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"PREDICTIVE TESTING OF METALLIC PARTS"

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ABSTRACT

Safety and reliability of a product must be demonstrated by carefully planned studies before releasing items for sale. Detailed evaluation (both analytically and experimentally) must verify materials selection, design details, and adequacy of processing and fabrication. Accurate simulation of environment, loading history, deterioration, and life performance present many difficulties, but extensive laboratory and field testing can pay good dividends in avoiding later field modifications or costly replacements. Some of the problems of accelerated testing and life predictions are emphasized, including the necessity of foreseeing reasonably possible misuse or abuse of the product by the customer. Statistical variations in loads and operating conditions emphasize the need for interpretation of results on a probabilistic basis.

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INTRODUCTION

Quantitative prediction of the safety and reliability of a product is essential before releasing mechanical equipment for sale in today's markets. Studies must be conducted to evaluate the resistance of every component of the product to all possible modes of failure. Only through a detailed evaluation in carefully planned tests may verification be made of the proper materials selection, the adequacy of design details and the appropriateness of the processing and fabrication. In addition, it is necessary to measure the performance in abnormal but reasonably foreseeable service conditions in a simulated service test to evaluate the loading history and environmental conditions of the field service in which it will operate. Of particular importance is a study of the influence of processing and fabrication in altering the materials properties, and the adequacy of the design contours, fastening details, etc. For example, fracture of the fan, Fig. 1, illustrates fatigue failures due to a combination of circumstances involving interaction of design, fabrication and service conditions.

Hastily planned tests usually result in discovery that the data do not contribute significant knowledge of the factors which caused the failure. Careful selection of the environment, instrumentation, and observations must be organized to measure the significant structural action associated with the service condition. All experimental work must be supplemented by a rational analysis of the important variables to be assured that the data are realistic and interpretable.

Initial studies are frequently made to establish basic design concepts that are sound and reasonable; detailed tests should be made of critical components of the product. Finally, simulated service tests of a full scale prototype are necessary to verify design objectives, and to evaluate the influence of unknown loading, effects of differences in service environments, and operator idiosyncrasics.

Each predictive study presents the manufacturer with major technical data that must provide the information to make informed decisions (rather than rely upon intuition or guesses). Hopefully these studies will result in the development of an inspection method and modifications or monitoring procedures that will assure satisfactory service for a specified period in cases such as:

(a) estimating the reliable life of a new product

(b) predicting remaining life of a product after prolonged service

(c) evaluating the significance of a premature failure in service (23)*

Simulated service testing to study each of the factors listed in Table I is important because of the many <u>uncertainties</u> that exist with respect to:

(a) uniformity of the materials and their processing

(b) the service loads and environmental conditions

(c) correctness or accuracy of the stress formulas employed

(d) significance of the quantity selected to measure the nearness to failure

(e) non-linearities that develop between the measured loads and the significant strains, and the quantity (such as fatigue strength, toughness, chemical attack, flaw size, etc.) that really measures damage. (10) Complex conditions, such as those shown in Fig. 2, require complete simulation of the actual processing and environment in predictive testing to avoid troublesome field failures.

TEST PHILOSOPHY

Before a "standard" test method is adopted, the user should carefully consider: "Just what is it good for?" Each test may measure some "property" of the article or material, but is the user interested directly or indirectly in this property? Does he have enough experience (and analysis of the real need) to be able to interpret the results in terms of service? <u>Value</u> is measured by how well the article is adapted to the

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* Numbers in parentheses refer to references appended.

intended use; not only the nature of the article, but also the nature of the intended use must be considered. A large variety of test methods are used primarily for "plant control;" the results of these tests merely tell whether today's material or product is similar to or different from that made yesterday, but not whether today's product is better or worse.

For example, the tensile strength is sometimes thought of as being a "property" of the material, but it is primarily a control test and does not measure how well the article is adapted for the intended use. There is a tendency in industry to measure the tensile strength of every material and jump to the conclusion that the material having the highest strength is the best. However, the structural resistance of the material to the complex conditions encountered at stress raisers in different types of products (such as a rocket engine, a tractor, a gas transmission line, etc.) frequently bears no direct relation to the tensile strength. The fundamental structural action in the highly stressed zones may be quite different in each instance, and require different methods to determine the maximum utilizable "strength" of the metal under each specific environmental condition and loading.

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

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

(2) Processing and fabrication (about half of these may be due to metallurgical factors such as quench cracks, improper heat treatment, forging or casting defects, nonmetallic inclusions, etc., and the other half due to misalignment, weld flaws, improper

machining or assembly, grinding cracks, cold straightening, etc.).

(3) Environmental and service conditions (including overloads, chemical attack, wear, corrosion, embrittlement, improper maintenance, etc.).

Increased tensile strength is frequently detrimental where the potential mode of failure may be brittle fracture, low-cycle fatigue, stress-corrosion cracking, etc. (14) Materials of lower tensile strength with greater toughness may be more desirable for the application under consideration. Ductility, resistance to embrittling conditons of low temperature, or resistance to hydrogen or stress-corrosion cracking may be the important properties for the particular service intended. Failures due to excess strain in a local zone, such as that in Fig. 3 can be avoided by employing a metal with greater ductility. Except in those few cases where gross yielding may be the limiting condition for failure, the tensile strength and yield strength are not sufficient design criteria. Many engineers assume that the fatigue strength is proportional to the tensile strength. Unfortunately this is not the case except in small carefully polished laboratory specimens. The fatigue strength of "high strength" steels is disappointingly low in components containing welds, as-rolled surfaces, rough machining, or which operate in a moist environment.

In a general way, it is necessary to appreciate the arbitrary character of tests and to carefully interpret their significance. Tests employing variable and complex stresses, elevated temperatures, corrosion, erosion, etc. give only a relative measure of performance of the particular prototype or sample tested; these data are often too limited to completely qualify a new system or component for long term field service under the variable conditions in which the component will operate.

The investigator must analyze in detail and track down any correlations obtained to be assured that they are not chance effects or that he has not been guilty of over simplifications in order to obtain a level of rigor in the analysis or experiment. Do not anticipate the results before the data is in, nor neglect "contrary data" in appraising the significance of the test. Do not forget that the behavior observed is that of a single individual or sample of performance; wide variability in some instances makes it necessary to use statistical methods to plan and interpret the data.

PRINCIPAL USES OF PREDICTIVE TESTS

The material properties and peak stresses (or strains) are both portions of the general problem of estimating reliability of the product. Full-size tests of structural components cannot be interpreted in terms of material strength without a detailed experimental stress analysis of the critical zones; accurate data is essential to interpreting the significant behavior of the component. Fastenings, joints and power transmission systems are critical items that need careful evaluation in every machine or structure. Tests of alternative fastening methods are often beneficial.

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 loads, 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 and stress calculations by measurements of actual behavior (such as vibrations, localized strains, temperature gradients, buckling strength, etc.) in the actual physical structure. In some instances this may be done to prove that a former "problem" has been "fixed."

(4) To locate regions of excessive strain concentration or other indications of potential future damage.

(5) Scale model studies are useful in many instances where it may be economically unsound (or even impossible) to construct and test full scale prototypes, but more complete technical knowledge must be obtained before designs can be completed. Preliminary studies may also be made of individual components of the product.

(6) Limited life testing may involve studies of durability against fatigue fracture, accelerated wear, corrosion, etc., by increased dosage or moderate overload testing. The influence of "reasonable" abuse of the product by some customers must be anticipated.

(7) Serviceability for the job: meets the planned function, satisfactory response to load history, acceptability of materials and processing, no deterioration of major nature anticipated during normal service life.

(8) Analyse the needs for periodic maintenance, and for preparation of instruction and operation manuals.

Sometimes the results from an "overload" test such as that in Fig. 4 can be misleading since it may not be truly representative of actual service conditions and may cause failures of a type different from those in service. Further studies from time to time may be necessary to appraise the uniformity of results, to estimate the variability of the population or to handle troubles that may arise from shop operations (such as that shown in Fig. 5) when the item is mass produced.

One must determine the important parameters that are to be varied and the range over which these variables are combined in the prototype structure. The investigator must often rely upon intuition as well as objectivity to plan the experiment to encompass all important variables anticipated in service, and not allow the test to deteriorate into one of determing "standard performance." The experimental procedure gives the answer only to a particular question which must be posed by experimenter by the manner in which he compounds the environmental conditions and restraints imposed at the critical sections of the prototype. The answer obtained cannot be extrapolated or transposed beyond the conditions of operation; frequently the tests cannot be accelerated to predict long time behavior for the expected service life.

Carefully documented case histories of past failures form a valuable background from which to plan a testing program to insure against recurrance of similar failures. (The appended references 1 through 10 show many examples of failure and the associated causes).

SOME PROBLEMS OF SIMULATION

Some of the major problems that may be encountered in making predictive testing realistic, might be listed as follows:

(1) The product will, when produced in quantity, have variable physical and/or operating characteristics. It is frequently impossible, to predict in advance those changes which are a function of the variation in materials, wear of tooling, quality control procedures, etc.

(2) The effectiveness of a test may be limited somewhat by the inability to predict or to simulate all the environmental conditions to which the product will be exposed over its useful lifetime.

(3) There often is a lack of complete technical knowledge in some phases of the design and development, or a lack of insight into all foreseeable uses and abusive conditions in which the customer may operate the product.

The loading history of most mobile equipment is frequently quite random, and a statistical approach may be necessary to estimate the distribution of the loadings expected in use. Furthermore, different operators or the performance in different sectors of the country can be expected to vary over a wide range. Thus, one of the first objectives in planning a predictive test must be that of designing a realistic method of determining typical "customer duty cycles" and the expected deviations from the typical. For test purposes a rational compromise must be selected for durability predictions within the scope of the customer duty cycles. Planned overload testing must be limited to realistic approximations of the loadings imposed by severe customer service, but tests with constant amplitude overloads can be misleading (or in some cases overly conservative). (19) In general, applications of blocks of prescribed loadings with different intensitites (but applied in random sequence) are to be preferred in contrast to constant amplitude loadings from the viewpoint of estimating fatigue durability. The loading history should be representative of typical severe service and should be analyzed rationally for comparison with material strength characteristics for the life-time prediction.

It may not be possible to simulate all factors of service loading: time, temperature, environment, prior processing operations, strain history in critical zones, interface effects at surfaces of the component, etc. The predictive test must be interpreted with caution particularly 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 life-time performance cannot be accurately predicted by a simple short time testing technique. Furthermore, if simultaneous repeated loading is a factor the interactions affecting the fatigue strength must be taken into consideration. (18) Acceleration of the testing procedure by higher frequencies of load application will accelerate the <u>cyclic</u> fatigue effects, but do <u>not</u> give sufficient time for true representation of creep or corrosion effects which are <u>time</u> dependent. Conversely, if one accelerates the creep effects by increasing the temperature, there is danger of induced metallurgical changes and overemphasis 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.

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, or

(d) deterioration of properties.

A study of the fundamental material response in each mode of failure emphasizes the specific factors that must be considered in the selection of an optimum material, but other characteristics must be considered such as chemical or thermal stability, fabricability, wear resistance, ductility, etc. before optimum selection can be made of the most suitable metal or treatment, and before a satisfactory predictive test can be planned.

PROCESSING & FABRICATION

The design and materials must accomodate modifications due to processing, fabrication, improper maintenance, or repair operations that might lead to failure. Sometimes what appears to be a minor shop induced defect may cause premature failure as illustrated in Fig. 6.

There are few standard tests that can be used to evaluate all of the possible inherent defects that may be introduced by operations such as: casting, forging, welding, machining, grinding, cold forming, plating, heat treating, or careless assembly operations. Localized stresses, porosity, micro-cracks at welds, severe cold work, etc. may be categorized as "defects or flaws" which drastically affect the resistance of the member, and often determine the nearness to failure. All of these influences that will occur in processing should be present in the developmental testing if it is to be truly representative. Fig. 7 shows failure from a deficiency in processing (or design) that should be evident from a well conducted predictive test.

Thus, the interpretation of the testing program should consider not only the design and expected service conditions, but also recognize that the prototype may have been produced by special processes, and not be truly representative of the component as it will be mass produced. Furthermore, variations may occur between various batches or lots in production processing. The aspects of quality control, reproducibility in fabrication and processing, and the adequacy of final inspection procedures need to be considered as part of the overall predictive planning. The modern concepts of fracture mechanics are useful in setting standards for maximum permissible flaw sizes in the product.

A specific study should be made of the technical worth of each of the critical components of the prototype from the viewpoint of formability, weldability, fracture resistance of material, ductility available for overloads, etc. Where adverse environments of operation are important, the "time dependent" factors cannot readily be appraised; operations in processing and fabrication should also be thought of as conditions that may change with time depending upon the degree of control exercised in the shop operations. Any change in production and operating conditions from those existing in the prototype or 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.

ACCELERATED TESTING

Environmental conditions involving creep, corrosion, chemical attack, etc., are all difficult to analyse because they are dependent upon time, temperature, and dosage of the environment. (10, 11) Thus, for these conditions any attempts to speed up or accelerate the test program cannot be defended upon a quantitative rational basis. Those conditions which lead to deterioration must be given special consideration as highly non-linear with respect to time, temperature, etc., and seldom can be quantitatively expressed on the basis of simple short-time laboratory experiments.

Industrial firms frequently use accelerated testing of a part to produce failure within a limited period of time. This may require the application of excessive loads or temperatures, etc., not 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, it is desirable to retain loading conditions (including magnitudes and sequence) as near as possible to those expected in service. (13) The data in Fig. 8 illustrate one example of overloading for the same steel in two different conditions of heat treatment. Obviously, for unnotched samples the quenched and drawn condition results in better fatigue strength than the annealed condition. However, for sharply notched parts the annealed steel has the higher fatigue strength at long life. If one were to run an accelerated test on these notched parts at 30,000 psi the annealed parts would fail at much lower life than those quenched and drawn; at stress levels below 22,000 psi the reverse would be true. Thus the accelerated test would be misleading if the actual operating stresses never exceeded about 20,000 psi.

Overloading also may readjust residual stresses by yielding or redistributing the peak stresses in a notch or in a complex redundant structure. The beneficial effect of shot peening on leaf springs is well known; but in a reversed bending test it may not show up as well because the compressive residual stresses are reduced by yielding where subjected to high reversed stresses. As indicated in Fig. 9 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.

Proof testing of pressure vessels, piping, etc., is widely used and may be considered as one form of predictive test; however, the proof test should be regarded primarily as an inspection test to insure against gross flaws that would cause failure on the first overloading. The proof test also furnishes an opportunity of enlarging small flaws to make them more readily detectable during final inspection. Unfortunately, localized plastic deformations in zones of peak strain and the extension of micro-flaws can be expected to occur on overload cycles; repeatedly proof testing may develop a low cycle fatigue failure. A proof test gives no real assurance that the vessel will not fail if the same pressures are applied a second time, nor does it give any assurance that cyclic pressures of lower magnitude will not cause fatigue failure. Proof pressures must always be set at a value low enough that will not cause excessive plastic deformation or depletion of ductility, nor substantially increase existing flaw sizes.

DETERIORATION

It is difficult to duplicate the exact environmental conditions that lead to deterioration in service. Unique problems are encountered in the predictive testing of many types of consumer goods such as automobile tires, outboard motors, farm implements, etc. or in predicting the deterioration or wear of gears, cams, valves, etc. Various kinds of abrasive wear may occur which is not measured by relative hardness of the metal, and for which the type of abradent in the presence of (or absence of) lubrication are vital factors (e.g. fibers, plastics, and hard rubber may wear cutting tools amazingly). Various factors such as work hardening and embrittlement of the surface followed by spalling, incipient welding or seizure may occur when an oil film has been broken down or when no lubricant is present.

Deterioration needs to be judged on the basis of the specific environment of operation and the structural conditions that limit the usefulness in the service intended. Realistic testing may reveal latent defects before field failure such as those in Fig. 10. The rate of damage from corrosion, abrasion, wear, or slow flaw growth are frequently difficult to predict. Thermal and chemical environments are especially troublesome because of diffusion and alloying from foreign elements or metallurgical changes that may occur with prolonged service. The resistance to attack, and the stability with the time and temperature must be carefully considered. Hydrogen embrittlement is also a factor at high pressures and temperature.

If the experiment can faithfully reproduce service conditions of the finished part, data of engineering significance are obtainable. However, this is difficult in parts under complex service conditions such as shown in Fig. 11. The failures obtained must closely simulate the failures observed or expected in service before true simulation of the service condition is achieved.

LIFE PREDICTIONS

The technical worth of the metal in resisting damage needs to be evaluated quantitatively for the critical conditions in each specific application. Unfortunately, laboratory tests of metals are not always complete enough in their simulation to give realistic measures of a quantitative nature in those instances where time, chemical activity, or elevated temperatures become a factor. The designer may not fully understand the necessity of studying every possible mode of failure and assuring himself that the characteristics of the material are sufficient to resist the complex interactions encountered. For example, if we are dealing with a threaded shaft subjected to cyclic loading at low temperature in the presence of a corrosive atmosphere, has he considered whether the material has adequate notch toughness, resistance to slow-flaw growth, corrosion-fatigue strength, and resistance to stress-corrosion cracking? Many of the commonly used design codes for components are based upon tensile or yield strengths with an empirical "factor of safety;" they do not guide the designer to a critical review of the various possible modes of failure that must be avoided. Occasionally a failure such as that in Fig. 12 result from careless operating procedures or lack of periodic servicing that were not anticipated. Simultaneous corrosion is extremely severe in reducing the fatigue strength. (11)

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 fatigue strength of parts with unnecessary stress-raisers as shown in Fig. 13. 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 zones of high strain.

For some products realistic prediction of deterioration can be evaluated by putting the article through its complete service history, and determine the rate at which components will need replacement. Unfortunately, careless maintenance combined with peculiar aging characteristics of the metal has sometimes initiated a catastrophic fracture as shown in Fig. 14, that usually would not have been anticipated by predictive testing, and was not foreseen by the designer.

Laboratory fatigue test data provide convincing evidence of the inherent scatter in fatigue life even for the most carefully controlled conditions. This observation, together with uncertainties in the uniformity of materials, statistical variations in service load history, and subtle changes in manufacturing processes, make it clear that probabilistic considerations have an essential role in "life estimates."

The prediction of the fatigue life of a component that is subjected to a complex randomly applied load history has always been a difficult problem. However, rapid progress has been made in recent years in developing realistic methods of cycle counting, and interpreting the damage produced by each strain excursion by comparison with cyclic stress-strain curves for the metal involved. (21) In addition, computer programs are being evolved (22) that will enable the interpretation of strain readings from actual components in service to calculate the fatigue life the part will sustain before cracks develop. The cumulative fatigue damage from a given random strain history can now be evaluated to obtain good predictions of the fatigue life if the material properties under cyclic loading are obtained from laboratory tests of small samples.

SUMMARY

Predictive testing can be of utmost importance in developing the product for reliability under all foreseeable conditions of use. There still exist difficulties in making an accurate estimate of some types of deterioration (that are dependent upon exposure time and temperature) which may limit the safe or economical life of a structural or machine component. Many of the answers obtainable will be probabilistic in nature (and thus susceptible of wide variation) because of the inherent statistical variability of materials, loadings, environmental service conditions and manufacturing processes. Nevertheless, carefully planned and interpreted simulated service tests can give quantitative information of utmost importance in development and production planning, and in scheduling of maintenance of the product throughout its service life. While detailed and lengthy testing is expensive, it can pay good dividends in avoiding field modifications or costly replacements after the product has been marketed.

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TABLE I

Reliability Appraisal of a Design

1.	GEOMETRY:	Determined by size and space limitations, or functional shape	Components Assemblies
2.	WEIGHT:	Material selected for min. or max. requirements, cost, availability, etc.	Methods of production processing reconsidered
3.	LOADS:	Computation from 1 & 2 + past observations, and cyclic history estimate	Strain measurement for load history, scale models, temperature measurements
4.	STRESS:	Nominal calculations Localized stresses Residual stress Thermal stress Shock loads	Re-estimation of peak stresses Recalculations from measured loads Peak strain measurements
5.	STRENGTH:	Material & processing Resistance to each mode of failure Ductility requirements Toughness requirements	Re-evaluation of material properties as altered by production processing.
6.	ENVIRONMENT:	Temperature Time Chemical activity Corrosion, erosion Service-induced damage	Simulated service testing for life prediction with expected environments.
7.	RELIABILITY:	Chance variability of above items Margin of safety	Synthesis of observations Reappraisal of all factors

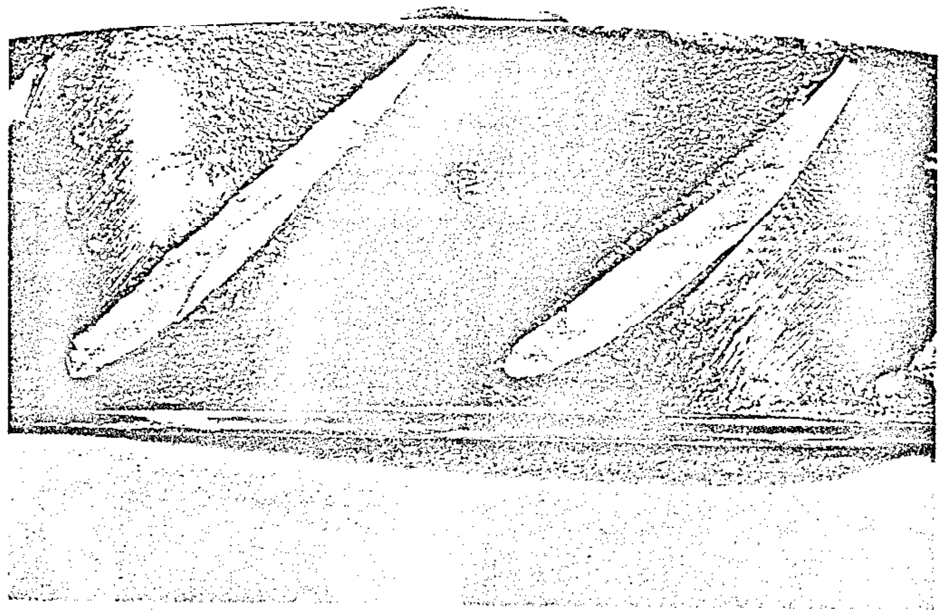


Fig. 1 Multiple Fatigue Fractures in Cast Magnesium Alloy Fan.
Unknown flexural vibrations developed maximum stresses at fillet joining blade to ring; as-cast surfaces, rough contour, plus residual stress at change in thickness of the casting; all contribute to failure.

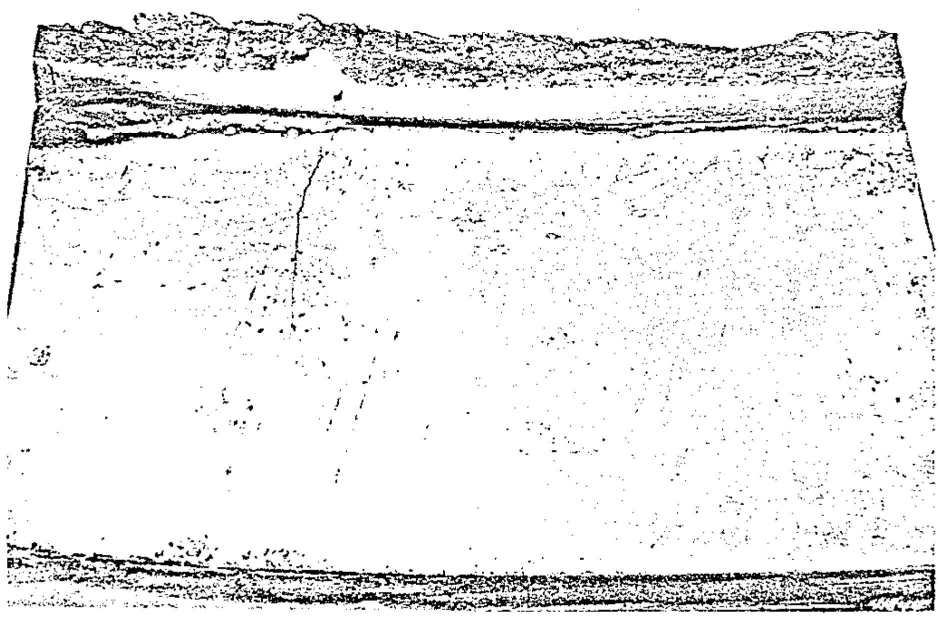


Fig. 2 Extensive Fine Cracking in a Band Near the Weld in Anhydrous Ammonia Tank.
Stress-corrosion extended only to the heat affected zone of the circumferential weld in the cold worked head, cracks caused by accumulation of service stresses plus those from cold forming, welding, and poor fitup during assembly. Study of complete environment necessary to prevent this type of problem.

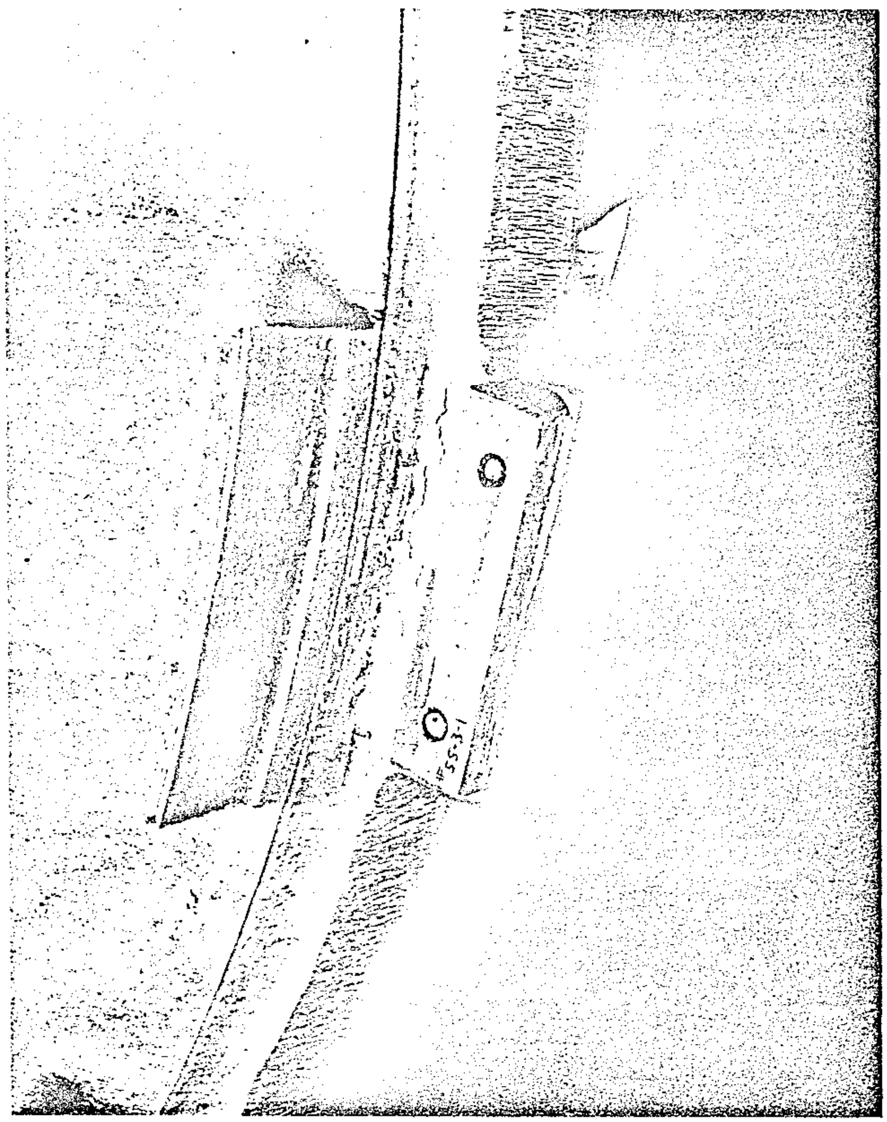


Fig. 3 Service Failure in Portion of Six Foot Diameter Cover for Pressure Vessel.

Cracks formed in a region next to the steel contact pad which locked the cover in by a breech lock action. Aluminum sand casting weighing about 260 pounds developed excessive clamping strains in this local region upon assembly.

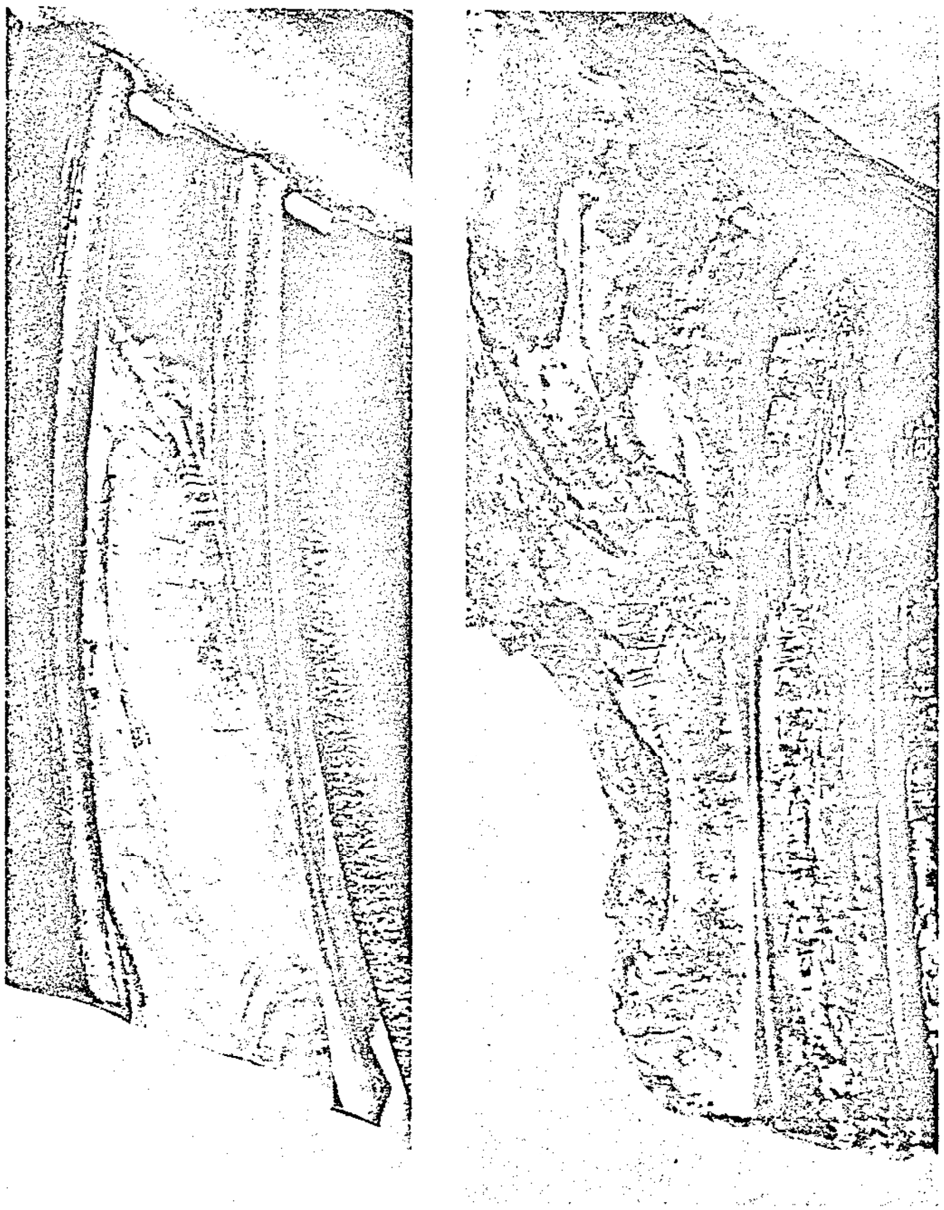


Fig. 4 Flexural Fatigue Failure of Gear Tooth From Root Area in Eight Inch Diameter Bevel Gear.

From laboratory tests of power transmission gear box of AISI 9310 steel gear. Overload test, but may not be realistic in predicting service preformance.

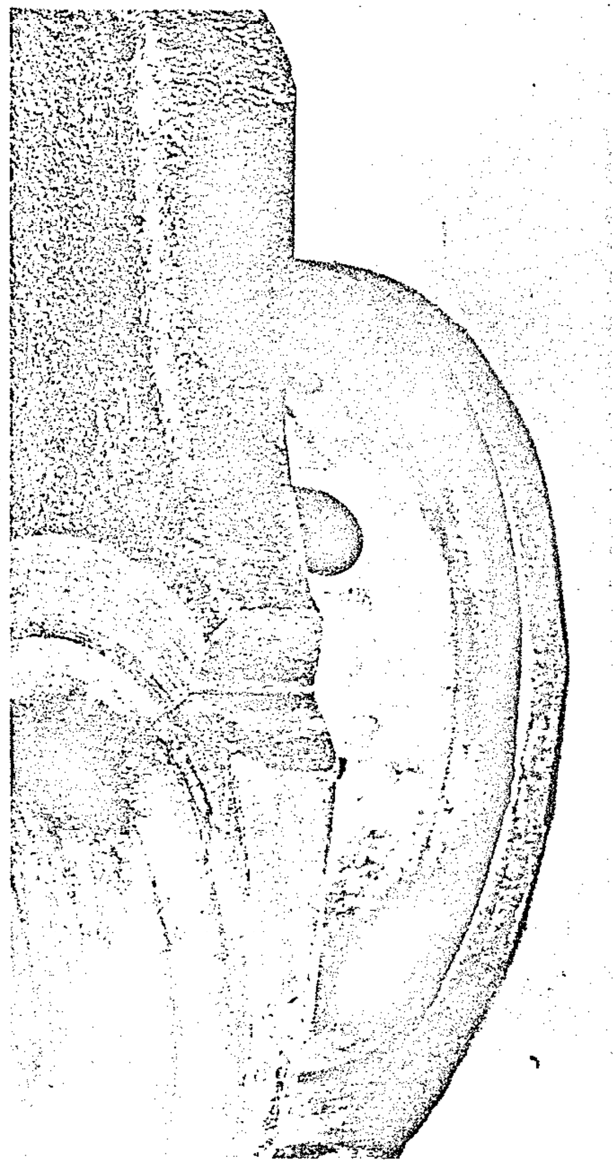
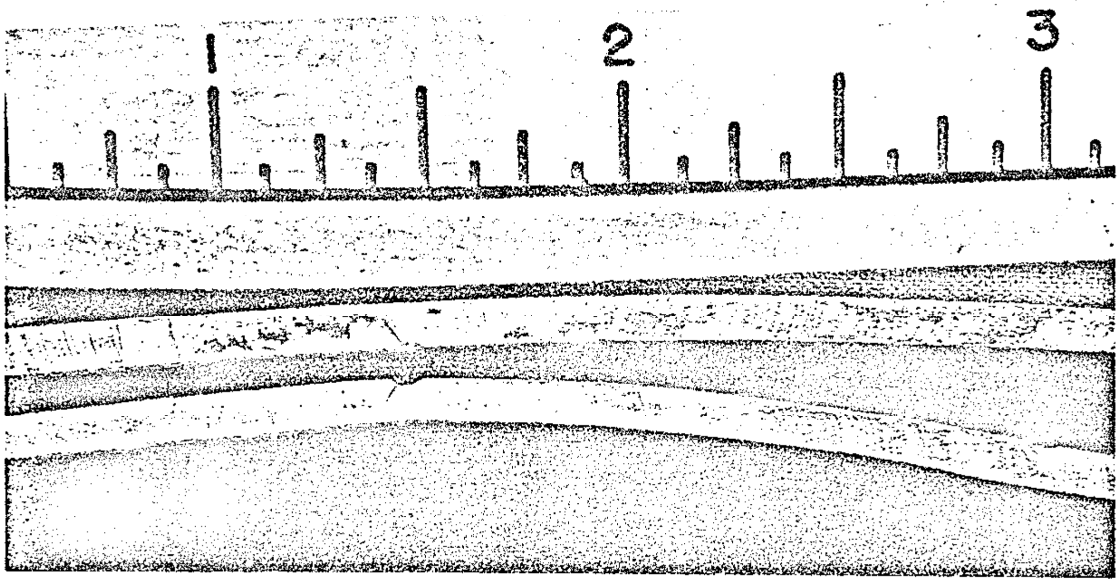


Fig. 5 Crack Originating at Notch in Crank Shaft of Diesel Engine.
While not anticipated by the designer, this notch was probably added by the shop for proper setup in machining operations.



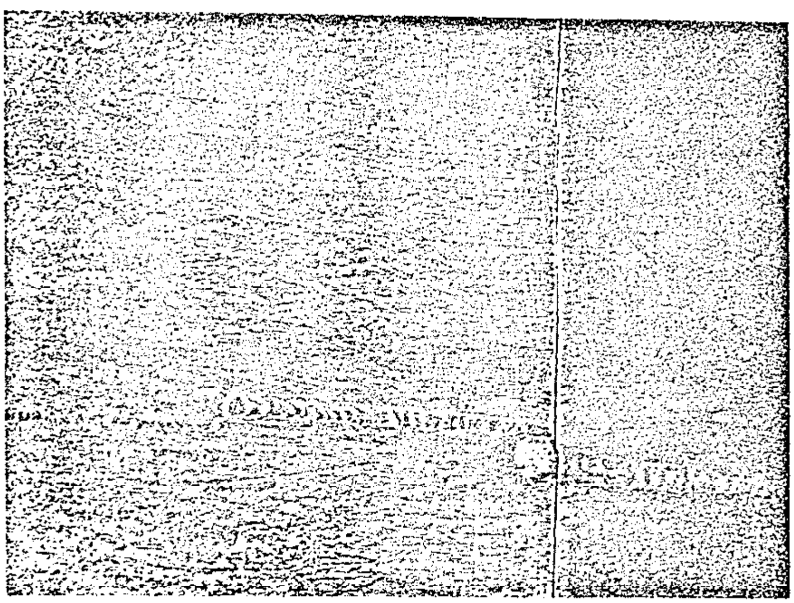


Fig. 6 Failure of Hollow Aircraft Propeller Blade of Steel.
6-A - - Fracture face 6-B - - Surface gouges
A crack initiated at one of several defects on the inside of the blade. These defects appeared to have resulted from a gouging or galling action, probably due to scraping against a mandrel during fabrication. (4)

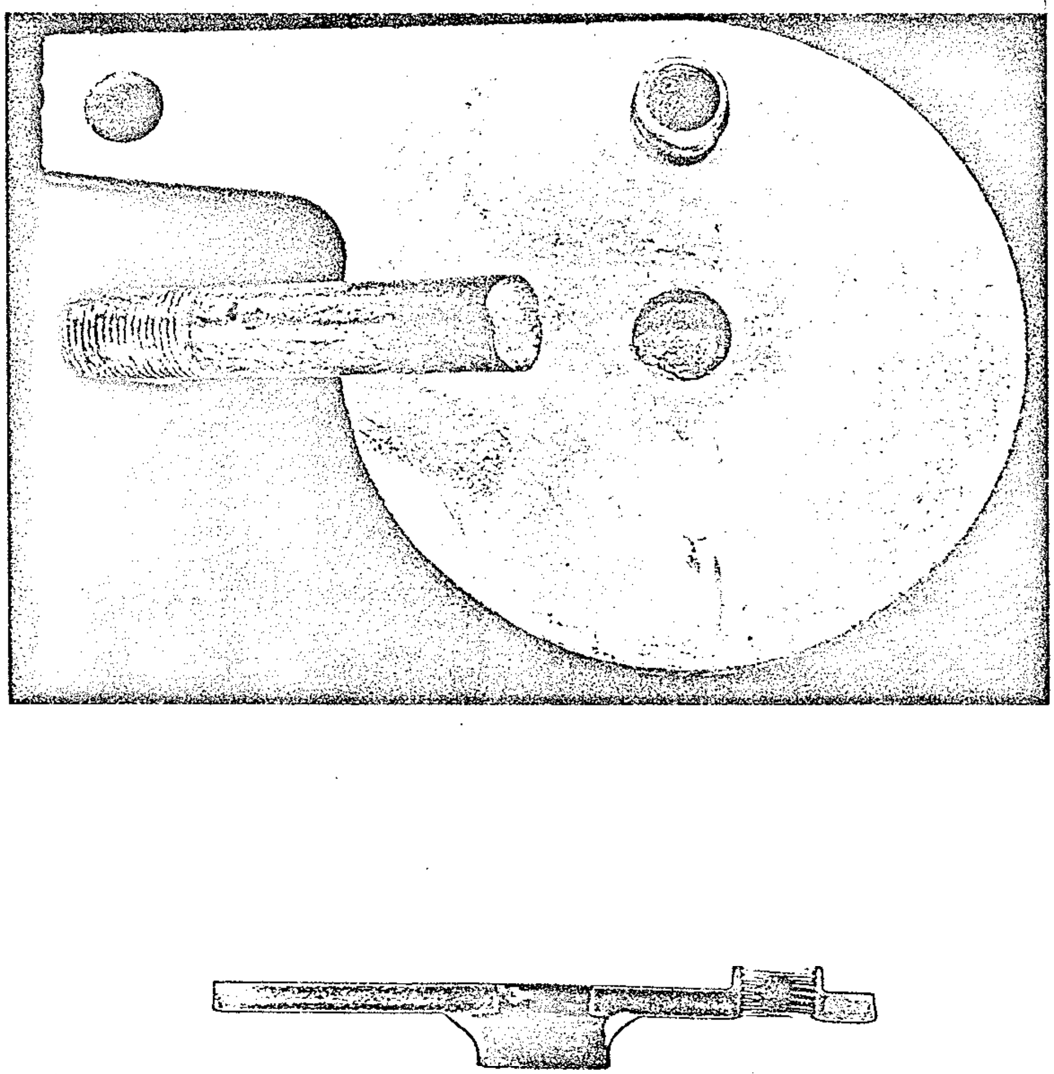


Fig. 7 Broken Assembly (top) and Etched Cross Section (bottom).
Failure caused by excessive brittleness of bolt due to case carburizing after assembly. Since only the plate needed wear resistance, the bolt should have been protected from carburization. Deficiency could be detected in a simulated service test.

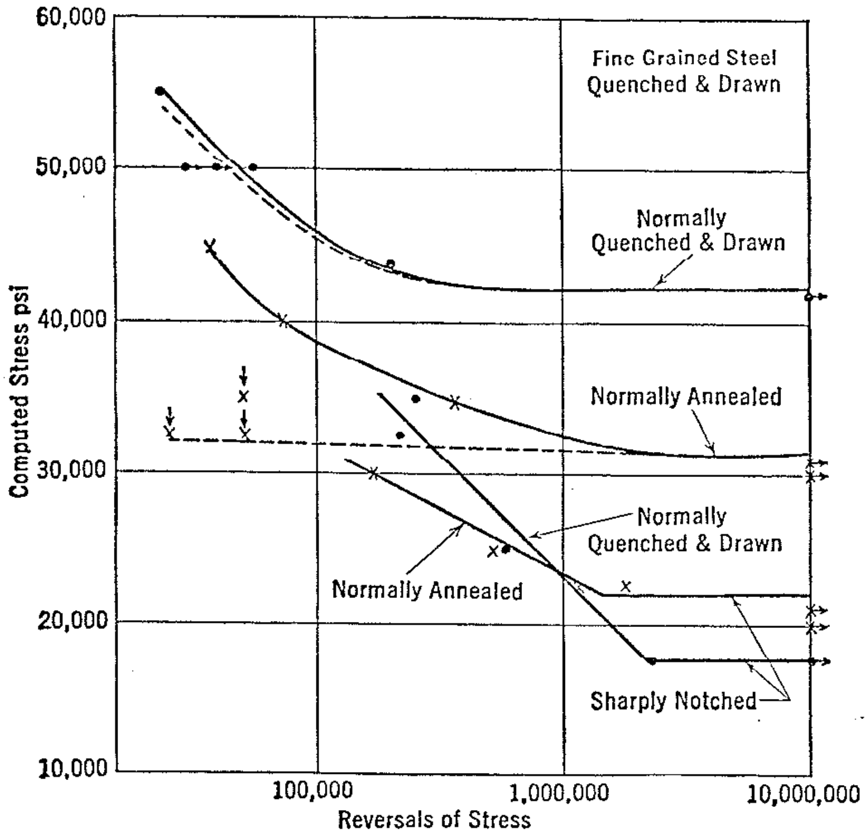


Fig. 8 S-N Curves for Notched and Unotched Specimens of a Steel in Two Conditions of Heat Treatment. (20)

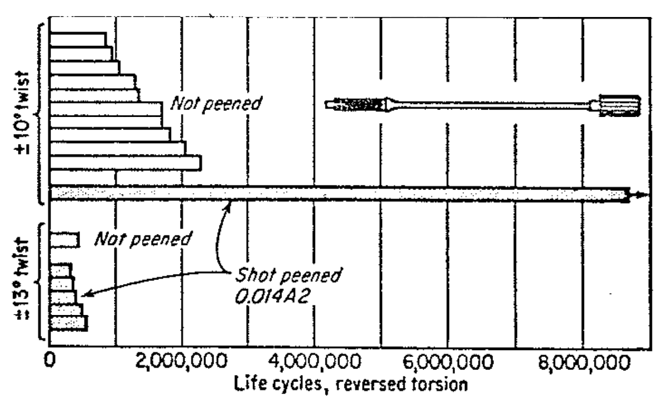


Fig. 9 Severe Overload Testing can be Misleading.

SAE 6150 Steel at Rockwell C34-38. At normal operating loads shot peened shafts show significant improvement in fatigue life. At high overloads the beneficial effect of compressive residual stress is masked out by yielding and redistribution of stress under reversed loading. (16)

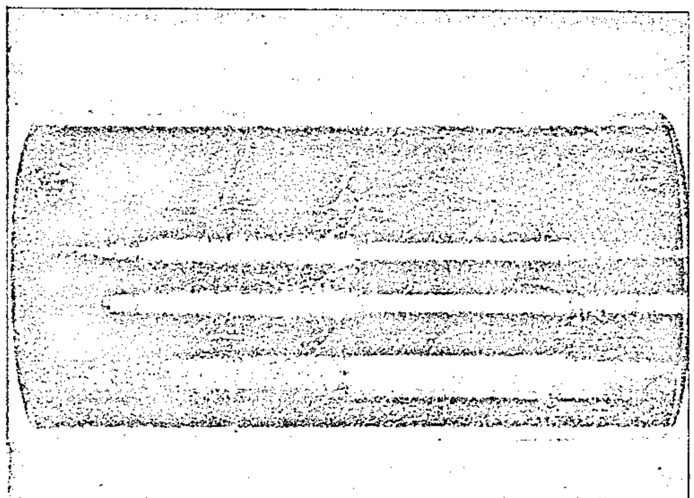


Fig. 10 Pinion Shaft Made from AISI 1024 Steel and Case Carburized.

Cracks shown by magnetic particle inspection were caused by crushing of the core allowing the case to crack. The trouble was caused by too soft a core and too shallow a case; either a design or a processing deficiency.

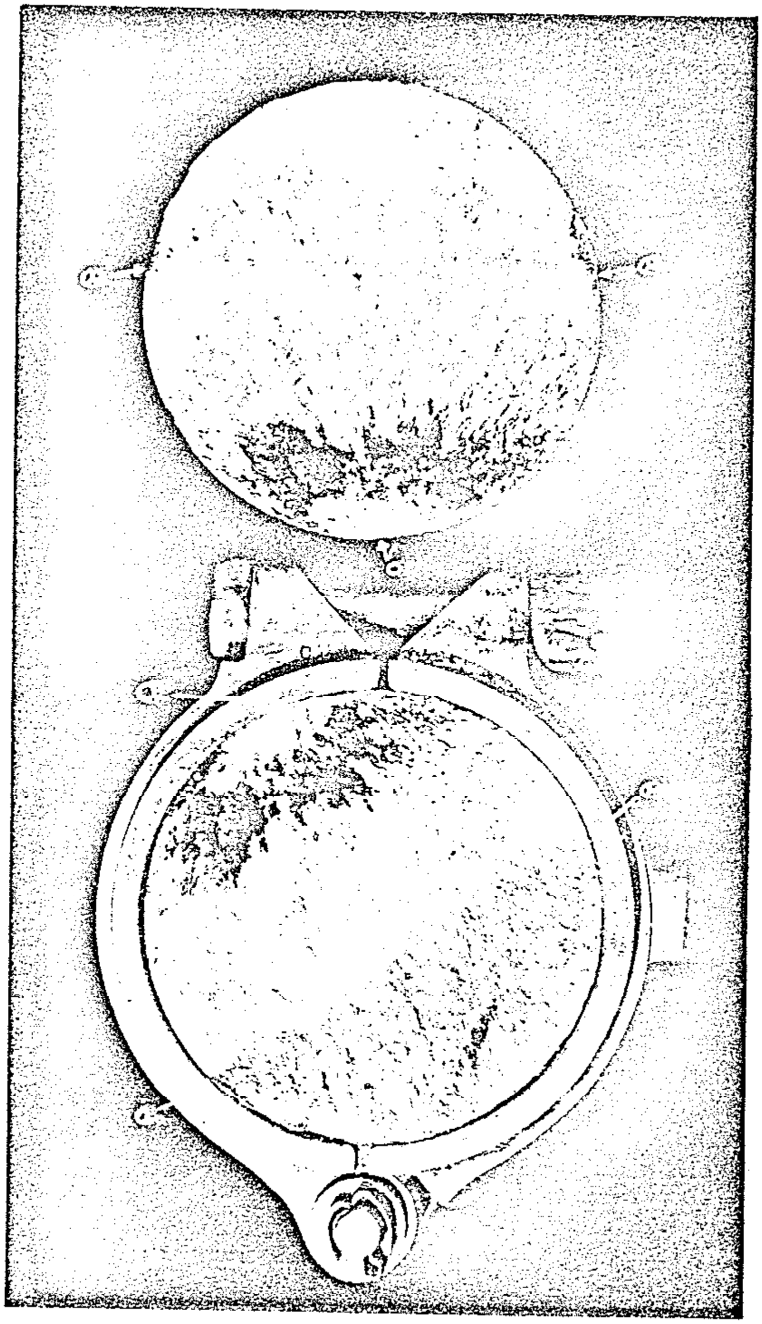


Fig. 11 Fracture Surfaces of an Aluminum Propeller Hub.

Rupture originated under the hub clamp at arrow 0. A fatigue crack extended to a, then the remaining area broke from the overload. Dark areas are caused by the powdered material from rubbing of mating parts during vibration as the crack progressed. A "fretting fatigue" failure developed after millions of cycles of vibration due to microscopic rubbing against the clamp. (4)

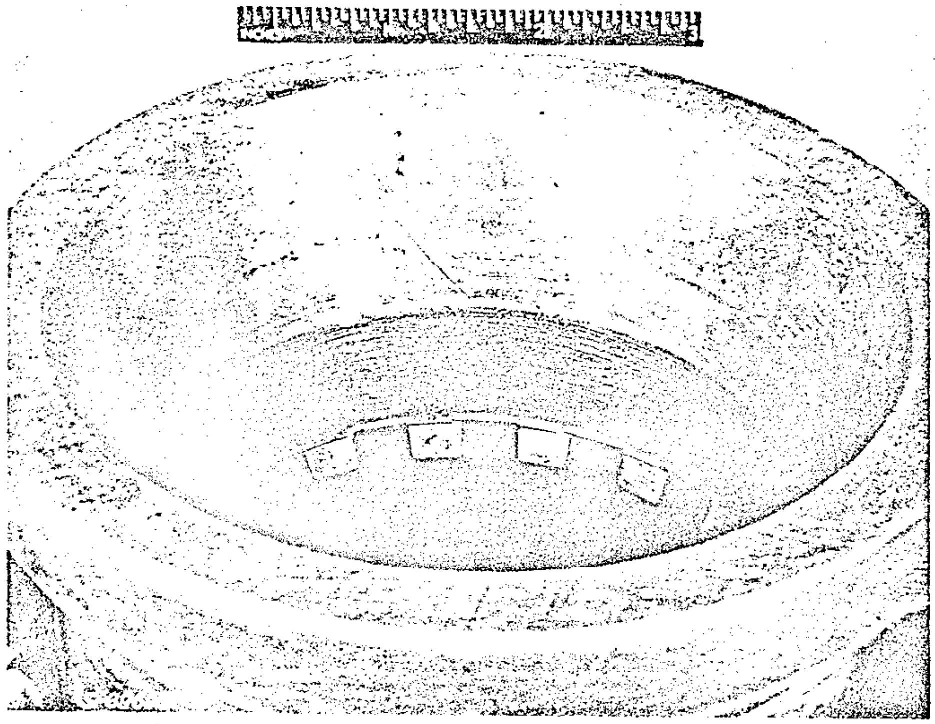


Fig. 12 (a) Corrosion-Fatigue Failure of Special Shaft of AMS 6415. Complex vibratory loadings developed fatigue cracks nucleated by small corrosion pits; the normal oil environment became contaminated with water and developed a corrosion-fatigue failure. Improper and unforeseen operating conditions.

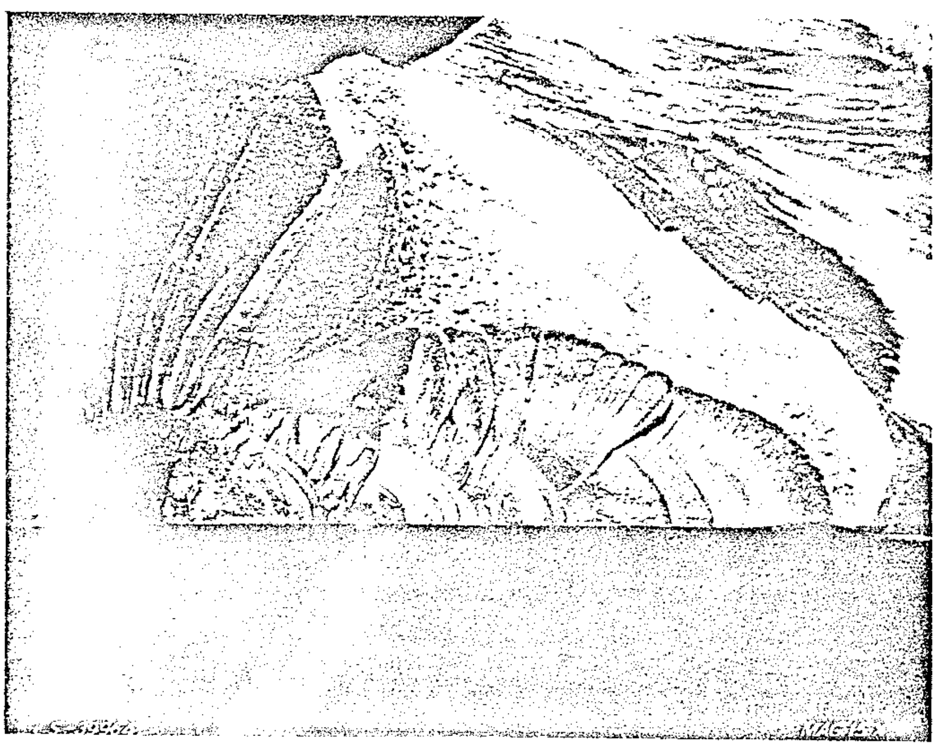


Fig. 12 (b) Enlarged view of Multiple Fatigue Cracks in the Shaft in Fig. 12 (a).

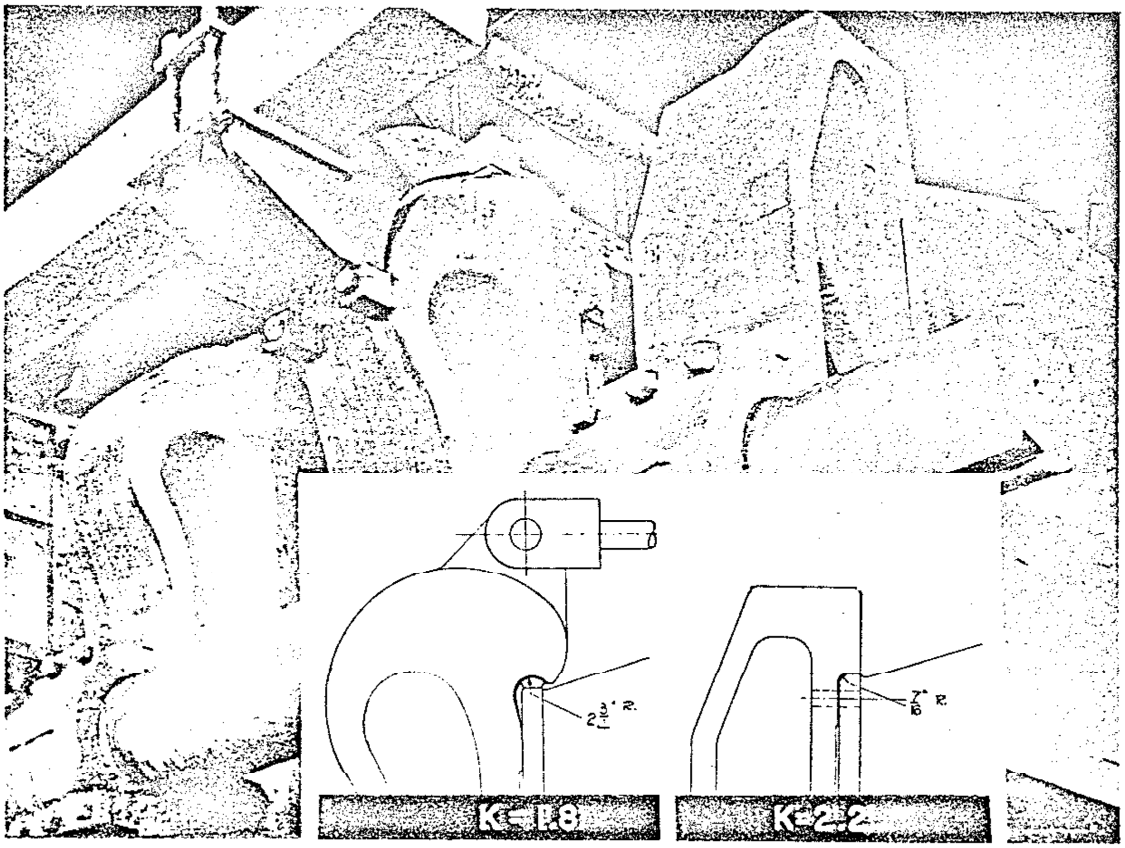


Fig. 13 Redesign of the Frame of a Large Forging Press.
The original design, (shown on the right), fractured through the throat after several years of service. A redesign (as shown at the left) was used for a replacement frame with lower stress concentration in the critical region. Component too large for simulated service testing to predict life.

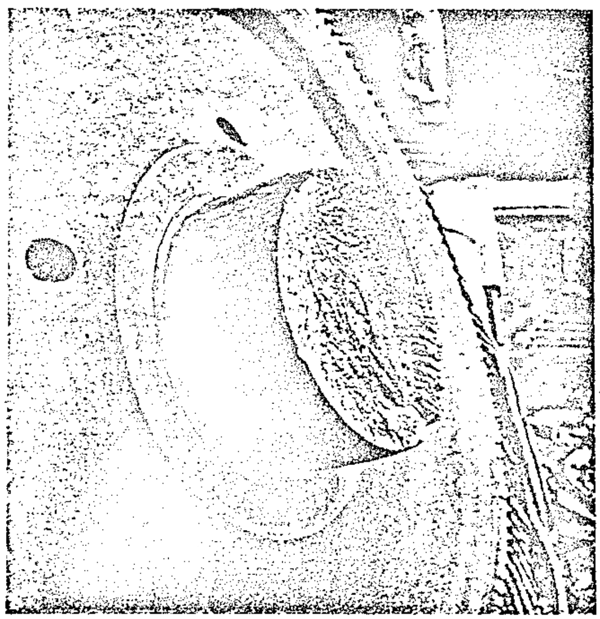


Fig. 14 Brittle Fracture of Steam Turbine Rotor Shaft.
Failure initiated from score mark on the surface developed during improper reassembly after maintenance. Severe local deformation accompanied by superficial tearing and subsequent aging of the cold worked surface embrittled the steel in the local zone and initiated a flaw which resulted in complete fracture of the shaft during overspeed acceptance test. (2)