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Elevated Temperature Fatigue Testing of Metals

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SUMMARY

The major technology areas needed to perform a life prediction of an aircraft turbine engine hot section component are discussed and the steps required for life prediction are outlined. These include (a) the determination of the operating environment, (b) the calculation of the thermal and mechanical loading of the component, (c) the cyclic stress-strain and creep behavior of the material required for structural analysis, (d) the structural analysis to determine the local stress-strain-temperature-time response of the material at the critical location in the component, and finally, (e) from a knowledge of the fatigue, creep, and failure resistance of the material, a prediction of the life of the component. This paper focuses primarily on the area of material characterization and evaluation conducted for the purpose of calculating fatigue crack initiation lives of components operating at elevated temperatures.

INTRODUCTION

Since materials in advanced aircraft turbine engines will be used to a high fraction of their ultimate capabilities, there is a great need for meaningful elevated temperature mechanical property tests of these materials as well as improved analytical techniques for the prediction of their service life. One particularly vexing problem has been the difficulty in describing and predicting the behavior of materials at elevated temperatures and in complex environments, such as the creep-fatigue interactions present in low-cycle high-temperature fatigue of engine components.

The AGARD Structures and Materials Panel (S&MP) has had a long and active interest in researching and exchanging information on this subject. At the Fall 1972 S&MP meeting, Mr Drapier, who was charged by AGARD with coordination of the various activities on this subject, submitted a document (reference 1) which reviewed the work being carried out by the NATO laboratories involved in this problem and, in 1974, published an in-depth report (reference 2) on his findings. Through his continuing efforts and the support of the S&MP, AGARD sponsored a Specialists' Meeting on Low-Cycle High-Temperature Fatigue (reference 3). These first three references constitute an excellent background on the subject of this paper.

As a vehicle for integrating the various elements of elevated temperature fatigue testing of metals, the problem of the durability of aircraft gas turbine engines has been used. Figure 1 shows a cross-section of an advanced high-bypass turbofan engine. Due to the very severe environment, temperatures, and loading conditions within the "hot section" of the engine, this region is responsible for the largest portion of the maintenance costs. The life prediction of components in the hot section are very difficult and require a great deal of sophistication in their analysis.

The most common problem areas within the hot section are shown in figure 2. Typical modes of failure are listed for each of the components that suffer degradation during engine operation. These include combustor liners, seals, disks, vanes and blades. With the exception of the centrifugal loads on the blades and disks, the primary source of cyclic loading is due to the severe thermal cycling associated with each start-up and shut-down of the engine, although high frequency excitation problems are sometimes encountered.

Low cycle fatigue and thermal fatigue occur in components where the strain in a small localized region is larger than in the surrounding region because of notches or holes that concentrate the strain, or because of constrained thermal expansion as in the case of thermal fatigue. The key feature is that local strain is prevented from exceeding certain bounds because the bulk of the component part remains elastic. Hence, the local material is caused to cycle between approximately constant strain limits. When the local strains are large, inelastic strains occur and the cyclic stress-strain behavior becomes nonlinear with a hysteresis loop forming, such as shown schematically in figure 3. Note the terms used to describe the characteristics of the hysteresis loop. The stress range and the elastic strain range are related by the modulus of elasticity. The total strain range is the sum of the elastic strain range and the inelastic strain range.

To study and be able to predict the effects of these large cyclic strains imposed at elevated temperatures, it was necessary to evolve a new testing philosophy, testing equipment and analytical models that accurately describe a material's cyclic flow and failure response to the above noted complex loading conditions.

LIFE PREDICTION

The key technology elements needed to perform crack initiation life predictions of turbine engine hot section components are shown in figure 4. The NASA-Lewis Research Center has substantial research efforts in each of these areas. We begin with the determination of the operating environment and a calculation of the thermal and mechanical loading of the hot section component of interest. We then determine the cyclic stress-strain and creep behavior (constitutive relations) of the material so that finite element nonlinear structural analyses can be made. The results of these analyses are the local stress-strain-temperature versus time response of the material at the critical locations in the component. It should be emphasized at this time that damage accumulation leading to failure is a highly localized process and requires a knowledge of the local history. The better that this can be done, the more accurate the prediction of component life. Finally, from a knowledge of the fatigue, creep, and fracture resistance of the material, a prediction of the lifetime to crack initiation of the component is made. Several approaches in use or under development for elevated temperature creep-fatigue life prediction are given in references 4 through 12. A more detailed flow chart of the life prediction and evaluation process is shown in figure 5, where the areas requiring testing are identified. These are as follows:

Material flow behavior. - A necessary ingredient for inelastic structural analyses is a description of the nonlinear stress-strain response of the material. Under conditions of constant strain range and temperature, but different loading rates, this material response can be significantly affected, as illustrated by the rate dependent hysteresis loops in figure 6. Attempts to describe material response (constitutive behavior modeling) under the varying temperatures and complex cyclic loading histories encountered in engine components is most difficult and is an area of research currently under intensive investigation. Descriptions of a number of constitutive behavior models under investigation are given in references 13 through 22. The majority of the constants required by the analytical models for describing the cyclic flow behavior can come from measurements made at the time the creep and fatigue characterizations of the material are determined.

Experimental stress analysis. - In many instances, experimental stress analysis techniques are used in support of structural analysis. Photoelasticity, for example, is used to locate the most critical locations in a component and to "calibrate" theoretical solutions. Foil strain gages and brittle lacquers are also used to verify the location of high stress areas as well as the orientation of the principal stress axes. These experimental tools can help to define the locations in the structure where a more detailed, finer-mesh can be utilized to improve the accuracy of a finite element analysis.

Material failure behavior. - Once the local stress-strain-temperature history at a location of interest in known, this information is analyzed for the prediction of failure where failure will be defined as the initiation of a "small" crack. This is done by comparing the calculated accumulated damage with generic failure curves. Implicit in this approach is the assumption that the life of a complex loaded component can be predicted from simple specimens tested under isothermal idealized cycles if the correct analytical damage model is known. Also implicit in this approach is the fact that the definition of the failure being predicted is the same as the criterion used in generating the generic experimental data. A sample form of this approach is shown in figure 7. Here the failure relationships are a set of isothermal total strain range vs. life curves where life is defined as the initiation of a one millimeter surface crack. The damage accumulation model shown is the widely used Miner linear damage equation. Descriptions of several of the damage models currently in use are given in references 23 through 25.

Life testing. - In the development and verification of life prediction methods, it is essential that well controlled and documented experiments be conducted. These experiments should incorporate the major features that exist in the engine component (e.g., key geometry features and temperature gradients). In the development of a life prediction method for turbine blades for example, it is advantageous to use tests having different levels of complexity. This is shown in figure 8 where the tests range from simple specimen tests, to simple thermal fatigue tests, to various rig tests, and finally to the testing of the component of interest. One should not expect to conduct a full scale component test and predict component life if the predictive method had not been refined on the simpler and less expensive specimens and rig tests.

All of the testing done in support of life prediction fall into two general classes. The types of tests and their degree of complexity will depend primarily on whether they are being conducted for the purpose of developing and verifying life prediction methodology or for the purpose of applying existing methodology. That is to say, whether the tests are being run by a "developer" or a "user". This is a very important distinction and should be kept in mind when considering testing programs and equipment needs for elevated temperature fatigue testing of metals. The remainder of this paper will focus on the testing conducted at elevated temperatures for developing and verifying methods of life prediction and for characterizing the flow and failure behavior of materials.

MODEL DEVELOPMENT AND VERIFICATION

In the process of developing a life prediction method, it is essential that the individual "pieces" of the method be built up and evaluated in a systematic way. This requires a carefully designed testing program as will be discussed with the aid of figure 8. Let us assume that we have a promising new concept for predicting the crack initiation life based on a hypothetical strain-dependent surface roughness model and that this approach was arrived at through careful observations made on failed specimens. A testing program for developing and verifying this model could be as follows:

Material tests. - Assuming the model was based on a limited data base (as is usually the case), additional isothermal strain controlled testing over a wider range of temperatures and strain ranges and for several additional materials would be in order. This would give some early indication of the limits of the approach as to class of material, loading conditions and temperatures for which the model works. Let us assume that the model works well for the class of material (cast nickel-base superalloys) and temperatures (up to 1000° C) and for relatively simple isothermal loading cycles. The model should then be evaluated for more complex loading if this is to be an important feature of the real loading of the component of interest. This could be a "flight cycle", block loading, random loading, or combined cyclic and steady-state loading. Again, assuming the model also works reasonably well for the more complex cycle of interest, we can proceed by building into the tests some additional features of interest.

Thermal fatigue tests. - We will now modify the geometry and the thermal loading to more nearly represent the component of interest. The thermal fatigue specimen shown in figure 8 is a simple symmetrical wedge-shaped bar with leading and trailing edge radii similar to those found on turbine blades. These specimens will be thermally cycled by alternately quenching them in hot and cold fluidized bed furnaces as shown in figure 9 and described in reference 26. The thermal gradients imposed during the quenching cycles induce cyclic thermal stresses that develop edge cracks similar to those found in turbine blades. These evaluation tests are much more difficult to analyze than the simple material test specimens but still much easier than the real turbine blade. The specimen geometry and the transient thermal gradients are symmetrical and the cycle is simpler and very reproducible. For these tests, transient surface temperature measurements should be made for the input to a detailed transient thermal stress analysis. The life prediction model can then be evaluated for its applicability to a "blade-like" shape subjected to cyclic thermal stress loading. Assuming again, that the model works, or has been improved to work for these conditions, additional features of the blade life problem may be evaluated through the use of selected rig tests.

Rig tests. - The question of whether the model works for a specimen subjected to a flowing turbine combustion gas environment might be the next feature investigated. Figure 10 shows a specimen test rig for just such an investigation. Here, a simple blade-like specimen is alternately heated and cooled by moving the specimen into and out of the burner stream. Here too, the cyclic thermal stress loading history would have to be calculated (using thermocouple data) in order to evaluate the model. This evaluation approach can then be further developed to take a more complex blade shape (with or without internal cooling) and with the addition of a superimposed mechanical loading history on top of the cyclic thermal stress history. Such a blade test rig is shown in figure 11. If the model works reasonably well on these rig tests, one would also expect it to work reasonably well on the engine component since all the main features of the engine problem have been incorporated in a controlled manner in the evaluation program.

Along with the evaluation of a model's ability to predict life, the mechanistic assumptions that form the basis of the model (assuming it is not a purely empirical model) should also be verified. For the assumed hypothetical model proposed above, the verification program should also include basic metallography and detailed macroscopic and microscopic observations of the surface roughness for the various test discussed. These observations can reinforce the validity of the model or indicate shortcomings that when once understood might be used to improve the physical basis for the model and hence its predictive capability.

MATERIAL CHARACTERIZATION

Material characterization is that aspect of elevated temperature fatigue testing of metals common to both the "developer" and "user" of life prediction methods. The objective here is to generate a data base that can be used to describe a material's behavior over its range of use. It should be as general as possible and hence be applicable to any design or application. The link between these "generic" data and a specific component is through analysis. For example, uniaxial data can be applied to a multiaxial problem through an equivalent stress or strain model; constant amplitude data to a variable amplitude problem through a cumulative damage rule; and notch behavior through a Neuber type relationship.

As these models become further developed and newer more accurate models become available, the characterizing of a material can become more generic and less component specific. It was not too many years ago when, for example, an elevated temperature fatigue data-base consisted of stress amplitude vs. life curves generated at the frequencies, temperatures, stress concentration factors and mean stresses that the component was expected to see. This is a costly and time consuming approach but necessary when the analytical models are either not available or not trusted.

Several major advances were made in the 1950's that had a great impact on the whole field of high temperature low cycle fatigue. These were (a) the recognition that most of these types of fatigue problems were strain induced, (b) the formulation of the Manson-Coffin Law that related low cycle fatigue life to plastic strain range, and (c) the development of servo-controlled testing equipment that permitted the investigation of materials under conditions of strain cycling. It has been the exploitation of the above ideas and equipment that has permitted the development of most of the current cyclic flow and crack initiation failure models which has changed the way that elevated temperature fatigue behavior of materials is characterized.

The materials characterization that we will be examining is restricted to the isothermal, uniaxial loading of smooth specimens. Also, since the elevated temperature fatigue problems that are of major concern tend to be strain induced rather than load induced by nature, the characterization is performed under conditions of applied cyclic straining with failure defined as the initiation of a "small" crack. Let us now take a more in-depth look at what constitutes elevated temperature fatigue material characterization, that is, what should we be measuring and how these measurements can be made.

Material flow behavior. - As noted earlier, there are two aspects of material characterization required for life prediction that are obtained from the materials response to the test conditions. These are the cyclic flow behavior and the failure behavior as functions of the applied loading. The failure behavior is obtained from the "end" of the test while the flow behavior comes from hysteresis loops measured over the lifetime of the specimen. These loops can only be obtained if continuous simultaneous measurements of the applied load and specimen displacements are made. Stresses are then calculated knowing the loads and the cross-sectional area of the specimen, and the strains calculated knowing the displacements and the gage length over which these displacements are measured.

When conducting these experiments, some investigators prefer to control the applied strain range in such a way that the specimens are forced to cycle from zero to the maximum strain and then back to zero strain. We prefer to run these test with completely reversed strain cycles as shown in figure 12. It is felt that this is a more "generic" approach since it maintains a zero mean strain for all the data rather than have a variable mean strain equal to half the strain range. More importantly, as can be seen in figure 12, fully reversed cycling also develops a hysteresis loop having a zero or negligibly small mean stress.

Continuous recording of the first few hysteresis loops and then periodic sampling of the loops up to the time of failure can be very informative. Figure 13 shows an example of such a set of data. The shapes of the loops can yield information useful for obtaining an analytical description of the constitutive relationships needed for a cyclic inelastic structural analysis. The size and shape of the loops can change significantly over the life of the specimen. For the example shown, the material is cyclically softening as seen by the continuous reduction in the applied stress range required to reach the imposed strain range. Both the rate and degree of cyclic softening (or hardening) might be important features of material flow behavior requiring analytical modeling. It is common practice to use the hysteresis loop measured closest to the half-life of the specimen as the one representative of the test. This half-life hysteresis loop is used for calculating the elastic and plastic strain ranges as well as the stress range associated with the applied total strain range for this test.

Life to crack initiation. - The question of what is a good criterion for defining crack initiation has been a difficult one to resolve. A number of definitions have been used with the most common being the complete separation of the specimen. The logic of using this definition for crack initiation is based upon the experimental observations that once an engineering size crack (approximately 1 mm) is formed, it requires only a small percentage of the total life for that crack to grow to complete failure in a laboratory size fatigue specimen. Data generated using this definition is therefore assumed to represent a good approximation for crack initiation. It has been our experience, that the choice of the definition of crack initiation has been made more on the basis of convenience than on sound technical judgement. The most general advice that can be given at this time is to record as much information as possible from each test and thereby allow for the plotting and evaluation of all the data for a given material using as many definitions of crack initiation life as is convenient.

Having representative samples of these hysteresis loops over the entire life range (figure 13) allows one to look at some of these alternative definitions of crack initiation failure life. Changes in the shape of the loop in the region of maximum compression can sometimes be used to define the onset of cracking. A drop in the cyclic load range from the stable steady-state load range or from the half-life load range have been suggested. Several different values (5%, 10%, 20% and as much as 50%) have been proposed and used by some investigators as a definition for failure. Another definition of failure that is also based upon load response measurements is a fixed percentage drop (10% or 20%) in the ratio of peak tensile load to the peak compressive load for the same cycle. When a crack forms, these free surfaces cannot sustain normal tensile stresses, but as the crack faces are forced into contact during compression, compressive stresses can be developed. Hence, in the presence of a crack, the peak compressive load is not affected to any great extent but the tensile peak load is. This causes the ratio of tensile peak load to compressive peak load to drop as the crack grows. This definition of initiation avoids the ambiguities that may be brought about by the previous definition (percentage drop of load range) if the material is cyclically softening at the same time a crack is developing and growing.

These definitions of failure can only be used if the hysteresis loops are recorded or the load is continually monitored as a function of time. In any event, the more conventional definitions of failure can also by used. These include the use of surface crack observations and the most common definition of failure, complete specimen separation. Surface crack observations can include visual, accoustic emission, ultrasonics, or eddy current techniques for recording the life at which a crack of some predetermined size is first detected.

The control and measurement of test conditions. - There are five basic elements of a test that must be documented if the test is to be considered meaningful. These are temperature, stress, strain, cycles, and crack initiation. As will become obvious, there are no "standards" available for conducting these kinds of experiments. The greatest variations in testing methods are found among the "developers" of life prediction methods. This is understandable since these investigators are evaluating new approaches and require the maximum flexibility.

Temperature: It is essential that a "developer" have the capability to conduct evaluation experiments under conditions of variable or cyclic temperatures. This can best be done when the heating method used is either of the direct resistance heating or induction heating types. The heating method most convenient for a life prediction model "user" would be a conventional furnace which is ideal for maintaining a constant temperature over a long period of time. Examples of these three specimen heating methods are shown in figures 14 through 16.

There are both advantages and disadvantages to each of the above heating methods. For example, a furnace holds the most uniform temperature and is the simplest to operate but makes it difficult to observe the surface of the specimen and increases the difficulty associated with displacement measurements. This is caused by the fact that most displacement transducers cannot operate at the test temperature and therefore must be located outside of the furnace. Induction heating permits easy access to a part of the specimen surface but this type of system is more susceptible to thermal fluctuations and can create a problem with electrical interference with other instrumentation and control equipment. Direct resistance heating permits maximum access to the specimen surface but otherwise has the same disadvantages associated with induction heating systems.

In order to control the specimen temperature by any of these heating methods, a sensor for feedback and a control system are required. The two most commonly used sensors are thermocouples and infrared pyrometers. These sensors produce an electrical signal proportional to the temperature at some location on the specimen. This signal is compared to the desired (or programmed) signal in a temperature controller and if the two are not the same, the controller produces an error signal that causes the heating system (furnace, induction heater or transformer) to either raise or lower the specimen temperature. These systems are very widely used and commercially available. It is advisable to conduct a series of temperature calibration tests prior to fatigue testing. For thermocouple users, this would involve placing thermocouples at several locations both within and near the test section of a calibration specimen and recording their output for each of the temperatures to be used in the fatigue experiments. A thermocouple located away from the critical cross-section can then be used by controlling at the temperature it indicated when the cross-section of the calibration specimen was at the desired temperature. This calibration and procedure permits the testing of specimens without a thermocouple attached to the critical cross-section where it would act as a crack starter and thereby reduce the crack initiation life.

Strain: Strains are obtained from measurements of either the specimen diameter or a longitudinal gage length. Examples of these two approaches are shown in figures 16 through 19. Here again, a distinction should be made between a "developer" and a "user". The developer would find it very difficult to conduct any meaningful variable temperature experiments employing a longitudinal extensometer. Since a strain measurement would have little meaning if the entire gage length were not at a constant temperature, a variable temperature test has to be designed so that the entire gage length is at the same temperature even while this temperature is changing. This can most easily be accomplished using the diameter as the gage section where the symmetry of the geometry and heat conduction tend to keep any cross-sectional area at a relatively constant temperature. A "user" on the other hand, is not necessarily concerned with variable temperature testing and would find the longitudinal extensometer beneficial in that it produces a much greater signal than the diametral extensometer. This is because the diametral extensometer is measuring a Poisson displacement (1/4 to 1/2 the longitudinal displacement) and over a shorter gage length (usually 1/4 to 1/2 the longitudinal gage length).

As one will note when surveying the many technical papers describing experimental techniques for elevated temperature fatigue testing, the extensometers are generally "home-made" or adaptations of commercially available sensors. There seems to be almost as many different extensometers as there are investigators. This is understandable when one recognizes the number of combinations of test frames, specimen shapes and heating systems in use for which these extensometers have been adapted.

Crack Initiation: A number of different definitions of crack initiation were discussed earlier. The measurement of the number of cycles to specimen separation is the simplest and by far the most popular. The use of hysteresis loops or load response histories for defining crack initiation are gaining acceptence. These methods do not require any special crack detection equipment, are more conservative than the complete separation method but require a somewhat higher degree of subjectivity in their application. The use of accoustic emission, ultrasonics, or eddy current techniques are still in their early development stages with regard to their application to elevated temperature fatigue material characterization. Their inclusion, therefore, in this paper would be premature.

Stress and Cycles: The measurement of stress and the counting of applied cycles is the same for elevated temperature fatigue testing as for conventional room temperature testing. This is because the sensors are kept remote from the heated parts under test. These sensing methods, therefore, require no special discussion since they involve no special or unusual problems.

CONCLUDING REMARKS

The elevated temperature low cycle fatigue testing of metals is still in its development stage. There are as yet no "standard" methods of testing because there are no standard or fully accepted models for describing material behavior under these conditions. Each life prediction model has its own key parameters that must be evaluated if the model is to be used. These parameters therefore define some of the specifics of the way in which materials should be characterized. There are, however, many aspects of model development and verification, and material characterization that are not unique to any specific model and these have been discussed in this paper.

In attempting to keep abreast of the developments in this field, it is advantageous to know the key laboratories working in this area. Recently, AGARD sponsored a cooperative evaluation program of one of the newer methods under development for life prediction in the creep-fatigue range. This program brought together most of the key laboratories and investigators working in elevated temperature fatigue life prediction and resulted in a published AGARD report (reference 27). Independent of the method under evaluation this document contains an up-to-date source of information on testing methods and equipment.

Another excellent source of general information on this subject is the Special Technical Publications of the American Society for Testing and Materials. Their Manual on Low Cycle Fatigue Testing (reference 28) published in 1969 contains much information on equipment and testing procedures that is still considered current.

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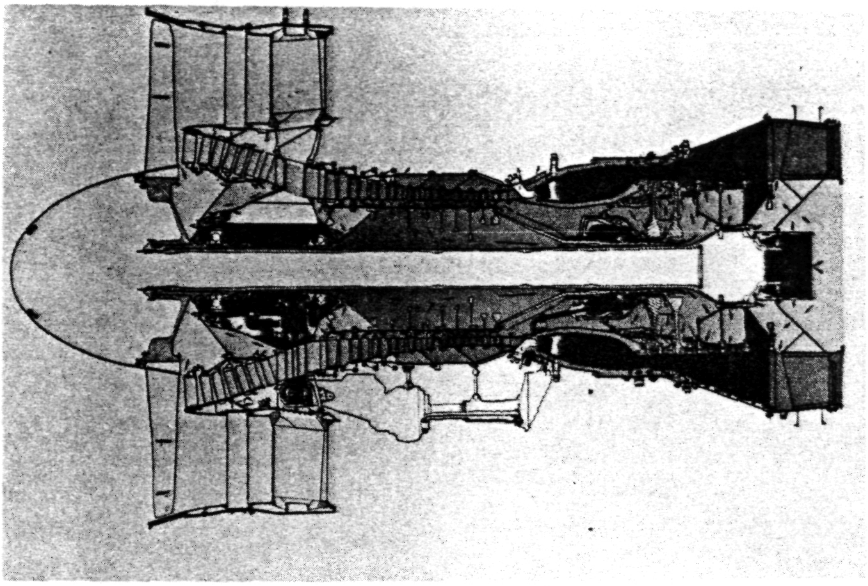

Figure 1. - Turbofan engine.

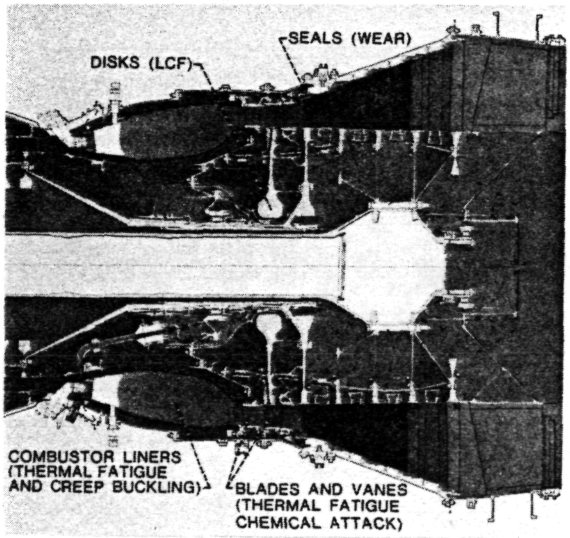

Figure 2. - Turbine engine hot section.

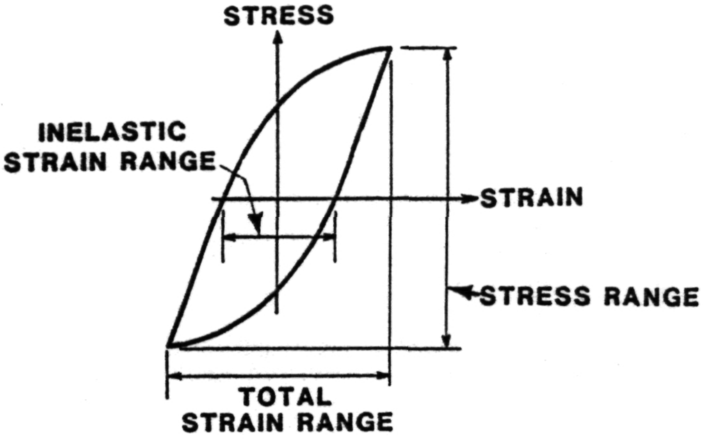

Figure 3. - Stress-strain hysteresis loop.

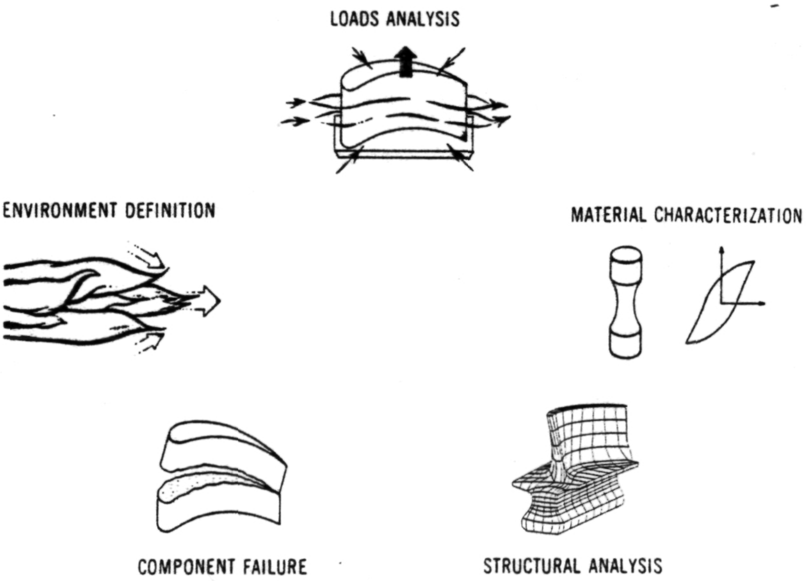

Figure 4. - Life prediction.

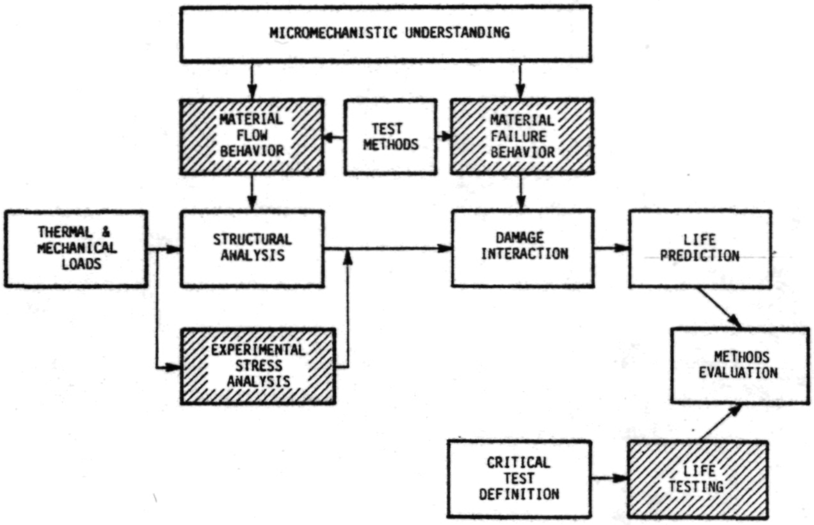

Figure 5. - Life prediction flow chart.

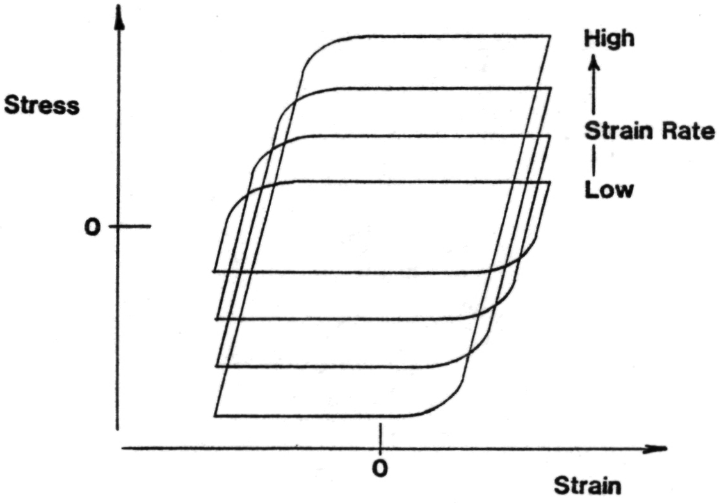

Figure 6. - Material cyclic response.

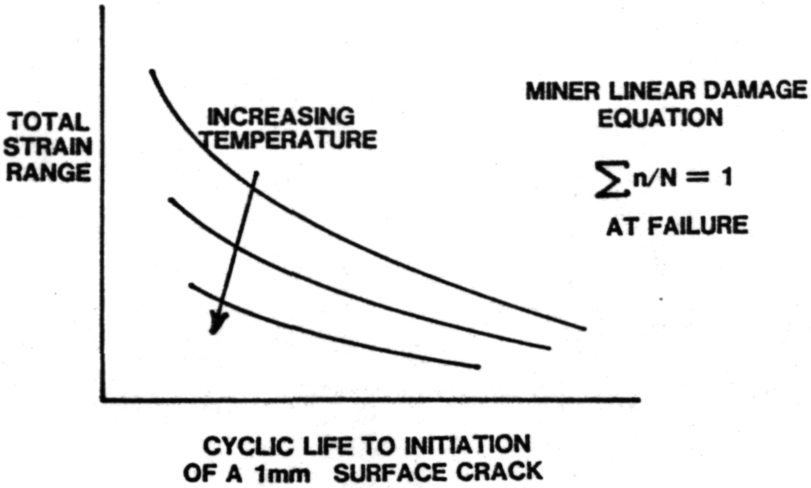

Figure 7. - Material failure description.

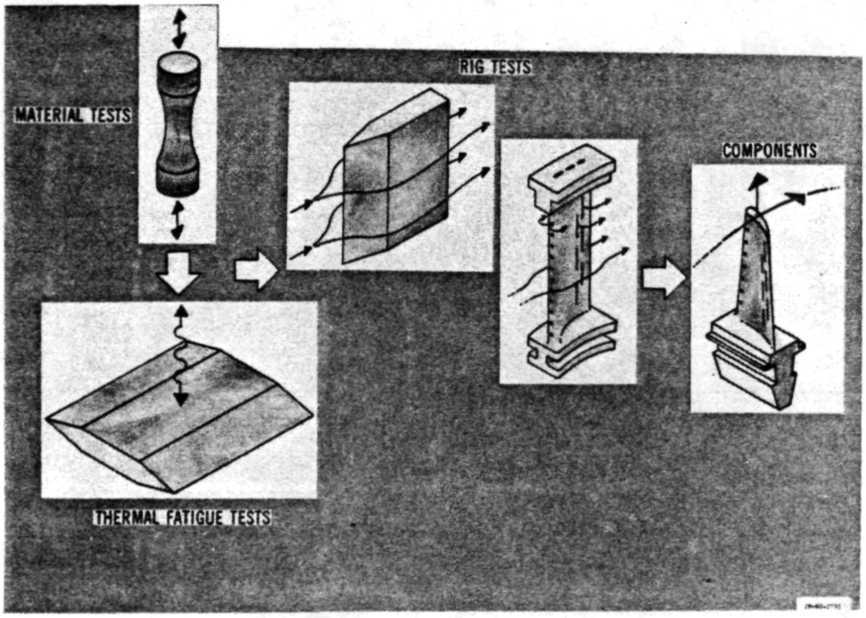

Figure 8. - Turbine component life prediction.

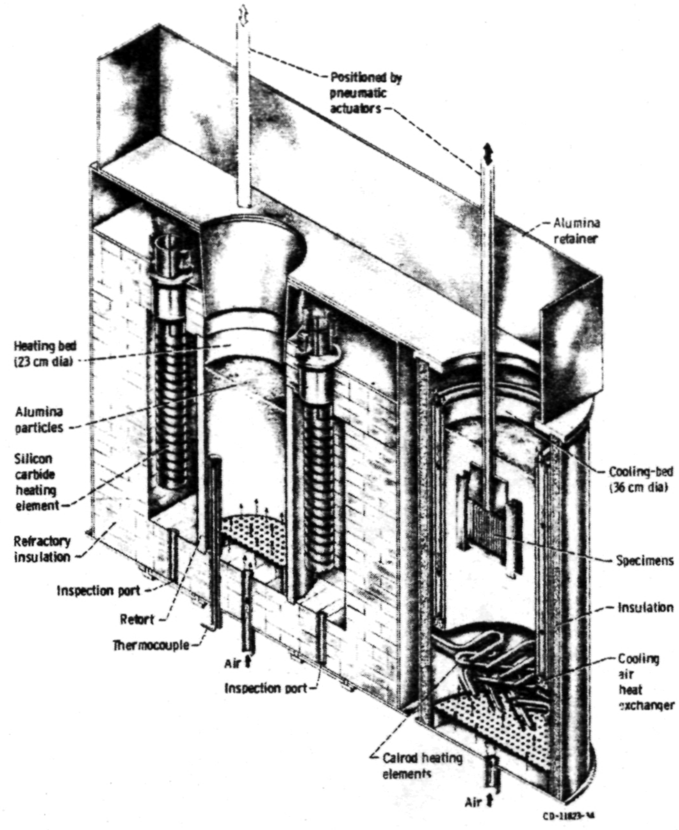

Figure 9. - Fluidized bed test facility.

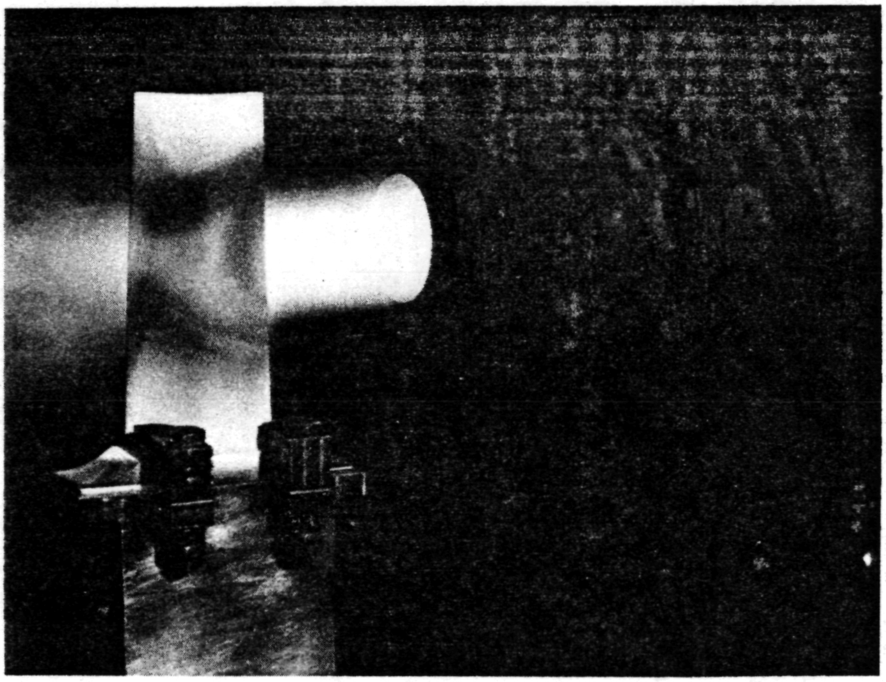

Figure 10. - Specimen thermal fatique in burner rig.

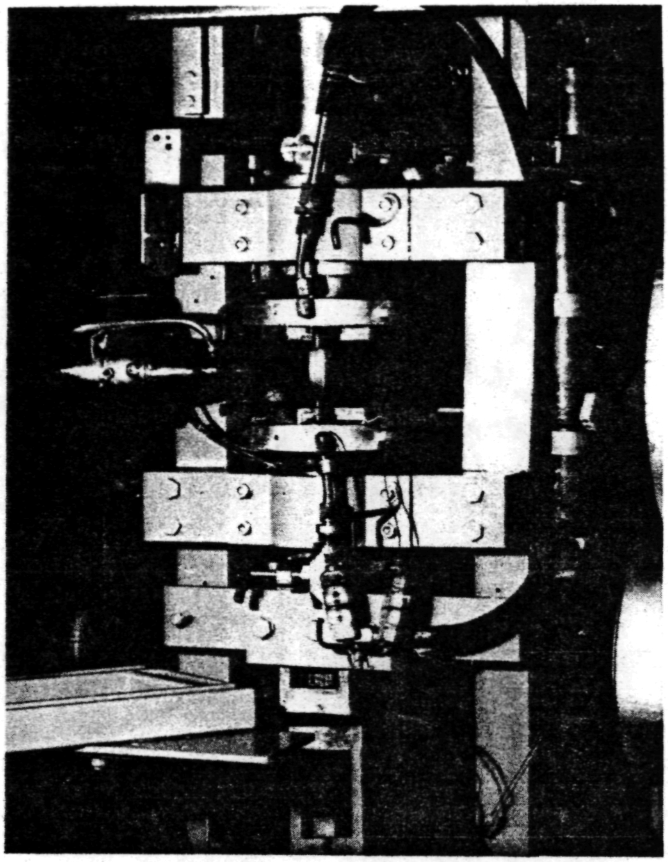

Figure 11. - Blade thermal fatigue in burner rig.

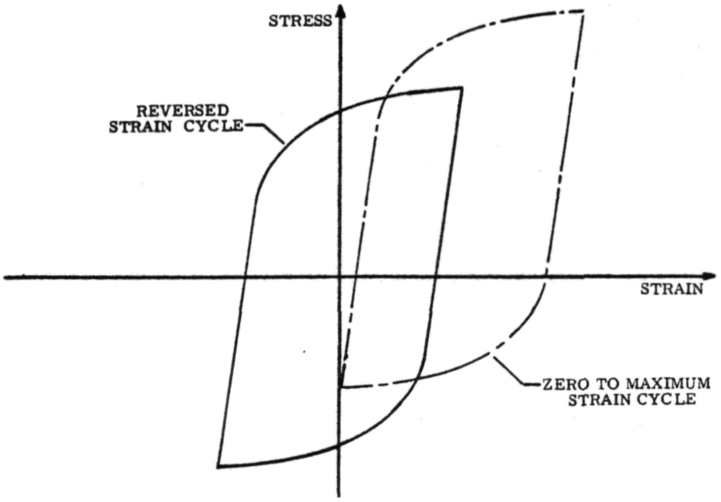

Figure 12. - Types of strain cycles.

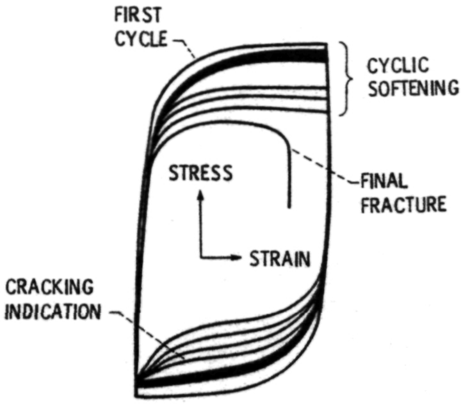

Figure 13. - Sample hysteresis loops.

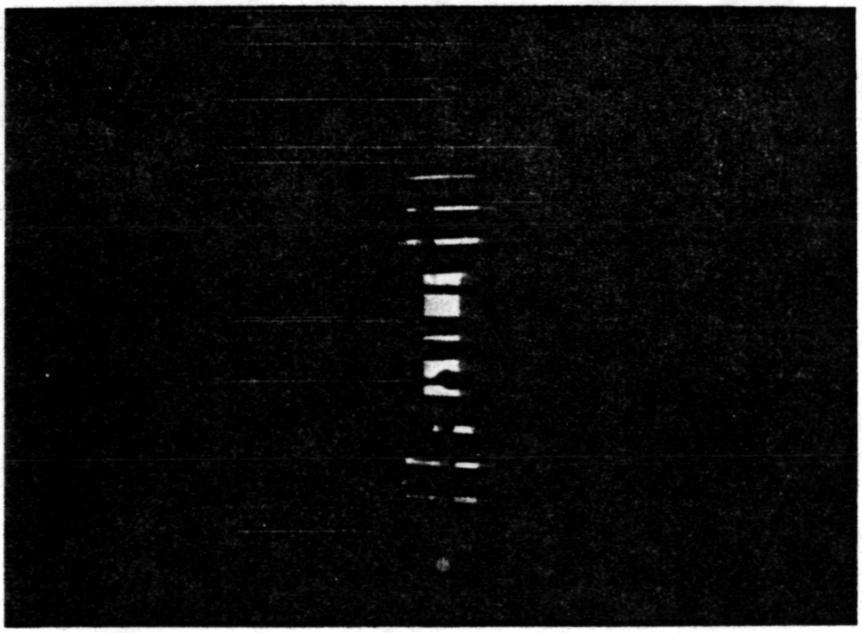

Figure 14. - Induction heating.

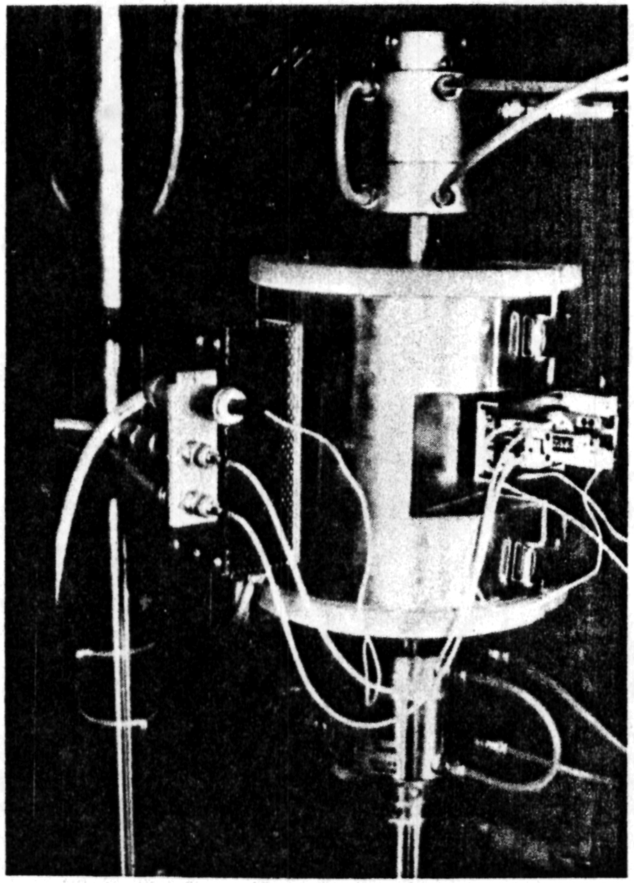

Figure 15. - Furnace heating.

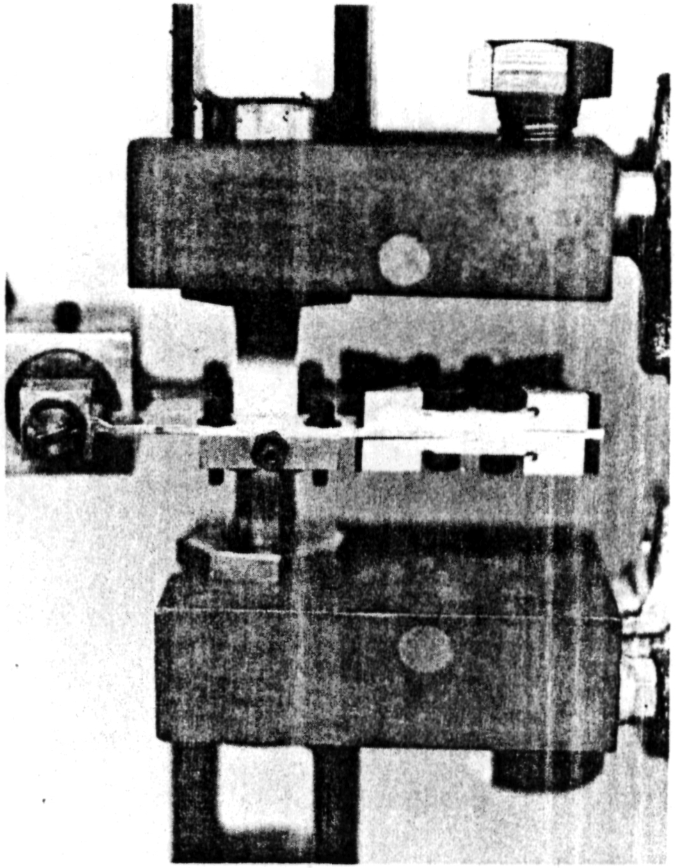

Figure 16. - Direct resistance heating with diametral extensometer.

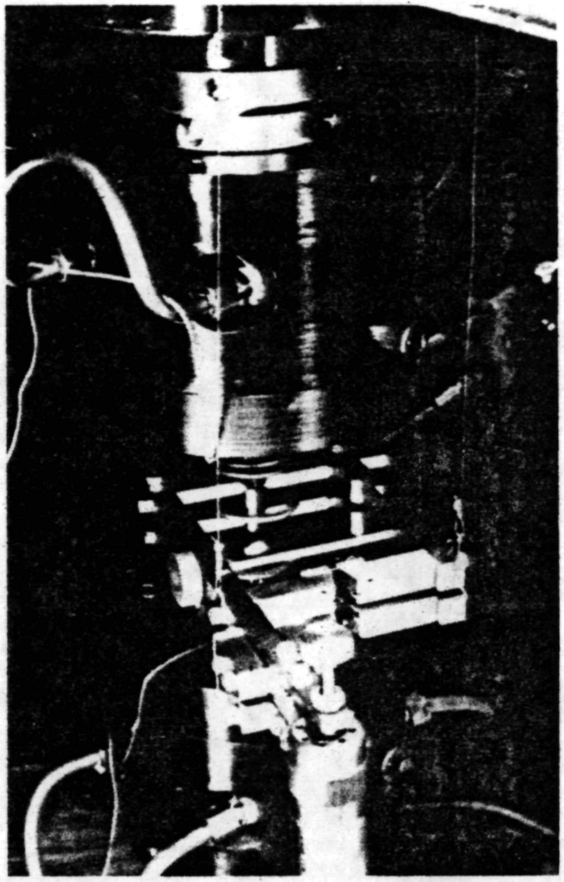

Figure 17. - Induction heating with longitudinal extensometer.

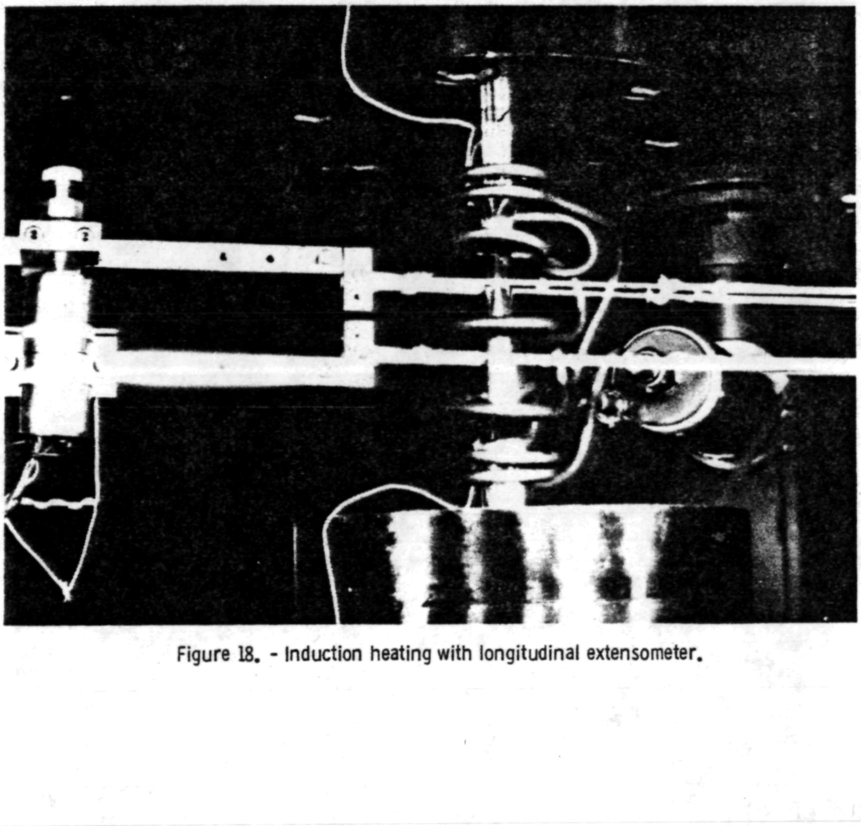

Figure 18. - Induction heating with longitudinal extensometer.

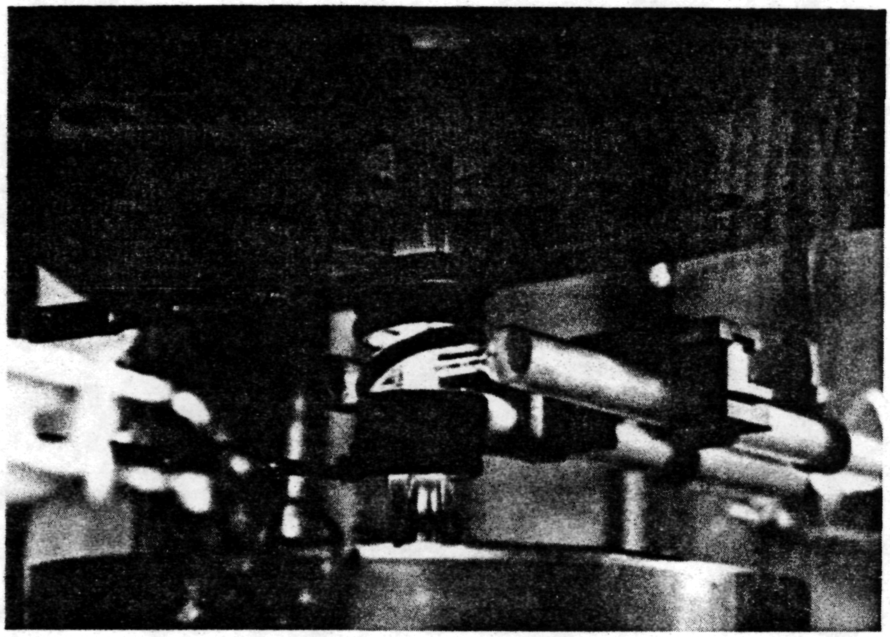

Figure 19. - Induction heating with diametral extensometer.

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16. Abstract

The major technology areas needed to perform a life prediction of an aircraft turbine engine hot section component are discussed and the steps required for life prediction are outlined. These include (a) the determination of the operating environment, (b) the calculation of the thermal and mechanical loading of the component, (c) the cyclic stress-strain and creep behavior of the material required for structural analysis, (d) the structural analysis to determine the local stress-strain-temperature-time response of the material at the critical location in the component, and finally, (e) from a knowledge of the fatigue, creep, and failure resistance of the material, a prediction of the life of the component. This paper focuses primarily on the area of material characterization and evaluation conducted for the purpose of calculating fatigue crack initiation lives of components operating at elevated temperatures.

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