmental conditions of operation that lead to modes of failure such as fretting, hydrogen embrittlement, or slow flaw growth. A broader outlook of the designer and project director in the development of complex equipment is necessary to supplement standardized codes and specifications to provide sound utilization of materials. A comprehensive analysis based on the prevention of all modes of failure under the foreseeable circumstances in future service must be the basis for prediction of the safe and satisfactory performance of the product with a high degree of confidence.

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REFERENCES

1. "The Lawyers Desk Reference," D. A. Robb & H. Philo, Lawyers Co-op Pub. Co., Rochester, N. Y., 1966.

2. Reports of Special ASTM Committee E-24 on Fracture Testing of Metallic Materials: First Report - "Fracture Testing of High-Strength Sheet Materials: A Report of A Special ASTM Committee," ASTM Bulletin, January,1960, pp. 29-40; No. 244, February,1960, pp. 18-28. See also subsequent reports in Materials Research & Standards, May,1961, pp. 389-393; November, 1961, pp. 877-885; and March, 1964, pp. 107-118.

3. "Fracture Toughness Testing and Its Applications," ASTM STP 381, 1965. See also: ASTM STP 410, 1967.

4. "Control of Steel Construction to Avoid Brittle Failure," Plasticity Committee, Welding Research Council, 1957.

5. "Brittle Failure in Carbon Plate Steel Structures Other than Ships," M. E. Shank, Welding Research Council Bulletin Series No. 17, January, 1954.

6. "Effects of Repeated Loading and Moisture on the Fracture Toughness of S.A.E. 4340 Steel," W. A. Van Der Sluys, Trans. ASME, Series D, June 1965, p. 363.

7. "Fracture of Engineering Materials," Am. Soc. Metals, September, 1964.

8. "Investigation of Hydrotest Failure of Thiokol Chemical Corporation 260-in.-Diameter SL-1 Motor Case," J. E. Srawley & J. B. Esgar, NASA TMX-1194, January, 1966.

9. "The Influence of Corrosion on the Cracking of Pressure Vessels," H. R. Copson, Welding Journal, Res. Supp., February, 1953, p. 75.

10. "Simultaneous Effects of Corrosion and Abrupt Changes in Section on the Fatigue Strength of Steel," T. J. Dolan, Jour. Appl. Mech. (ASME), December, 1938, p. A-141.

11. "High Pressure Testing - Pipeline Defect Behavior and Pressure Reversals," ASME preprint 68-PET-24, 1968.

12. "The Failure of a Welded Drying Drum by Caustic Embrittlement," George Sines & E. C. McLean, Mechanical Engineering, December, 1956, pp. 1105-1109.

13. "Stress-Corrosion Cracking of Type 304 Austenitic Stainless Steel," H. L. Logan & R. J. Sherman Jr., The Welding Journal Research Supplement, August, 1956, 8 pp.

14. "Nonlinear Response Under Cyclic Loading Conditions," T. J. Dolan, Proceedings, 9th Midwest Mechanics Conference, Madison, Wisconsin, August, 1965.

15. "Cyclic Plastic Strain Energy and Fatigue of Metals," J. Morrow, ASTM STP 378, 1965.

16. ASTM Jour. of Materials, Vol. 4, No. 1, March, 1969, contains four articles on low cycle fatigue, cyclic stress-strain behavior, and the influence of notches (Principal authors: Morrow, Landgraf, Topper, Wetzel).

17. "Design of Pressure Vessels for Low-Cycle Fatigue," B. F. Langer, Paper 61-WA-18 ASME, 1961.

18. "Fractographic Methods in Fatigue Research," G. Jacoby, "Experimental Mechanics, March, 1965, p. 1-17.

19. "A Photographic Study of the Origin and Development of Fatigue Fractures in Aircraft Structures," Jennifer Longson, Report Structures 267, Royal Aircraft Establishment, Ministry of Aviation, London, March, 1961.

20. "Studies of the Fatigue Strength of Pressure Vessels," S. C. Grigory, Southwest Research Foundation, Technical Summary Report SwRI 03-1384, "Fracture Tests of One-Half Scale Model Pressure Vessels," April, 1968, 134 pp.

21. "Failure Analysis of PVRC Vessel No. 5," Welding Research Council, Bulletin No. 98, August, 1964.

22. "Civil Aircraft Accident. Report of the Court of Inquiry into the Accidents to the Comet G," Her Majesty's Stationery Office, London, 1955. See also "Fatigue and the Comet Disasters," by T. Bishop, Metal Progress, May, 1955, p. 79.

23. "Lessons to be Learnt from Failures in Service," G. A. Cottell, International Conference on Fatigue of Metals, ASME-IME, Session 7, Paper 1, 1956.

24. "How Components Fail," D. J. Wulpi, Am. Soc. Metals, 1966.

25. "Mechanical Failures of Metals in Service," J. A. Bennett and G. W. Quick, Natl. Bureau of Standards, Circular 550, 1954.

26. "The Interpretation of a Failure of an Ordnance Structure," G. F. Jenks, presented at the Annual Meeting of ASME, December, 1939, 6 pp.

27. "Results of the Survey of the Study Group on Oil Storage-Tank Failures," Carl H. Samans, API Proc. Section III, Vol. 34, 1954, pp. 143-163.

28. "Technical Report," Vols. IV to VIII, 1965 to 1969, British Engine, Boiler and Electrical Insurance Company, Manchester, England.

29. "The Use of Overstressing Techniques to Reduce the Risk of Subsequent Brittle Fracture," R. W. Nichols, British Welding Journal, Jan., 1968, p. 21 and Feb., 1968, p. 75.

30. "Investigation of Cold Drawn Bridge Wire," L. S. Moisseiff, ASTM Proc., Vol. 30, 1930, p. 313.

31. "Effect of Shot Blasting on Physical Properties of Steel," R. L. Mattson and J. O. Almen, Final Report OSRD 3274, 4825, 6647; Washington, 1945.

TABLE 1

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

MODE OF FAILURE	LOADING MODE: Static	LOADING MODE: Repeated	LOADING MODE: Impact	STRESS TYPE: Tension	STRESS TYPE: Compression	STRESS TYPE: Shear	OPERATING TEMPERATURE: Low	OPERATING TEMPERATURE: Room Temp.	OPERATING TEMPERATURE: High	MATERIAL TYPE: Brittle	MATERIAL TYPE: Ductile	SIGNIFICANT MECHANICAL RESISTANCE OF THE MATERIAL MEASURED BY:
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_{1scc} measurements.

* Items strongly dependent upon elapsed time.

TABLE II. FAILURE DUE TO PROCESSING METHODS OR TO DETERIORATION

I.	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.
2.	Thermal	Heat treating Welding, brazing, etc.	
3.	Chemical	Processing base material Cleaning Plating Chemical coatings	

III.	Deterioration:	Each specific environment or operation needs unique analysis of the significant structural action that limits the usefulness in the service intended.
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.

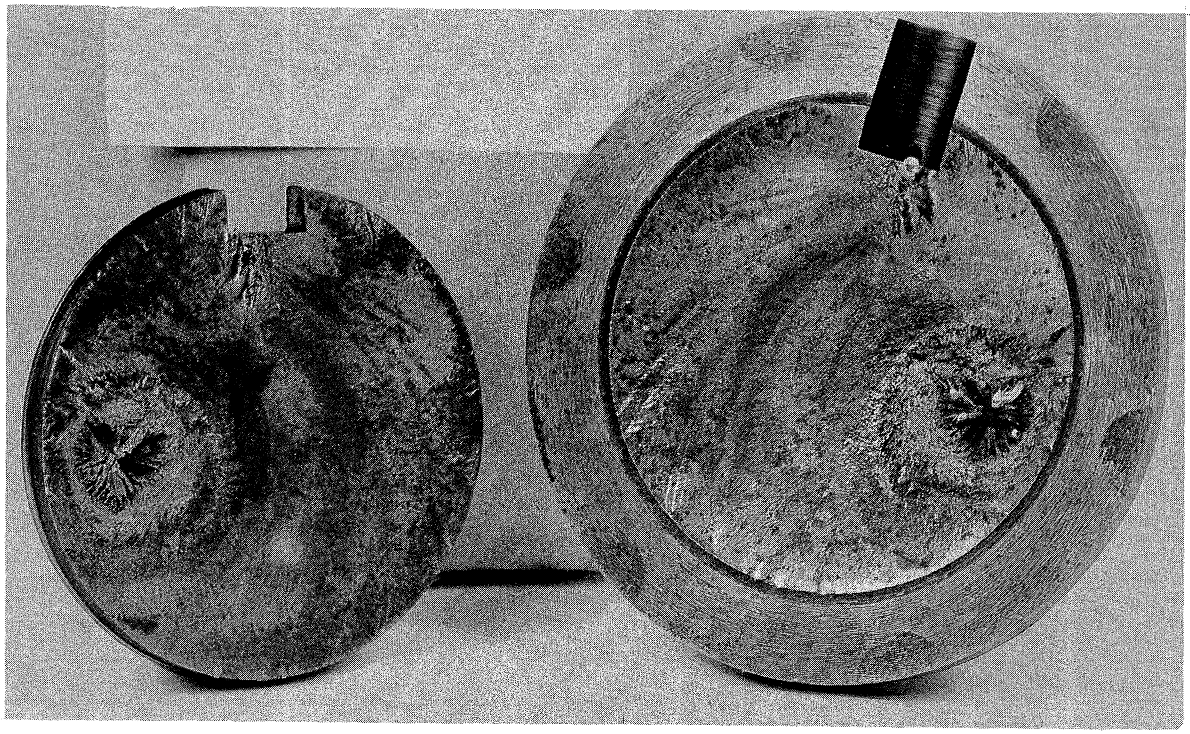

Fig. 1 Fracture Surfaces of Shaft in Rotating Bending Resulting from Poor Design Detail. (AISI 1046 Heat Treated to Rockwell C25)

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.

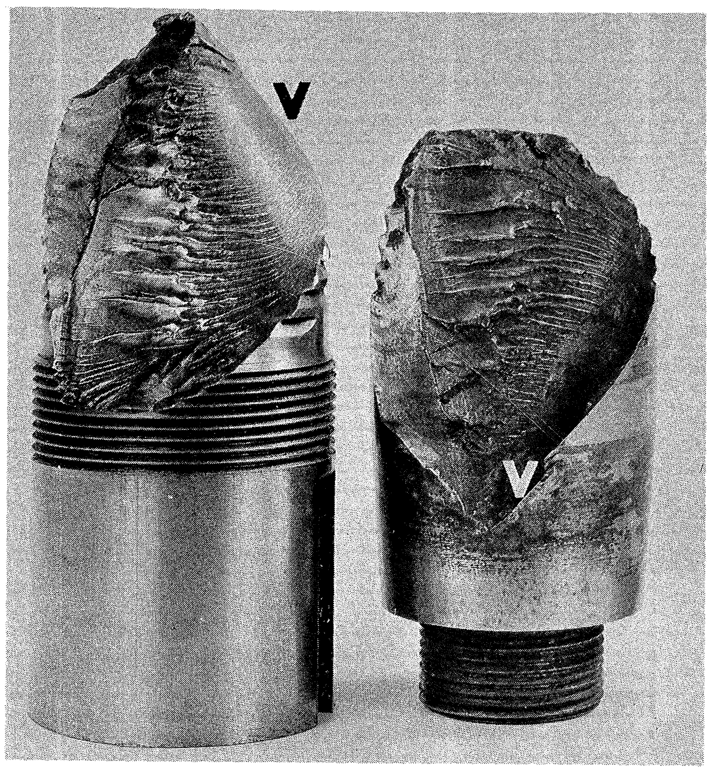

Fig. 2 Torsional Fatigue Failure at Front End of Crank Shaft.

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)

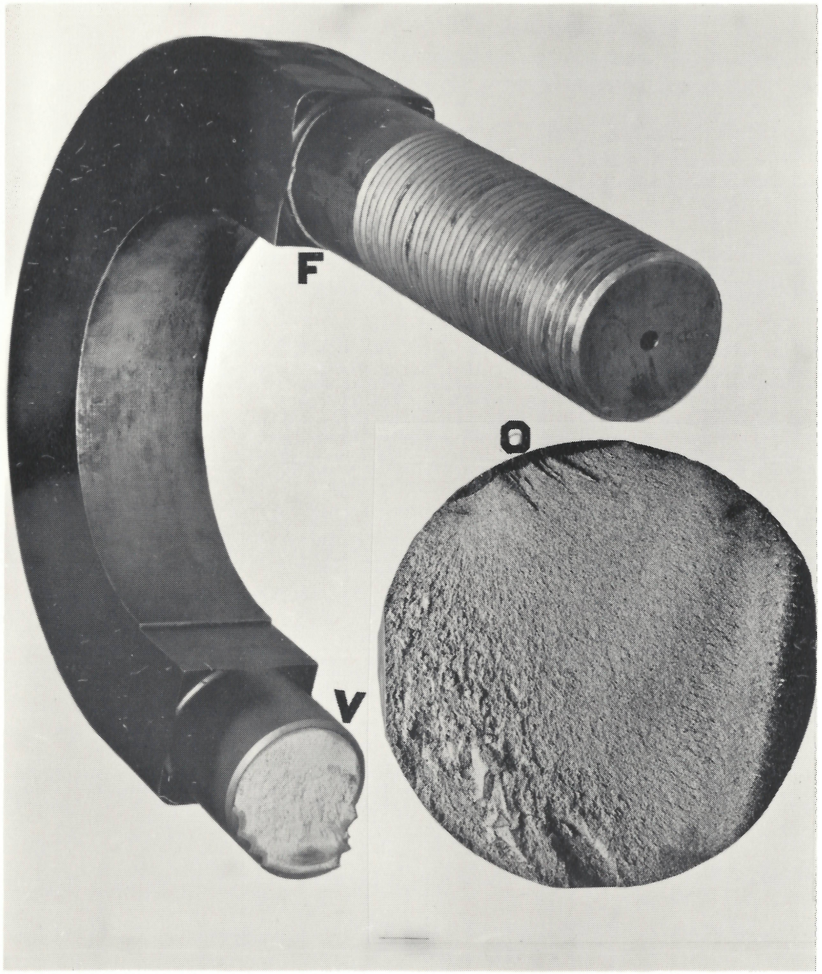

Fig. 3 Pulling Yoke of High Strength SAE 4340 Steel Fractured at a Stress of Only 30,000 psi.

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, Ref. 25)

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.

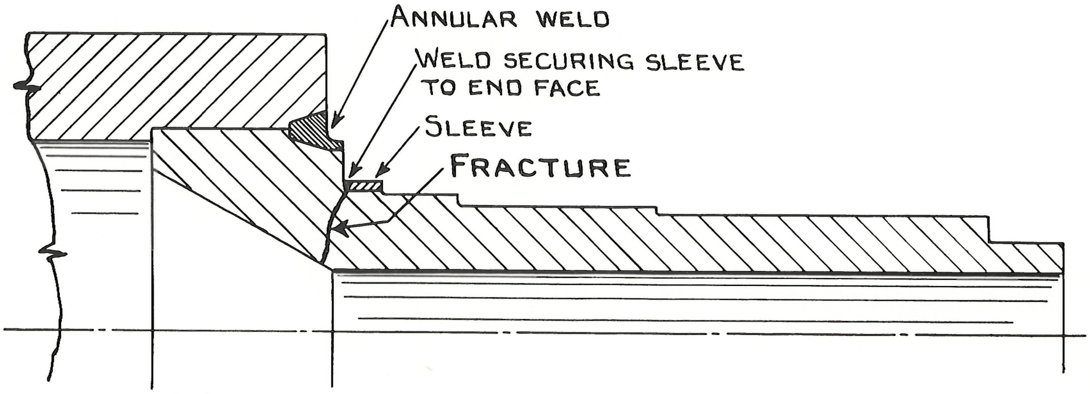

Fig. 5 Failure of a Steam Heated Roll Caused by Welding on Repair Sleeve.

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.

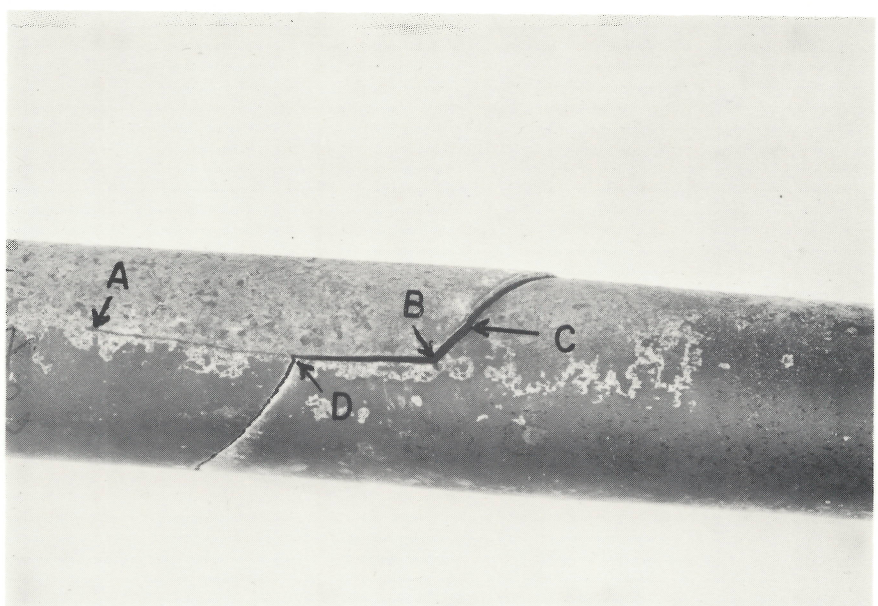

Fig. 6 Fracture of Torsion Bar from Highway Bus. (Steel Heat Treated to Tensile Strength of about 200,000 psi)

Stringers of oxide inclusions initiated fatigue crack on longitudinal shear plane AB; later developed diagonal tensile fatigue failures C and D.

(Courtesy of J.A. Bennett, Ref. 25)

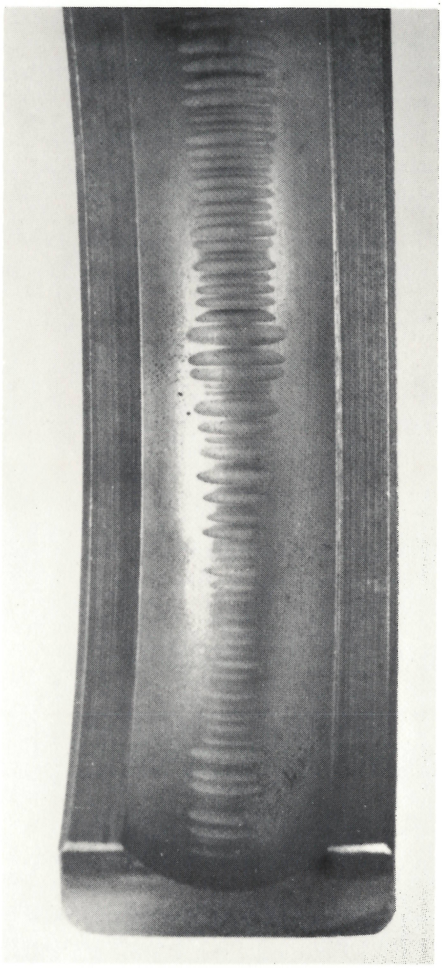

Fig. 7 Unusal Fluting in Outer Race of Ball Bearing.
Failure peculiar to rotating electrical machinery as the result of passage of current (or local sparking) through the bearing from defective insulation or induction effects. (28)

Fig. 8 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. (28)

Fig. 9 Brittle Failure of a Crane Hook Initiated at a Pre-Existing Defect. (28)
(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. (28)

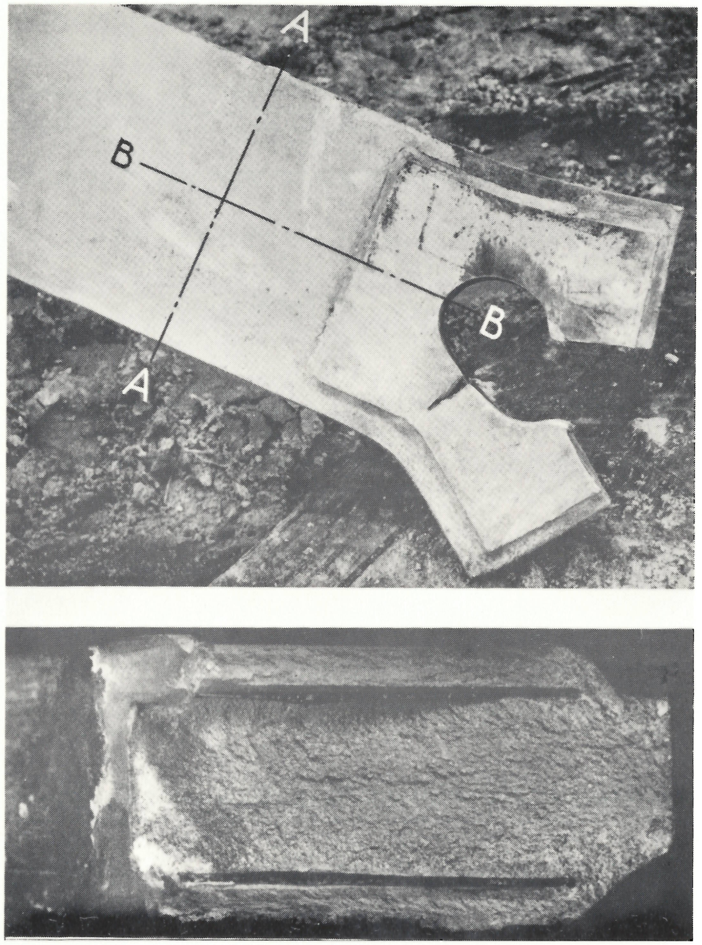

Fig. 11 Failure of Jib Tie-Bar of Tower Crane

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. (28)

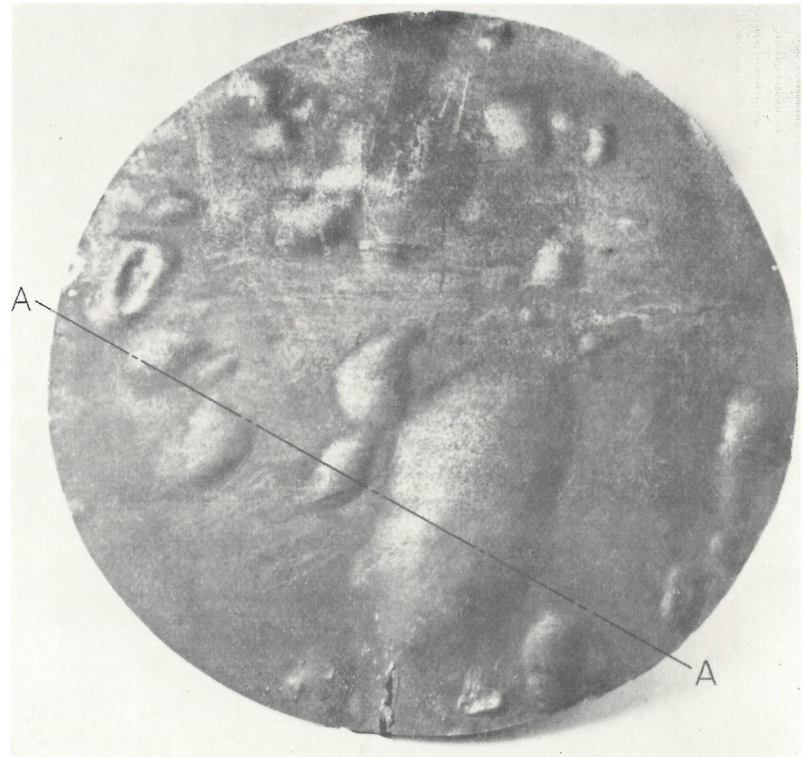

Fig. 12 Blistering Due to Hydrogen Occlusion in Tank for Transport of Concentrated Sulphuric Acid.

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. (28)

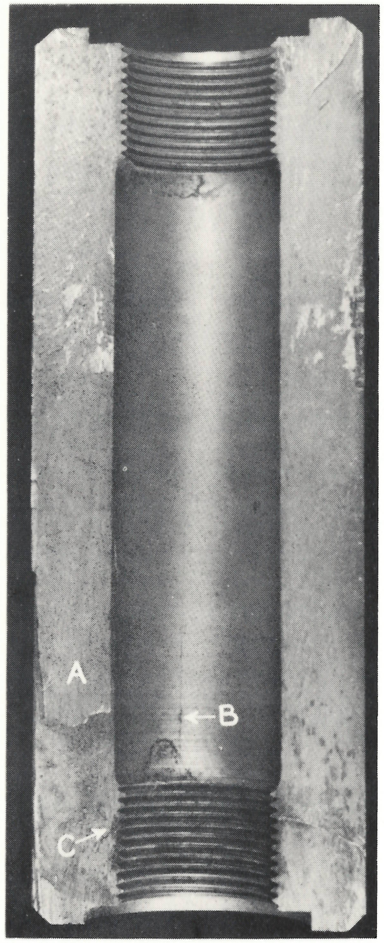

Fig. 13 Brittle Fracture of Stainless Steel Pressure Vessel.
Corrosion and intergranular cracking initiated at thread root "C" due to contact with bronze nut. After some 400 pressurizations to 9000 psi a small fatigue crack initiated from zone C and failure then occurred in a brittle manner across the 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. (28)

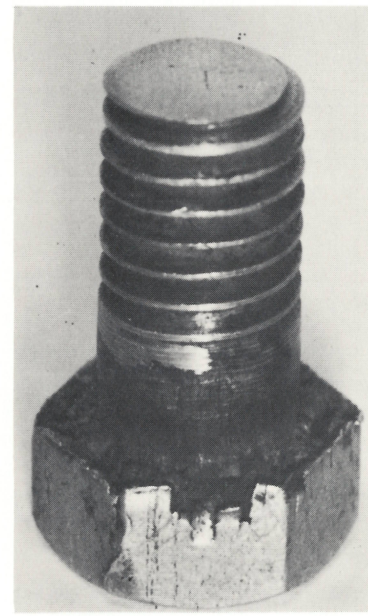

Fig. 14 Stress Corrosion Cracks in an Unstabilized Grade of Stainless Steel.
Bolt had brass washer; operated under marine conditions. Though corrosion resistant, many types of stress corrosion cracking and embrittlement may be caused by: (a) concentrations of various salts, (b) crevices or other surface adherents that shield the steel from oxygen in local zones, (c) certain acids etc. Fouling by marine organisms can cause an acid reaction of exceptionally severe nature in sea water. (28)

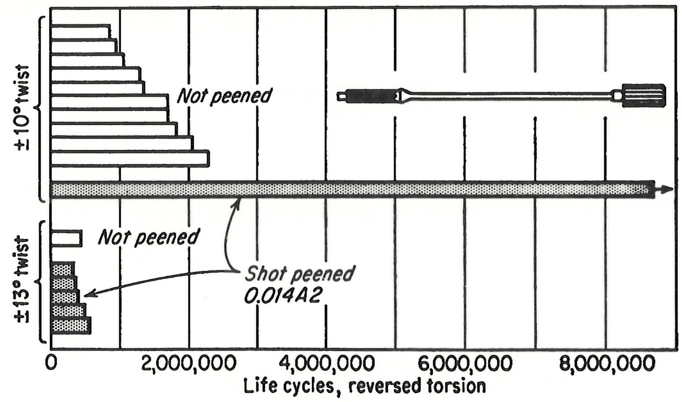

Fig. 15 Severe Overload Testing can be Misleading.
SAE 6150 steel at Rockwell C-34 to C-38. At nominal operating loads shot peened shafts show significant improvement in fatigue life. At high overloads this beneficial effect of compressive residual stress is masked out by yielding and redistribution of stress under reversed loading. (31)

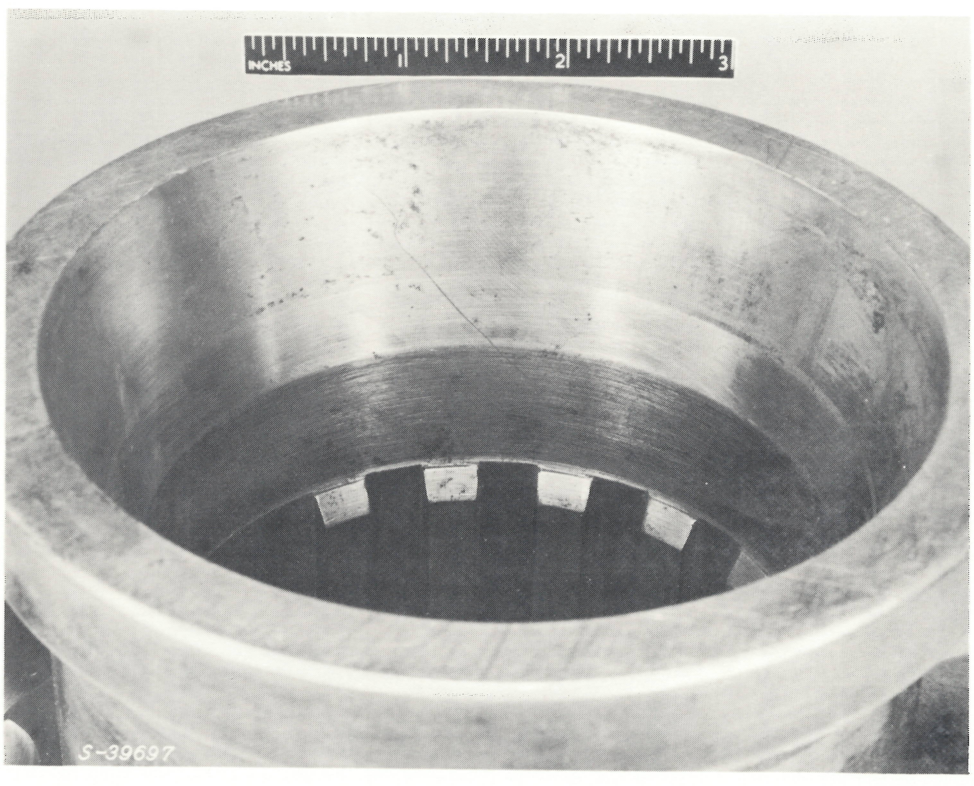

Fig. 16 Corrosion Fatigue Failure of Special Shaft of AMS 6415 at Rockwell C-45-49.
Complex combined loadings resulted in fatigue cracks nucleated by small pits.

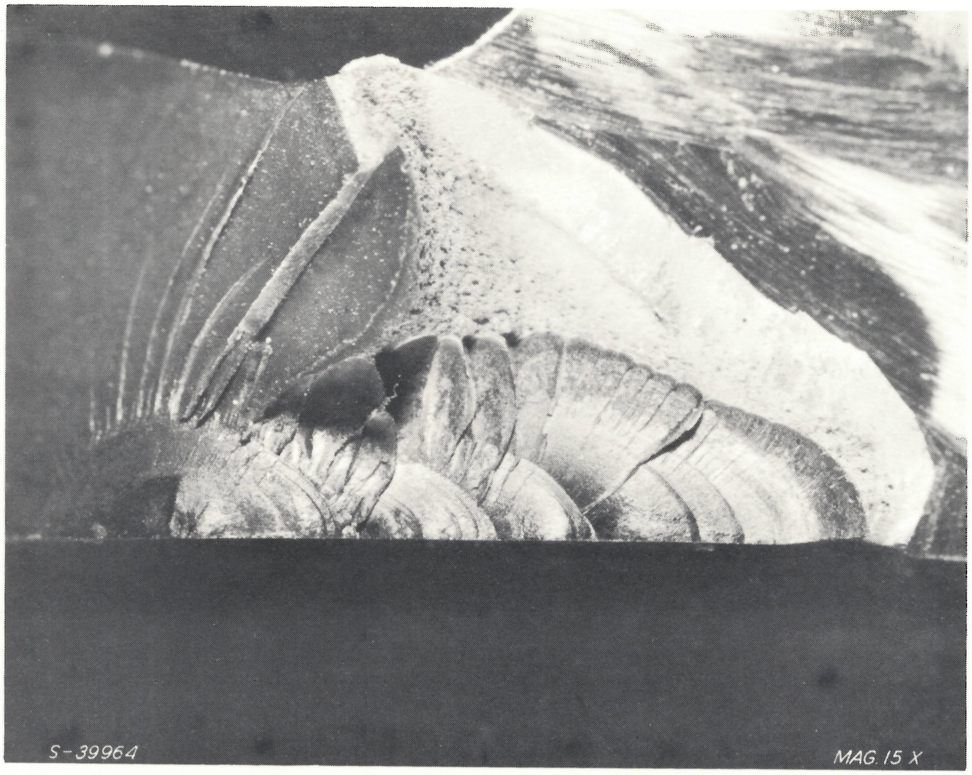

Fig. 17 Enlarged View of Multiple Fatigue Cracks Developing from Corrosion Fatigue Pits caused by Contaminated Oil on the Shaft Shown in Fig. 16.

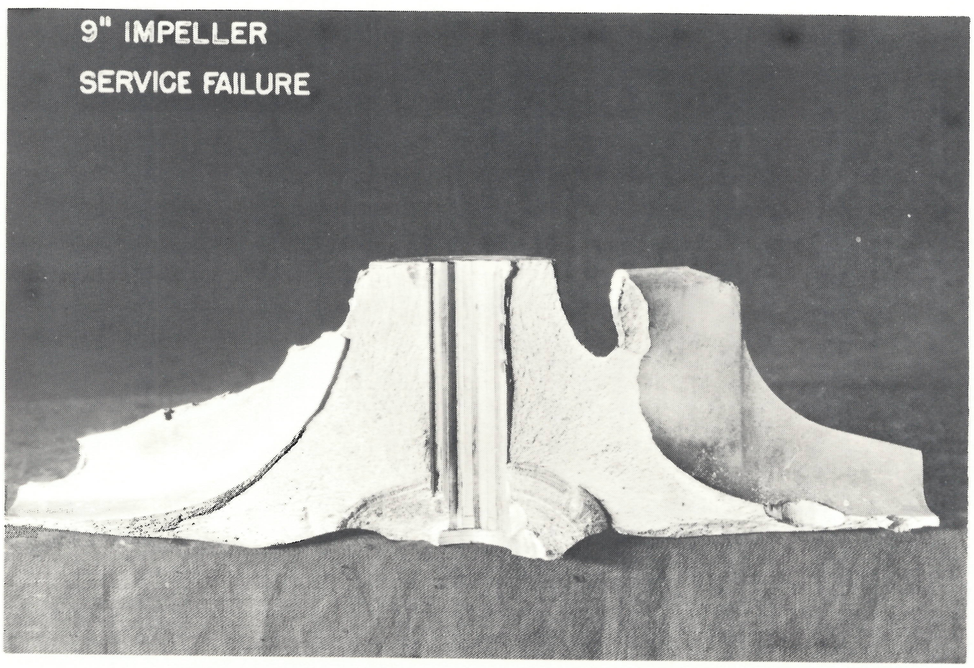

Fig. 18 Failure of Die-Forged Super Charger Driven Through a Splined Shaft.

Exhaust impulses led to torsional vibrations causing fatigue crack which developed to critical size for brittle fracture of the rest of the impeller.

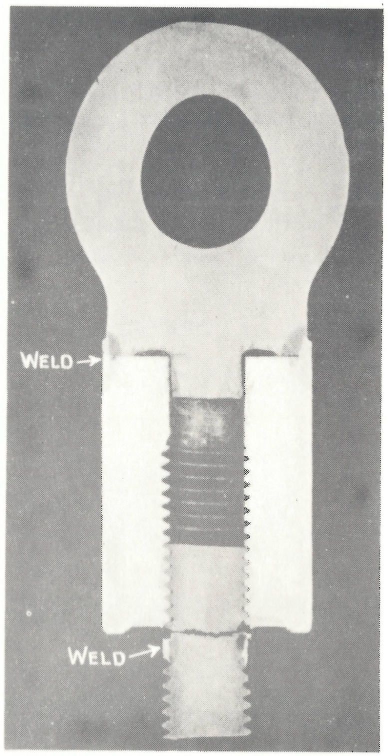

Fig. 19 Etched Section Through Special "Eye-Bolt" Showing Method of Construction.

Fracture initiated at cracks in the heat-affected zones in the region of the weld. Small runs of weld on heavy masses of high strength metals require extreme precautions in processing to prevent development of excess residual stress, unfavorable metallurgy, and micro-cracking around the weld zones.

Fig. 20 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.

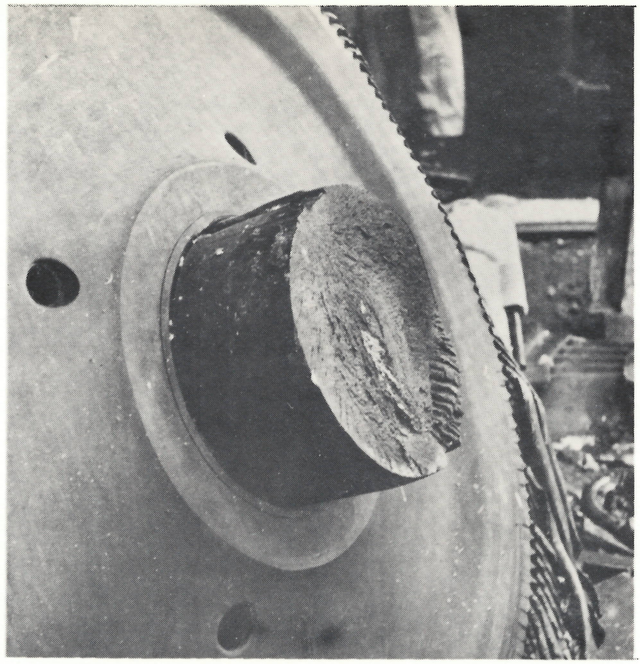

Fig. 21 Brittle Fracture of Steam Turbine Rotor Shaft.

Failure initiated from score mark on the surface developed during re-assembly after maintenance. Severe local deformation accompanied by superficial tearing and subsequent aging of the cold worked surface embrittled the steel in the local zone and initiated a flaw which resulted in complete fracture of the shaft during the overspeed test. (28)

Fig. 22 Fatigue Failure of Complex Type in Crankshaft Initiating from Subsurface Inclusions.

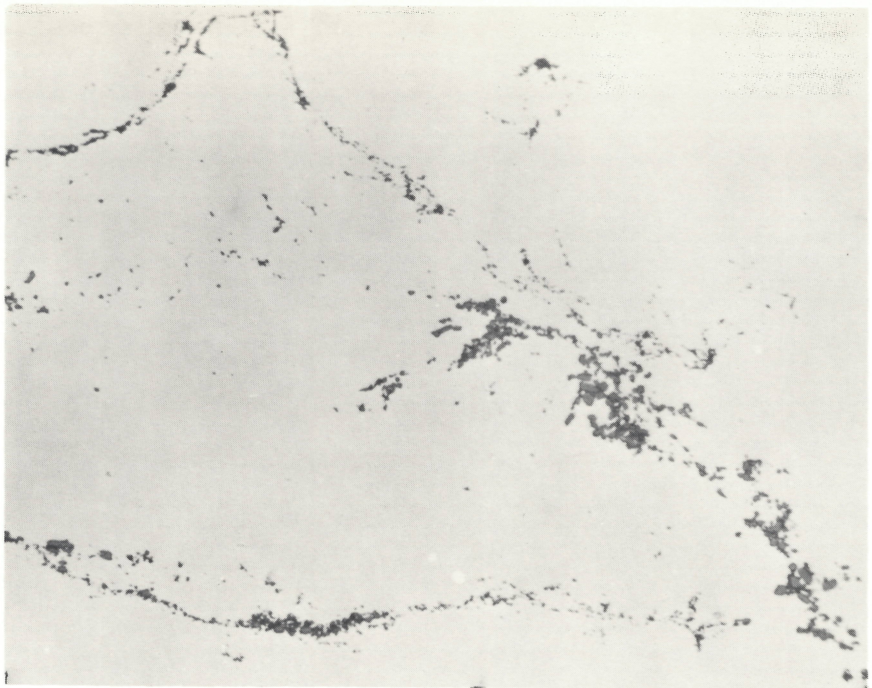

Fig. 23 Cross Section Near Fracture Origin of Crankshaft in Fig. 22 Showing Small Portion of Inclusion Concentration and the Striated or Laminar Nature of these Non-Metallic Inclusions. Magnification 100X

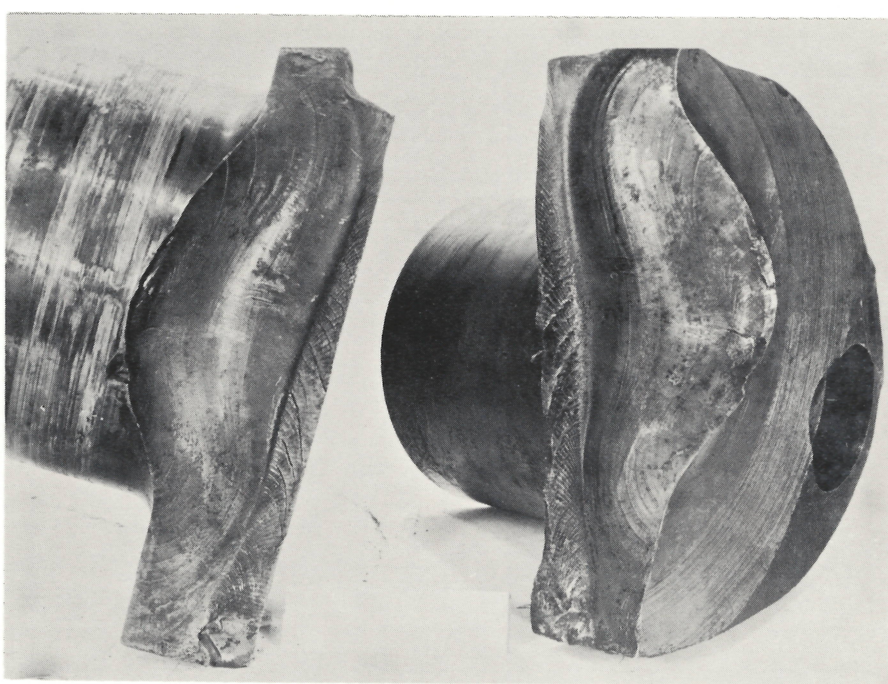

Fig. 24 Bending Fatigue Failure of Diesel Engine Crankshaft Resulting from Service Induced Damage.
Note that failure initiated at deep score or seizing marks in the crank pin and propagated across crank cheek.

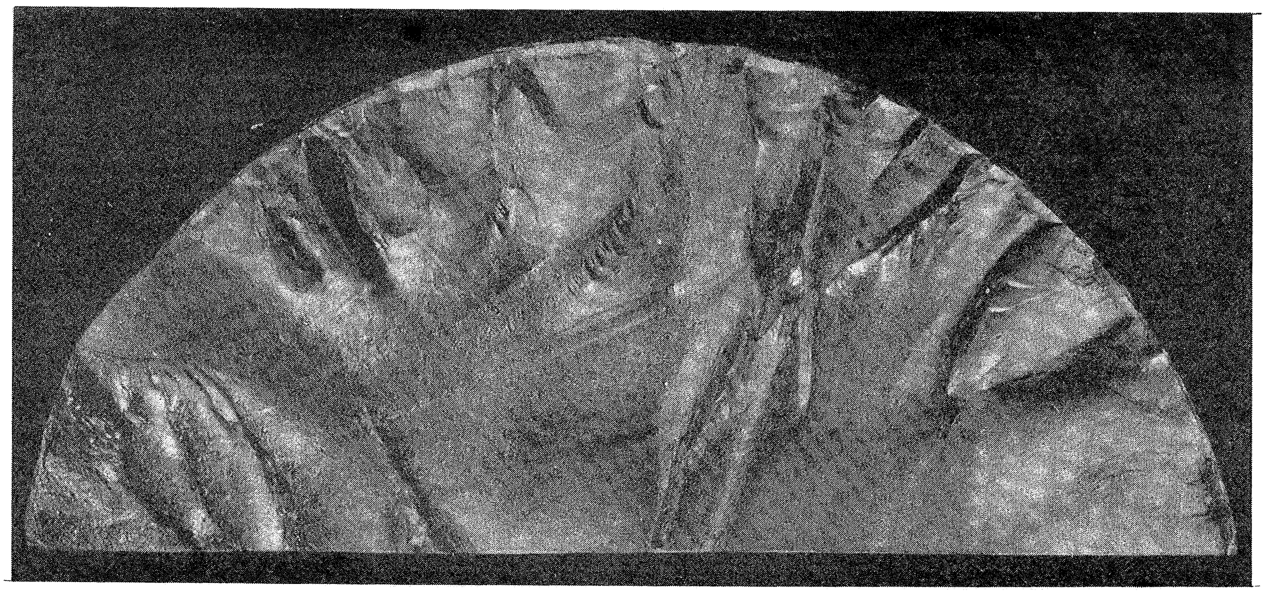

Fig. 25 Multiple Fatigue Crack Origins Around the Circumference of a Diesel Engine Crankshaft.

Worn crankpin had been built up by welding and remachining; multiple failure nuclei from various weld beads. (28)