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LIFE PREDICTION OF MATERIALS EXPOSED TO MONOTONIC AND CYCLIC LOADING — A TECHNOLOGY SURVEY

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16. Abstract

This Technology Survey Report is comprised of reviewed and evaluated technical abstracts for about 100 significant documents relating primarily to life prediction for structural materials exposed to monotonic and cyclic loading, particularly in elevated temperature environments. The Introduction to the report includes an overview of the state-of-the-art represented in the documents that have been abstracted.

The abstracts in the report are mostly for publications in the period April 1962 through April 1974. The purpose of this report is to provide, in quick reference form, a dependable source for current information on the subject field. It is a companion volume to NASA CR-134751, Life Prediction of Materials Exposed to Monotonic and Cyclic Loading - A Bibliography.

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FOREWORD

This Technology Survey Report was prepared by Martin Marietta Aerospace under Contract NAS 3-17640. It is one product of a research program initiated by the NASA Lewis Research Center to compile, evaluate, and organize for convenient access information on the mechanics of structural failure and structural materials limitations. The NASA Aerospace Safety Research and Data Institute (ASRDI) has technical responsibility for the research program. Preparation of this report was under the direction of George Mandel, ASRDI Program Manager.

Many people contributed to the preparation of the report. Their assistance and cooperation is appreciated and gratefully acknowledged. The authors wish to especially acknowledge the interest and assistance of the following individuals: H. Dana Moran, Battelle Memorial Institute; William F. Brown, Jr., John C. Freche, and Gary R. Halford, NASA Lewis Research Center; Walter P. Conrardy, Air Force Materials Laboratory; George R. Irwin, University of Maryland; and George C. Sih, Lehigh University.

KEYWORDS

Analysis methods; crack growth rate; crack initiation; crack propagation; creep; cumulative damage; cyclic loads; environmental effects; fatigue (materials); fatigue life; fracture (materials); high temperature; life prediction; low-cycle fatigue; temperature effects; thermal cycles; thermal fatigue.

PREFACE

Since June 1972 the Orlando Division of Martin Marietta Aerospace has supported the NASA Lewis Research Center's Aerospace Safety Research and Data Institute (ASRDI) in an investigation of the mechanics of structural failure and structural materials limitations. A series of technical reports have been produced.

Under Contract NAS 3-16681 a Register of Experts for Information on the Mechanics of Structural Failure was published as NASA CR-121200. Its purpose was to give visibility to a listing of recognized experts who might be available for consultation related to the mechanics of structural failure. This contract also produced other products: NASA CR-121201, Register of Sources of Information on the Mechanics of Stuructural Failure; NASA CR-121202, Bibliography of Information on the Mechanics of Stuructural Failure, and NASA CR-121199, Thesaurus of Terms for Information on the Mechanics of Structural Failure. The last of these reports is comprised of key words which facilitate access to an ASRDI mechanized data base that was augmented under Contract NAS 3-16681.

This Technology Survey Report is the result of one of several tasks included in NASA Contract NAS 3-17640. The contract provides for the expansion, revision and/or updating of NASA CR-121200 (Register of Experts), NASA CR-121202 (Bibliography), and the pertinent mechanized data base. It also provides for the preparation of two technology surveys, i.e., reports which include abstracts and assessments of key related documents published in the period April 1962-April 1974, or "classics" published prior to 1962. One technology survey reports on the availability and application of fracture toughness testing data. This survey describes information related to the problems of life prediction for aerospace structural materials subjected to specified environmental effects.

The focus of the report is the life prediction of materials exposed to monotonic and cyclic loading. Primary attention is directed toward low-cycle fatigue and thermal fatigue experienced at elevated temperatures equivalent to those found in the hot end of a gas turbine engine. Some visibility is given to information concerning high cycle fatigue data for materials used in components such as engine bearings. The report also includes a consideration of solar cell applications, the effect of cryogenic temperature and vacuum environments, and radiation effects, concentrating on experimental methodology having multiple use and data having broad meaning.

It is obvious that the foregoing scope is very broad. Because of limitations of time and budget and of ASRDI priorities, most effort was spent on information containing low-cycle and thermal fatigue data pertinent to high temperature environments. The report is comprised of interpreted and evaluated abstracts of about 100 key documents related to the subject. These documents have been surfaced and selected in a literature search performed between June 1972 and September 1974. Since a significant number of the documents relate to more than one aspect of the failure modes and mechanisms of structural materials, there are often multiple citations of the documents. All of the documents selected and abstracted for this technology survey report are included in ASRDI's mechanized data base. In addition, a majority of the references cited with the abstracted documents are also included in the ASRDI data bank. This affords a significant information resource for the interested researcher.

This report is a companion volume to NASA CR-134751, Life Prediction of Materials Exposed to Monotonic and Cyclic Loading - A Bibliography.

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SUMMARY

This Technology Survey Report is comprised of technical abstracts of 100 significant documents relating to life prediction for structural materials exposed to monotonic and cyclic loading, particularly in elevated temperature environments. Some consideration is given to other applications and other environments, primarily to show the applications of the same methodology in various environments. The Introduction to the report includes an overview of the State-of-the-art represented in the documents that have been abstracted.

The abstracts in the report are mostly for publications in the period April 1962 through April 1974. There are exceptions. In some instances a pre-1962 "classic" has been included because it is still the most authorative treatment available.

The prupose of the report is to provide, in quick reference form, a dependable source for current information on the subject field. The selection has been arbitrary but made with the guidance of outstanding researchers and authors in the field. The references supplied with the abstracts afford quick identification of additional documents.

INTRODUCTION-OVERVIEW OF THE REPORT

INTRODUCTION

AN OVERVIEW OF THE REPORT

This Technology Survey Report, in light of the qualifications cited above in the Preface, can only be a contribution toward the establishment of a larger and much needed information base. Nevertheless it is felt that the contribution is substantive and will cause the publication of other related, valuable knowledge. To introduce the abstracts included, the authors of the report have written this overview of the key contributions of the researchers represented by the abstracts. A significant reference list is offered to substantiate the authors conclusions.

The study of materials behavior at high temperature has been one of the most dynamic and productive since the development of the turbojet powered aircraft (ref. 1). The continuing development and improvement of the engine and associated high performance aircraft structure has provided a focus and driving force for this technology (ref. 2).

Basic and applied research has resulted in improvements in both performance and reliability. As alloys were improved to permit higher engine operating temperatures several performance improvements occurred. Fuel consumption decreased and thrust levels increased from about 500 pounds to over 50,000 pounds force. Significant understanding of materials behavior at elevated temperatures under fatigue and stress rupture conditions has been applied to life prediction of materials behavior in the engine environment (ref. 3). This resulted in an improvement of from 50 to over 5000 hours in the time between overhaul for typical commercial jet aircraft engines.

Today materials technology is challenged by environmental concerns about air and noise pollution as well as continuing pressure for better specific fuel consumption. Stated another way, materials must be provided which survive and respond satisfactorily at high temperatures and which also satisfy other operational constraints.

The NASA Lewis Research Center has been the focus of much of the effort to improve the high temperature behavior of materials. In a balanced program they have focused on improving both the reliability and performance of the materials employed in turbine engine components (ref. 4). This has involved an extensive program of basic mechanism and theoretical effort which has spawned both a number of life prediction approaches and significant alloy development. In addition the areas of protective coatings and basic engine design have and are continuing to receive much emphasis.

Until the mid-1960's the efforts directed toward understanding high temperature behavior were compartmentalized among the "classic disciplines" of creep, stress-rupture, fatigue, deformation phenomena, thermal stress and thermal shock (ref. 5). In that same period the mechanisms of plastic flow by dislocation motion were becoming more clearly understood due to the development and use of such powerful tools as X-ray analysis and electron microscopy.

These understandings led to the postulation that most high temperature phenomena were interrelated. Manson first presented these ideas in two publications in 1966, introducing some proposed relationships (ref. 6, 7). The philosophy of cumulative creep and fatigue damage was introduced at that time and helped to link the disciplines. It was shown that the interaction or as Manson characterized it the interface could account for the decreases in elevated temperature fatigue life observed. New terms and concepts such as creep-fatigue have been developed and given meaning. In the area of creep-fatigue two recent papers show an apparent significant effect of creep on fatigue at high temperatures (ref. 8, 9). This philosophy of creep fatigue interaction has not received universal acceptance, however. Convincing arguments also have been made about the environmental interaction being the significant factor in elevated temperature fatigue. Coffin and others have shown experimentally that the fatigue life at elevated temperatures is for some materials a function of frequency and can be increased several orders of magnitude at a vacuum of 10^{-8} Torr. (ref. 10, 11, 12).

The period before the mid-1960's was also characterized by extensive data generation and test technique development. This included refinement of the discipline of fractography, which more recently has been given additional depth with the wide spread use of scanning electron microscopy. This technique when used, has permitted a much more detailed look at fracture surfaces during high temperature testing. Collectively these techniques have revealed many aspects of cumulative damage and have led to better life prediction methodology.

With this background of detailed testing, basic understanding of mechanisms and detailed fractographic analysis, the last ten years has seen an effective development and refinement of theories. This has been examined in some detail in two recent reviews (ref. 1, 13). The concept of cumulative damage in high temperature fatigue was developed from Miner's Law and applied along with the method of Universal Slopes to begin the process of predicting behavior (ref. 14). These efforts resulted in linear damage rules and double linear damage rules (ref. 15, 16). More recently scientists at the NASA Lewis Research Center have introduced the concept of strainrange partitioning (ref. 17). This approach is based on cumulative damage concepts, and divides high temperature fatigue into its component strainranges. These ranges are classified as time independent plastic flow (P) and as time dependent plastic flow or creep (C). This gives rise to four possible strain ranges as shown in the table below:

TABLE I - STRAINRANGES

Notation	Tensile Strain	Compressive Strain
Epp	plastic	plastic
Epc	plastic	creep
Ecp	creep	plastic
Ecc	creep	creep

Each of these strainranges has associated with it a unique damage curve. The summation of these leads to life prediction. This technique has proven to be quite powerful and accurate. The development of closed loop testing for life prediction in the late 60's permitted the delineation of strainrange pertitioning to life prediction (ref. 17, 18).

The prediction of creep has been based on the cumulative creep laws expounded by Manson (ref. 6). These include (1) the time-hardening rule, (2) the strain-hardening rule, and (3) the life-fraction rule. More recently the concept of a minimum commitment station function approach has been introduced to refine the treatment of creep-rupture data for life prediction (ref. 19).

The use of a parametric approach to life prediction has been considered for the case of high temperature, low-cycle fatigue (ref. 20, 21). This is based on the concept that certain formulas can adequately define high temperature behavior which has been shown to have some validity.

A completely different approach to life prediction was introduced in 1972 by Payne (ref. 22). This statistical reliability approach had only recently become practical as large amounts of data on the service history of structures have been made available. The approach considers the statistical occurrence of failure and is not concerned with the detailed mechanisms of fatigue crack growth processes.

The maturing of fracture mechanics technology has led to a beneficial synthesis of the areas in terms of life prediction. S. O. Davis and L. F. Coffin, Jr., have recently examined the relationships between flaw size, flaw growth, crack tip plastic zone and critical flaw size (ref. 23, 13, 24). The concept of crack tip stress intensity factory was introduced and shown to be relatable to crack growth and fracture (i.e., service life). This focus on flaws and flaw growth has increased the importance of nondestructive testing technology to illuminate and monitor these dynamic flaws. Acoustic emission during low-cycle, high stress intensity fatigue has been well characterized (ref. 25). It was shown that acoustic emission as a precursor of failure may be employed both for the case of low-cycle, high-stress-intensity fatigue and for environmentally assisted fatigue. Fatigue life can also be estimated by combining fracture mechanics and acoustic emission techniques (ref. 26).

A recent review by C. J. McMahon, Jr., again called attention to the influence of the environment on high temperature life prediction (ref. 27). This paper illustrates that environment can often be a very important factor in the life of a sturcture and that our understanding is in the very early stages. Other investigators are taking a very basic approach to surface sensitive behavior by examining the basic nature of surfaces and how they interact with the environment (ref. 28). There remains much work to be done in this area to characterize behavior before adequate predictive technology is available. Other researchers have recently considered the effect of the environment and highlighted the lack of sufficient data on the behavior of materials when exposed to high temperatures and a chemically active environment.

In particular the extreme environmental sensitivity of titanium is shown indicating that much of the existing data from laboratory tests may be invalid.

The present state of high temperature materials behavior technology has paid considerable dividents in improved performance and reliability. The present high degree of development of conventional nickel-and cobalt-base super-alloys has resulted from the basic understanding of dislocation motion and defect structure. The use of these alloys at over 90 percent of their melting point leaves little margin for increased temperature capability. However, the application of fracture mechanics and sophisticated nondestructive evaluation technology will increase the reliability of these materials. This can lead to significant decreases in projected systems cost. The application of existing high temperature materials technology to the systems areas of analysis, design and operation has yet to realize the potential that has been exhibited by materials development. It has been shown for example that significant increases in fatigue life can be obtained by programmed loading and overloading sequences which could be introduced into service performance profiles (ref. 31, 32).

The summary of the present state-of-the-art highlights at least four areas where effort needs to be expended. The first is the area of technology transfer. A tremendous body of basic information on high temperature materials behavior exists. It has been only sporadically applied to practice. For example, as indicated earlier, the techniques of strainrange partitioning coupled with cumulative damage concepts can be powerful life prediction tools. The aircraft engine community has largely ignored these techniques. This is probably the result of the controversy over the role of creep vs environment on the high temperature fatigue behavior coupled with the volume of closed loop programed fatigue data required on the specific material of interest. The technology transfer between the materials behavior specialist and the design function continues to be a very pressing problem.

The second area of concern is the developing awareness of the influence of the environment, particularly corrosion fatigue at elevated temperatures. The basic information about the nature of surfaces and their interaction with the environment is only now being developed (ref. 28). In many instances the environmental interaction, particularly at elevated temperatures may be the most important consideration in life determination. The third area is information on the metal titanium. This metal is a key component of supersonic aircraft and the compressor end of turbojet engines. Titanium has demonstrated behavior different from other structural metals, particularly in terms of the environmental interaction.

The fourth area is the nondestructive technology of damage detection. There is insufficient damage detection feedback from actual systems to correlate the predictions and provide interactive improvements to the system.

In summary a great deal of progress has been made in understanding high temperature behavior of materials. Much of this has yet to be transferred to systems application where it could significantly affect improvements in reliability and performance. Further, the environmental challenges of the late 1970's have given new impetus to this type of research, which will continue to provide important contributions.

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TECHNICAL ABSTRACTS

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I. State of the Art Reviews and Overviews

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Key words: Analysis methods; bibliographies; brittle fracture; crack initiation; crack propagation; creep; creep properties; creep rupture; design; environmental effects; fatigue (materials); fatigue life; fatigue properties; fracture mechanics; high temperature; high temperature environments; life prediction; metallic materials; plastic properties.

AN OVERVIEW OF HIGH TEMPERATURE MATERIAL FATIGUE; ASPECTS COVERED BY THE 1973 INTERNATIONAL CONFERENCE ON CREEP AND FATIGUE

Manson, S. S. and Halford, G. R. (Case-Western Reserve Univ., Cleveland, OH; National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

ASTM, ASME, IME, Int. Conf. Creep and Fatigue in Elevated Temperature Applications, Philadelphia, PA (23-28 September 1973), and Sheffield, England (1-5 April 1974).

The International Conference on Creep and Fatigue included 82 papers. This paper is a summary of the papers presented at the conference. It is divided into six major subject areas: 1 - Materials development and characterization, this inclues papers concerned with the determination of properties, and papers concerned with data analysis; 2 - Environmental factors, treating fatigue life in air, vacuum, helium, iodine, sodium and radiation environments; 3 - General fatigue life relationships, bringing up the subject of strainrange partitioning, linear damage rule, strain hardening exponent, and others; 4 - Crack growth laws, pointing out factors that govern crack growth rate (stress intensity, specimen type, nature of loading, and mean stress); 5 - Design and service experience, dealing with specific components of real life structures; and 6 - Design codes, outlining the United States and European points of view. It is pointed out that attention must be directed to crack propagation as well as crack initiation, and that concepts of fracture mechanics are being extended to consider plastic and creep fractures as well as brittle (elastic) failure. The paper concludes with a list of references, which include all the papers presented at the conference. Selected figures from these papers are also included.

Comment:

The authors have taken this opportunity to not only discuss the papers at the conference, but to make a statement of their own on the progress and potential of high temperature materials technology. Their incisive discussions illuminate the present sophistication of materials behavior and prediction understanding. They show the potential of the strainrange partitioning and station function approaches to life prediction.

Important References:

The author's list of references includes all 82 papers from the conference, many of which are included as key papers in this document. In addition, the authors referred to several classic papers to support their thesis.

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Comment:

Manson's book is a basic text on this subject which covers in detail the subject from the basic standpoint. It is particularly useful because of the author's wide experience and ready accessibility to the numerous examples of thermal stress and low cycle fatigue failures, particularly in gas turbine machinery. The subject and author indices contribute to the usefulness of the book.

Important References:

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Key words: Analysis methods; brittle fracture; creep; cumulative effects; cyclic loads; ductility; elastic-plastic behavior; failures (materials); fatigue (materials); life expectancy; life prediction; low-cycle fatigue; metallic materials; structural safety; temperature effects; thermal cycles; thermal shock.

INTERFACES BETWEEN FATIGUE, CREEP, AND FRACTURE
Manson, S. S. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)
Int. J. Fract. Mech. 2, No. 1, 327-363 (1966).

A discussion is presented of the fatigue process as one of initiating a crack and propagating it to failure, and a formula is presented for estimating the effective point of crack initiation. This formula is speculatively applied to three interface problems in fatigue: (a) life of a quasi-brittle material which can sustain only a relatively small crack before failure takes place according to the laws of fracture mechanics. An example is presented to illustrate the procedure and to indicate the probable validity of the approach; (b) Estimation of the fatigue characteristics at high temperatures within the creep range of materials. By assuming that intercrystalline cracking has the effect of by-passing much of the crack initiation process, the number of cycles to failure becomes related more importantly to the crack propagation period. A numerical procedure for estimating life in terms of applied strainrange is described, and its validity investigated by application to a number of materials for which data have been presented in the literature; (c) Application of a linear damage rule individually to crack initiation and crack propagation. It is possible to predict the effect of order of application of loads in a two-step cumulative fatigue test. The method is checked by using literature data.

The common thread in the treatment of the three problems discussed here is the value of separating the fatigue process into one of crack initiation and crack propagation. That such a separation is desirable is now becoming more and more recognized in other published investigations. The difficulty is in defining the meaning of a crack and assigning quantitative formulae to use in computations involving these phases. Only a first approach is taken in this report toward a quantitative aspect.

While the application is intended for the analysis of laboratory specimens rather than engineering structures, the principles involved may perhaps be extended to practical geometries. For example, we have used local strain as a measure of crack initiation, and therefore the relations established between strain range and cycles to crack initiation may continue to be valid for other geometries as well as the test specimen from which the relations are evolved. The crack growth process would, however, depend on geometry. Perhaps an approach expressing instantaneous crack growth in terms of microscopic local strain range, would prove more useful in the treatment of general problems, instead of attempting to express the crack propagation as a closed-form solution that would be applicable only to specific cases. Likewise the fracture condition for quasi-brittle materials, while treated specifically for the laboratory specimen, could be extended, according to the fast-developing field of fracture mechanics, to other geometries by the same method of treatment. Similar extensions could perhaps be made to the subject of cumulative fatigue, using small laboratory specimens to obtain information on crack initiation and crack growth laws together with fracture mechanics to obtain the damage rule for the crack propagation stage. Also, in the discussion of high temperature the main emphasis has been on intercrystalline cracking. But the principles involved may have more significant generality. A similar approach may have utility in the treatment of surface imperfections and pernicious environments, that would also have the effect of cutting short the crack initiation period more than the propagation period.

Comment:

The author discussed in detail much of the work in progress at the time to improve the understanding of and prediction of fatigue life. Many of the ideas discussed in the paper have since matured to become active subjects of research and related theories. The author presents an overview which interrelated the technologies of fatigue, creep and fracture by showing the mechanistic relationships at the microstructural level and casting everything in terms of a cumulative damage philosophy.

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4. Manson, S. S., Nachtigall, A. J. and Freche, J.C., A Proposed New Relation for Cumulative Fatigue Damage in Bending, Proc. ASTM 61, 679-703 (1961).

5. Boettner, R. C., Laird, C. and McEvily, Jr., A.J., Crack Nucleation and Crack Growth in High Strain Low-Cycle Fatigue, Trans. AIME 233, No. 2, 379-387 (February 1965).

See Also:

1. Manson, S. S., The Challenge to Unify Treatment of High Temperature Fatigue - A Partison Proposal Based on Strainrange Partitioning, ASTM STP 520, 744-782 (1973).

2. Halford, G. R., Hirschberg, M. H. and Manson, S. S., Temperature Effects on the Strainrange Partitioning Approach for Creep Fatigue Analysis, ASTM STP 520, 658-669 (1973).

Key words: Analysis methods; crack initiation; crack propagation; creep; creep analysis; cumulative damage; fatigue (materials); fracture mechanics; fractures (materials);high temperature; strainrange partitioning; universal slopes.

A SURVEY OF THE EFFECTS OF NONSTEADY LOAD AND TEMPERATURE CONDITIONS ON THE CREEP OF METALS
Manson, S. S. and Brown, Jr., W. F. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)
ASTM STP 260, 63-104 (December 1959).

Published information relating to the effects of non-steady load and temperature conditions on the creep of various metals and alloys is surveyed. The information is presented in three sections. The first considers fundamental investigations of "stable" materials, where the object was to accurately study certain basic effects such as the recovery of strain or loss of strain hardening on removal of the load. The second section summarizes the data for nonsteady creep of engineering alloys subjected to complex variations in load and/or temperature. The final section is devoted to a review of the several analytical procedures which are proposed to calculate the nonsteady behavior from steady state tests.

Comment:

This classic statement of the state-of-the-art examined much of the basic information relating to the analytical understanding of creep processes. It was shown that a number of mechanical and metallurgical factors must be considered when component design involves changing load and/or temperature at high temperatures. These include: a) anelastic effects on the creep flow; b) loss of strain hardening; c) changes in the microstructure; d) thermal stresses arising from nonuniform heating of the body; e) intergranular oxidation or corrosion; and f) thermally induced internal distortions. It will be recognized that the relative importance of these various factors will depend on the material and loading conditions involved.

Key words: Creep; creep properties; cyclic loads; metallic materials; random load cycles; temperature effects; thermal cycles; variable temperature.

MECHANICAL BEHAVIOR OF MATERIALS AT ELEVATED TEMPERATURES
Dorn, J. E., Ed., McGraw-Hill Book Co., New York, NY (1961)

Comment:

This book on the behavior of materials at elevated temperatures is an expansion of a lecture series by twelve of the outstanding contributors to the field. It contains fifteen chapters as follows. The general introduction by F. R. Shanley treats the relationships between structural design and the prediction of the mechanical behavior of materials under various conditions of loading and environment. J. J. Gilman contributed a chapter on the nature of dislocations, which discussed the role of crystallinity in plastic deformation and the nature of the crystallographic line defects found in crystals. J. C. Fisher considered the behavior of dislocations which involves the stress fields and mobility or lack of it for these defects and in particular the ability of the defect for multiplication. G. Schoech contributed two chapters one on the thermodynamic principles in high-temperature materials followed by a chapter on the theories of creep. In the first he considers the thermodynamics of lattice defects such as vacancies and solute atoms as related to creep. In the chapter on theories of creep he considered the time laws of creep; the creep mechanisms; rate controlling process and the effects in technical alloys. J. Washburn discussed the mechanism of fracture by consideration of the Griffith crack phenomena, crack nucleation and propagation at elevated temperature and the ductile-brittle transition temperature. E. R. Parker discussed theories of fatigue from a phenomenological standpoint consisting of crack nucleation and crack growth. H. Conrad contributed two experimentally based chapters, first on the experimental evaluation of creep and stress rupture and second on the role of grain boundaries in creep and stress rupture. These chapters review the advances in testing techniques which illuminated the mechanisms of creep and stress rupture and, in particular, the microstructural aspects of creep. His second chapter focuses on the role of grain boundaries both in terms of sliding and pinning of deformation. Grain boundary failure as a function of the equicohesive temperature for transgranular or intergranular failures. R. W. Guard discussed alloying for creep resistance in terms of the effect on deformation resistance, fracture resistance, recovery resistance and microstructural stability. J. A. Pask discussed the mechanical properties of ceramic materials, particularly at elevated temperatures where they exhibit some creep characteristics. J. D. Lubahn focused on the inelastic or plastic flow part of deformation phenomena in his chapter. He provides considerable insight into the nature of the creep test and the implications of an interrupted or stepped test. S. S. Manson contributed two chapters, one on thermal stresses and thermal shock and the other on creep under nonsteady temperatures and stresses. In these two chapters he introduces the nonisothermal consideration derived from gas turbine engine experience. In particular, he shows that additional mechanisms may be pertinent to nonsteady stressing and heating. He also discusses analytical methods of proposed creep laws involved in nonsteady loading situations approaching the concept of cumulative damage. B. J. Lazan in a final chapter discussed damping and resonance fatigue properties of materials considering elevated temperatures.

This book now almost 15 years old, is still an excellent overall summary of high temperature creep and stress rupture behavior of materials.

Important References:

Each chapter has an extensive list of references which delve into the original work in each area.

Key words: Creep; creep properties; creep rupture; creep strength; dislocations (materials); fatigue (materials); grain boundaries; high temperature; mechanical properties; metallic materials; microstructures; stress rupture; temperature effects; thermal shock; thermal stresses.

FATIGUE
Coffin, Jr., L. F. (General Electric Co., Schenectady, NY)
Annu. Rev. Mater. Sci. 2, 313-348 (1972)

This review attempts to approach the fatigue problem from an interdisciplinary position, emphasizing a broader view that may help to bridge the gap between strongly focused viewpoints. Particular emphasis will be given to the effect of temperature and to environment since these topics are close to the author's present interest, and because, by their inclusion, a broader view of the fatigue problem can be had.

The fatigue process is considered in three stages: nucleation and early growth, crack propagation through a plastic regime, and crack propagation through an elastic regime. Each of the stages is discussed, where practical, from three approaches: the phenomenological, the microstructural, and the atomic, so that some perspective may be gained on the relative roles and states of development of each approach to the total problem.

Fatigue as a crack propagation process, owes its existance to the ability of the crack tip, once blunted by the application of a tensile stress, to resharpen upon stress reversal. Without this feature the crack remains blunt and the regenerative aspects of the failure process are halted. Efforts toward a clearer understanding of the substructural features of the cyclic strain-hardening processes and the possible application of this understanding to better control the strain hardening exponent in a particular alloy would appear to be the most rational direction to follow for improved fatigue-crack-propagation resistance in structural metals. From a phenomenological view the strain-controlled description of the fatigue process involved consideration of the separate effects of elastic and plastic strain, whether time-independent or time-dependent failure was being considered. Depending upon the level of strain, one or the other or both of these strain quantities govern fracture. This approach has been applied to practical problems rather successfully, since it translates quite readily into the analytical procedures of the design engineer. Difficulties arise when the loading history departs significantly from the testing methods used to determine phenomenological relationships.

Account must be taken of the very important effect of environment and temperature on crack growth. Attention has been given here to the similarities between the two, supporting the position that an air environment can account to a large degree for the reduced fatigue resistance at elevated temperature.

The approach to the fatigue problem of a viewpoint ranging from the substructural to the phenomenological is readily apparent to those who work closely with the physical aspects of the problem, it has not been fully recognized by those in the engineering profession, particularly when dealing with complex problems such as notch geometries, variable loadings, thermal fatigue, and the like.

Comment:

Dr. Coffin in this wide ranging review has made a significant and successful effort to synthesize the variant technologies involved in the understanding of fatigue and the application of this understanding to metallic systems.

Important references:

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3. Coffin, Jr., L. F., The Effect of Frequency on High-Temperature, Low-Cycle Fatigue, AFFDL TR-70-144, 301-312 (September 1970).

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Key words: Crack initiation; crack propagation; design criteria; environmental effects; fatigue (materials); fatigue life; high temperature environments; microstructures; plastic zone; structural reliability.

FATIGUE AT HIGH TEMPERATURE
Coffin, Jr., L. F. (General Electric Co., Schenectady, NY)
ASTM STP 520, 5-34 (August 1973).

It was the author's intent to treat the high-temperature fatigue problem as a failure process in a notch in some structure in terms of nucleation and early growth at the notch-root, high-strain crack propagation through the plastic zone of the notch, and elastic crack growth to ultimate failure. A number of points were made and are summarized here:

1. In developing models employing constitutive equations and failure criteria for structural design more attention needs to be paid to fatigue as a process of failure by nucleation and growth.

2. Greater attention should be given to the transition fatigue life in determining the approach taken to the problem both in testing and design.

3. More effort is needed in the development of improved constitutive equations for elevated stress analysis commensurate with the advances that have occurred in computational methods.

4. Fatigue nucleation at elevated temperature is very complex. Greater attention to the categorization of the multiplicity of fatigue nucleation mechanisms is required, together with recognition of the specific aspects of the environment.

5. More work in the development of crack growth relationships to the regime of initiation and early growth would be helpful in extending design crack growth procedures to cover a greater proportion of the total fatigue process.

6. Although progress has been made in studying high-strain crack growth, much more effort is needed, particularly to the effect of very low frequencies and of various atmospheres on specific materials.

7. It has been shown here that the environment may be more important than creep in fatigue failure. Greater attention should be paid to the effects of specific atmosphere in future work in material evaluation and failure criteria.

8. Studies on mechanisms for ratchetting and investigations of failure criteria for cyclic-monotonic strain interaction at elevated temperature should receive more attention.

Important References:

1. Coffin, Jr., L. F., The Effect of Frequency on the Cyclic Strain and Low Cycle Fatigue Behavior of Cast Udimet 500 at Elevated Temperature, Met. Trans. 12, 3105-3113 (November 1971).

2. Manson, S. S., Halford, G. R. and Hirschberg, M. H., Creep-Fatigue Analysis by Strain-Range Partitioning, NASA-TM-X-67838 (1971).

3. Nachtigall, A. J., Klima, S. J., Freche, J. C. and Hoffman, C. A., The Effect of Vacuum on the Fatigue and Stress-Rupture Properties of S-816 and Inconel 550 at 1500°F, NASA-TN-D-2898 (June 1965).

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5. Coffin, Jr., L. F., The Effect of High Vacuum on the Low Cycle Fatigue Law, Met. Trans. 3, 1777-1788 (July 1972).

6. Boettner, R. C., Laird, C. and McEvily, A. J., Crack Nucleation and Growth in High Strain Low Cycle Fatigue, Trans. AIME 233, No. 2, 379-387 (1965).

Key words: Corrosion; crack initiation; crack propagation; deformation; elastic properties; environmental effects; failures (materials); fatigue (materials); fracture analysis; high temperature; metallic materials; microstructures; plastic properties; stress analysis; thermal fatigue.

FATIGUE, A COMPLEX SUBJECT - SOME SIMPLE APPROXIMATIONS
Manson, S. S. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)
Exper. Mech. 5, No. 7, 193-226 (July 1965)

Comment:

A wide ranging discussion of the fatigue spectrum is presented. On the one hand, the present state of understanding of the mechanism is reviewed and the complexity of the process observed. On the other hand, some approximations useful in design are outlined and their application illustrated.

The usefulness of photoelastic techniques in illuminating the stress distribution in the vicinity of a crack as a contributor to the understanding of fatigue is illustrated. The use of transmission electron microscopy and replica techniques predating the development of scanning electron microscopy are shown. The techniques of NDE are also discussed.

The strain cycling concepts are discussed in detail. The development of strain range concepts in which a universal slope of the elastic strain range and for the plastic strain range were postulated. These slopes are for a linear representation on log strain range/log cycles failure plots. A geometric summation of these universal slopes leads to a failure curve which is a distinct simplification of the data. It shows that at low cycles to failure the curve becomes asymptotic to the plastic strain range line, while at high cycles it becomes asymptotic to the elastic strain range line. With these concepts an attempt to establish this diagram for specific materials based on materials variables such as reduction in area, tensile strength, yield stress and notch sensitivity was undertaken. It was shown that these relationships could be established and measured fatigue life and predicted fatigue life correlated within a life factor of 2 for better than 60 percent of the data.

Cumulative fatigue damage concepts were discussed in detail. It was shown that these concepts are applicable to many fatigue situations although the phenomena of strain softening and strain hardening present difficulties.

The author concludes with a brief survey of the fundamental aspects of fatigue and in particular the events occurring in the material that influence the final fracture.

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2. Oppel, G. U. and Hill, P. W., Strain Measurements at the Root of Cracks and Notches, Exp. Mech. 4, No. 7, 206-211 (1964).

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9. Gatts, R. R., Application of a Cumulative Damage Concept to Fatigue, J. Basic Eng. 83D, No. 4, 529-540 (1961).

Key words: Crack analysis; crack detection; crack propagation; crack tip plastic zone; cumulative effects; fatigue (materials); fatigue properties; low-cycle fatigue; photoelastic measurements; S-N diagrams; strain; stress; x-ray diffraction.

FATIGUE AT HIGH TEMPERATURE - PREDICTION AND INTERPRETATION
Coffin, Jr., L. F. (General Electric Co., Schenectady, NY) Proc. Inst. Mech. Eng. London 188 (September 1974)

The significant developments in fatigue over the last twenty years as they pertain to the prediction of life in high-temperature service are reviewed. Particular attention is given to the interpretation of fatigue test results for both low and high cycle fatigue at room and elevated temperatures. Emphasis is given to such effects as environment, frequency and strain rate, metallurgical factors, wave shape and thermal cycling, and some attempt is made to sort out their relative improtance. Applicability of low-cycle fatigue information to notch geometries is discussed. Lastly considered is the significance of these several factors to the current state of life prediction as well as to future directions for development of this important topic.

Comment:

Dr. Coffin in the James Clayton Lecture has attempted the difficult job of placing this technology in perspective. He presents some very convincing data illustrating the frequency/environment effects on high temperature fatigue. In this experimental illustration he shows that in A286 the fatigue life in a vacuum is the same at 593°C and 20°C, while in air the degradation between 20°C and 593°C is two to three orders of magnitude. He also illustrates how the smooth specimen simulation concept may be applied to the prediction of notch fatigue behavior at high temperatue with low frequencies or with hold times.

He summarizes the challenge of the fatigue problem for the future including:

(a) the development of appropriate constitutive equations to permit wider application of finite element analysis to cycle problems;

(b) the development of predictive methods to account for the multiplicity of effects discussed frequency or strain rate, environment, time-dependent material behavior, wave shape, and thermal fatigue;

(c) attention to the above effects in high-strain crack growth and consideration of high-strain crack growth techniques for predictive purposes;

(d) the merging of high-temperature, low-cycle fatigue phenomenology with linear elastic crack growth analysis through the concepts of smooth specimen simulation;

(e) clearer definition of the role of environment both with regard to nucleation and propagation particularly with respect to those situations corresponding to service applications.

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9. Henry, M. F., Solomon, H. D. and Coffin, Jr., L. F., A Comprehensive Characterization of the High Temperature Fatigue Behavior of A286, ASTM, ASME, IME, International Conference Creep and Fatigue in Elevated Temperature Applications, Philadelphia, PA (23-28 Sept. 1973), and Sheffield, England (1-5 April 1972).

10. Solomon, H. D. and Coffin, Jr., L. F., The Effects of Frequency and Environment on Fatigue Crack Growth in A286 at 1100°F, ASTM STP 520, 112-122 (1972).

11. Halford, G. R., Hirschberg, M. H. and Manson, S. S., Temperature Effects on the Partionioned Strain-Range Life Relationships for Creep Fatigue Analysis, ASTM STP 520, 658-669 (1972).

Key words: Crack analysis; crack propagation; cyclic loads; cyclic testing; environmental effects; experimental data; fatigue (materials); fatigue life; frequency effects; high temperature environments; life prediction; low-cycle fatigue; metallic materials; notch tests; oxidation; thermal cycles.

II - Creep of Materials

THE STATIC AND CYCLIC CREEP PROPERTIES OF THREE FORMS OF A CAST NICKEL ALLOY
Harrison, G. F. and Tilly, G. P. (National Gas Turbine Establishment, Farnsborough, England)
Proc. ASTM, ASME, IME, Int. Conf. Creep and Fatigue in Elevated Temperature Applications, Sheffield, England. 222.1-222.9 (1-5 April 1974)

The static and cyclic creep properties of conventionally cast, directionally solidified and single crystal forms of a cast nickel superalloy, MAR M246, have been evaluated at 850°C and 900°C. Tensile and compressive creep curves have been obtained at constant stress and the results analyzed using power law creep terms. Typically, directionally solidified specimens have tensile lives twice those of comparable conventionally-cast materials, and rupture strains three or four times greater. Increase in specimen size raised the life of conventionally cast material but had no effect on single crystals. Differences between tensile and compressive creep properties were accentuated in the tertiary stages of deformation. No improvement in compressive creep resistance was obtained using directionally solidified or single crystal specimens. Equations developed previously from strain hardening theory gave an accurate estimate of behavior under cyclic tension. This theory has been extended to include push-pull loading and is shown to give a satisfactory correlation with the data.

Comment:

The data demonstrate the superior properties of the directionally solidified material in the critical tensile creep regime, which is typically the design criteria for gas turbine blades.

Important References:

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2. Tilly, G. P. and Harrison, G. F., Comparison Between Tensile and Compressive Creep Behavior of a 11% Chromium Steel, J. Strain Anal. 7, No. 3 (1972).

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Key words: Coatings; creep; creep properties; creep strength; cyclic creep; cyclic loads; directional solidification; high temperature; nickel alloys; static loads; tensile creep.

STRESS RUPTURE OF A DISPERSION STRENGTHENED SUPERALLOY
Cairns, R. L. and Benjamin, J. S. (International Nickel Co., Inc., New York, NY)
J. Eng. Mater. Technol. 10-14 (January 1973)

A dispersion strengthened nickel-base superalloy, designated IN-853, has been made by a new process called mechanical alloying. This provides a long sought combination of properties typical of dispersion strengthened and precipitation hardened materials. The alloy has flat rupture curves over a wide temperature range. Rupture stress/temperature curves for the alloy show a transition separating the low temperature regime where precipitation hardening controls the strength, and the high temperature range where dispersion strengthening predominates. The slope of a Larson-Miller plot of stress rupture temperature vs stress rupture test data also decreases at high values of that parameter. At high temperature rupture stress is less sensitive to temperature changes than is the case with conventional nickel-base superalloys. At a fixed stress level the rupture life of the dispersion strengthened superalloy is more sensitive to temperature changes.

Comment:

This paper introduces a new class of alloys which may slightly expand the high temperature range of gamma prime strengthened nickel base superalloys. These offer promise of improvements in turbine operating temperatures when they are employed as turbine blades.

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3. Eiselstein, H. E., Metallurgy of a Columbium Hardened Nickel-Chromium Iron Alloy, ASTM STP 369 (1965).

Key words: Creep rupture; creep strength diagrams; dispersion strengthened materials; high temperature tests; mechanical alloys; nickel alloys; precipitation hardening.

THE PROPAGATION AND PROPERTIES OF CAST BORON-ALUMINUM COMPOSITES
Hill, R. J. and Stuhrke, W. F. (AVCO Corp., Lowell, MS.; Air Force Materials Lab., Wright-Patterson AFB, OH)
Fiber Sci. Technol. 1, No. 1, 25-42 (January 1968)

A simulated pressure casting technique was used for producing high modulus and improved tensile strength reproducible boron-aluminum composite structures comprising both continuous and discontinuous fibers. The fibers used were both, uncoated and coated - some with nickel electroless plating and some with aluminum. The preheating was performed in argon as well as in air. The optimum conditions consisted of vacuum infiltration with aluminum at temperatures between 720°C and

800°C for times of two to four minutes. Although voids may be present in the discontinuous case, these are entirely absent from specimens of continuous fibers prepared in the correct temperature range. It is shown that there is no significant difference in either microstructure or mechanical strength for specimens produced in either argon or air. There are large differences, however, between uncoated- and nickel-coated fiber specimens. The uncoated fibers produce superior specimens in every respect. Both continuous- and discontinuous-aligned fiber specimens have been prepared by this method.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 164).

CREEP OF PRESSURE VESSELS

Penny, R. K. and Marriott, D. L. (Liverpool Univ., England)

ASTM ASME, I.M.E., Int. Conf. Creep and Fatigue in Elevated Temperature Applications, 204.1-204.9 Philadelphia, Pa. (23-28 September 1973), and Sheffield, England (1-5 April 1974).

A series of tests were made on model aluminum pressure vessels at 180°C. There were two objectives in this work: (1) to generate experimental data on creep of complex components, and (2) to assess the ability of some of the analytical tools at present available to designers for strain accumulation and rupture predictions. Three pressure vessels have been creep tested to rupture so far, two of slightly different configuration, under steady internal pressure, and a third under cyclic pressure conditions. A finite difference analysis has been used to predict deformations, and experimental results are also compared with the approximate reference stress techniques. Some attempt has been made to predict rupture life using both finite difference, and reference stress methods and these predictions have been compared with experiments.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 159).

TIME-TEMPERATURE PARAMETERS - A RE-EVALUATION AND SOME NEW APPROACHES

Manson, S. S. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

Time-Temperature Parameters for Creep-Rupture Analysis, Proc. Symp. Time-Temperature Parameters; Methods and Applications for Creep Rupture Data I and II, Mat. Eng. Cong., Detroit, Mich., ASM Publication D8-100, 1-113 (October 1968)

A critical evaluation is presented of commonly-used time-temperature parameters and their validity for use in extrapolations of stress-rupture properties to long times. The limitations of parametric forms and methods of determining associated constants are discussed and new approaches are presented which overcome many of these limitations. New parametric forms are also suggested. Both graphical and high speed computer methods are described. A station-function procedure is introduced for minimizing errors associated with conventional use of polynomial approximations. Parameters with universalized constants are discussed and their limitations outlined. The potential effect of material instabilities on the invalidation of predictions used by time-temperature parameters is considered, and possible procedures for improving predictions for cases involving such instabilities are discussed.

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Key words: Analysis methods; creep; creep rupture; high temperature; life (durability); metallic materials.

A SPECIALIZED MODEL FOR ANALYSIS OF CREEP-RUPTURE DATA BY THE MINIMUM COMMITMENT, STATION-FUNCTION APPROACH

Manson, S. S. and Ensign, C. R. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

NASA-TM-X-52999

The use of minimum commitment, station-function approach for correlating creep-rupture data is discussed. A hypothesized time-temperature-stress relation is taken in sufficiently general form to include all commonly used parameters. The functional forms involved in the relation are not taken into analytical form; rather they are defined as "station functions" - their numerical value at selected station values of the independent variable. Using station functions not only avoids "forcing" the pattern of the data, but provides an incidental benefit in avoiding ill conditioning of the system of resulting equations, which are computer-solved for the optimum data representation. This feature also contributes to the objectiveness of the method, and gives each time-temperature parameter consistent with the model an equal chance to demonstrate itself as the correct one.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 83).

A CRITICAL ASSESSMENT OF THE LIFE FRACTION RULE FOR CREEP-RUPTURE UNDER NONSTEADY STRESS OR TEMPERATURE

Woodford, D. A. (General Electric Co., Schenectady, NY)

ASTM, ASME, IME, Int. Conf. Creep and Fatigue in Elevated Temperature Applications, 180.1-180.6 Philadelphia, PA (23-28 September 1973), and Sheffield, England (1-5 April 1974).

Under conditions of incremental stress or temperature changes, the life fraction rule predicts that failure will occur when the sum of the fractions of life equals unity. Experimental data on ferritic steels are used to show that although this rule may be reasonable for temperature changes, it is inconsistent with material response to stress changes. The reasons for these differences are considered in terms of the phenomenology of creep damage. There is a strong sensitivity to stress history resulting in a loading sequence effect on cumulative life fraction at failure. On the other hand, for temperature changes, the apparent insensitivity to temperature history is shown to be consistent with the generality of time-temperature parametric representations of rupture life. These characteristics are revealed by a new analysis involving the generation of constant damage curves in terms of remaining life for both stress and temperature changes. It is shown how families of these curves may, in principle, be used to predict failure for multiple stress and temperature changes. Some possible limitations and restrictions in the use of this approach are considered.

Comment:

The introduction of constant damage curves as a method of overcoming the deficiencies of the life fraction rule is an approach which should receive further experimental verification.

Important References:

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4. Wareing, J., Tomkins, B. and Summer, G., Extent to Which Material Properties Control Fatigue Failure at Elevated Temperatures, ASTM STP 520, 123-138 (1973).

5. Goldhoff, R. M. and Woodford, D. A., The Evaluation of Creep Damage in a Cr-Mo-V Steel, ASTM STP 515, 89-106 (1972).

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Key words: Analysis methods; creep; creep rupture; cumulative effects; failures (materials); fatigue (materials); high temperature; linear damage rule; steels; stress; temperature effects.

ENHANCEMENT OF THE CREEP RESISTANCE OF METALS
Kramer, I. R. and Balasubramanian, N. (Martin Co., Denver, CO)
Met. Trans. 4, 431-436 (February 1973)

Large improvements in creep resistance have been obtained in representative materials (Haynes 188), 321 steel, and titanium (6Al-4V). Enhancement of creep resistance was accomplished by eliminating the surface layer which forms during the loading portion of the creep tests. The treatment consists of prestressing to the proportional limit and then eliminating the surface layer formed as a result of this prestressing operation. An analysis of the creep data showed that the activation energy for creep was increased by removal of the surface layer. In addition elimination of the surface layer decreased the relaxation constant markedly.

Comment:

The effects observed in this paper are not altogether unexpected as a result of the treatments. Attributing the effects to some undescribed phenomena in the surface layer is not demonstrated by the critical experiments of specimen size effect or of testing the specimens before surface removal. For these reasons the data on the untreated specimens is subject to further interpretation and clarification.

Important References:

1. Kramer, I. R., The Effect of Surface Layer Stress on Transient Creep of Polycrystalline Aluminum, Trans. ASM 60, 310-317 (September 1967).

2. Kramer, I. R., Influence of the Surface Layer on the Plastic Flow Deformation of Single Aluminum Crystals, Trans. AIME 233, No. 8, 1462-1467 (August 1965).

3. Kramer, I. R. and Haehner, C., Low Temperature Recovery of Polycrystalline Aluminum, Acta Met. 15, No. 2, 199-202 (February 1967).

4. Kramer, I. R. and Kumer, A., Relaxation and Cyclic Hardening of the Surface Layer of Copper, Met. Trans. 3, No. 5, 1223-1227 (May 1972).

Key words: Activation energy; creep; creep analysis; creep tests; metallic materials; surface layers; surface treatment.

THE ROLE OF CREEP IN HIGH TEMPERATURE LOW CYCLE FATIGUE
Manson, S. S., Halford, G. R. and Spera, D. A. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)
Advances in Creep Design, Halstead Press, New York NY, 514-530 (1966)

The role of creep damage in governing elevated temperature, strain cycling fatigue lives is investigated in this chapter. Experimental and analytical results are presented for two high temperature alloys. Type 316 stainless steel and the cobalt base alloy L-605, tested in axial strain cycling over a range of frequencies, strain ranges and temperatures. Observed cyclic lives are compared with lives computed on the basis of a linear creep fatigue damage rule.

The pure fatigue life for a given cyclic strain range is assumed to be given by the method of universal slopes at the temperature of interest. Fatigue damage is then computed as the ratio of the number of applied cycles to the pure fatigue life.

The pure creep rupture resistance applicable to cyclic stress conditions is evaluated using a cyclic creep rupture test wherein the direction of the rupture stress is reversed each time the creep strain reaches a preset tensile or compressive strain limit. A plot of the cyclic rupture stress against the elapsed rupture time under only the tensile portion of the loading (corrected for any fatigue damage that may have occurred as a result of cycling) serves as the creep rupture curve used in computing creep damage during the ensuing strain cycling fatigue tests. To calculate creep damage in these latter tests, the complete stress history is measured from cycle to cycle and throughout individual cycles as the tests progress. In evaluating creep damage during the axial strain cycling tests, the compressive stresses are assumed to be equally damaging as tensile stresses.

Creep damage is taken as the ratio of time under a given stress to the time to rupture under the same stress. Since creep damage is based upon a stress-time-failure criterion, an accurate analysis can be made only if the complete stress history is determined accurately - a difficult task to perform in most practical situations outside the laboratory.

Summing the creep and fatigue damage and equating the sum to unity establishes the criterion for failure in accordance with the linear creep-fatigue damage rule. Cyclic lives computed according to this rule are then compared with the experimentally observed lives. Calculated lives based on previously proposed methods of life estimation developed at the NASA laboratory are also presented for comparison.

Although there is generally good agreement between the experimental data and the present analysis, further verification is required before the analysis can be applied to other situations with confidence.

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2. Manson, S. S., Interfaces between Fatigue, Creep and Fracture, Int. J. Fract. Mech. 2, No. 1, 327-363 (1966).

3. Manson, S. S. and Halford, G. R., A Method of Estimating High Temperature Low-Cycle Fatigue Behavior of Materials, Thermal and High Strain Fatigue, The Metals and Metallurgy Trust, London, England, 154-170 (1967).

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7. Manson, S. S., Fatigue: A Complex Subject - Some Simple Approximations, Ext. Mech. 5, No. 7, 193-226 (1965).

Key words: Cobalt alloys; creep rupture strength; creep strength; cumulative damage; fatigue (materials); fatigue life; heat resistant alloys; linear damage rule; low-cycle fatigue; stainless steels.

TOWARDS THE STANDARDIZATION OF TIME-TEMPERATURE PARAMETER USAGE IN ELEVATED TEMPERATURE DATA ANALYSIS
Goldhoff, R. M. (General Electric Co., Schenectady, NY)
ASTM, ASME, IME, Int. Conf. Creep and Fatigue in Elevated Temperature Applications, 174.1-174.8, Philadelphia, PA (23-28 September 1973), and Sheffield, England (1-5 April 1974).

A task group was formed with the goal of defining an ASTM standard practice for correlating and extrapolating creep-rupture data. An intensive study of manual and computerized techniques was performed. The minimum-commitment method was found to be the best of the time-temperature parameter techniques considered. Good extrapolations can be obtained by manual methods. However, since highly experienced analysts are needed for the manual methods, itis felt that such methods cannot serve as a universal standard.

Comment:

This task group report has clarified the plethora of techniques for prediction and recommended additional effort on the minimum commitment method. This method shows the greatest promise of development into a standard practice.

Important References:

1. Manson, S. S., Time-Temperature Parameters - A Re-Evaluation and Some New Approaches, ASM Publication D8-100, 1-115 (1970).

2. Goldhoff, R. M. and Hahn, G. J., Correlation and Extrapolation of Creep-Rupture Data of Several Steels and Superalloys Using Time-Temperature Parameters, ASM Publication D8-100, 199-247 (1970).

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4. Murray, J. D. and Truman, R. J., The High Temperature Properties of Cr-Ni-Nb and Cr-Ni-Mo Austenitic Steels, Joint Int. Conf. Creep, IME, Sect 5, 55-69 (1963).

5. Widmer, R., Dhosi, J. M., Mullendore, A. and Grant, J. H., Mechanisms Associated with Long-Time Creep Phenomena, AFML-TR-65-181, Pt. 1 (June 1965).

Key words: Analysis methods; creep; creep rupture; design; high temperature; life (durability); life prediction.

CONSIDERATIONS OF CREEP-FATIGUE INTERACTION IN DESIGN ANALYSIS
Ellis, J. R. and Esztergar, E. P. (Gulf General Atomic, San Diego, CA)
Design for Elevated Temperature Environments, ASME, New York, NY, 29-43 (1971)

A review is made of recent investigations into the effects of strain rate and hold-periods on the high-temperature fatigue properties of engineering materials. A new method for analyzing data generated in these investigations is presented based on diagrams in which time-to-failure (T) is plotted against cycles-to-failure (N). These T-N diagrams are used to isolate the effects of time on fatigue behavior. It is demonstrated that T-N diagrams can also be used to predict rate and hold-period effects outside the range practicable for testing. A method of high temperature design analysis is described based on T-N diagrams and on a form of Miners law modified to account for creep-fatigue interaction. An analysis performed for sample load histories illustrates that this method involves simple procedures similar to those currently used in low-temperature design analysis.

Comment:

This paper presents T-N daigrams which can be usefully employed in prediction of life and separation of the fatigue and creep components. This technique should find wider application in the future.

Important References:

1. Berling, J. T. and Slot, T., Effect of Strain Rate on Low Cycle Fatigue Resistance of AISI 304, 316, and 348 Stainless Steel at Elevated Temperature, ASTM STP 459 (1969).

2. Edmunds, H. G. and White, D. J., Observations of the Effect of Creep Relaxation on High Strain Fatigue, J. Mech. Eng. Sci. 8 (1966).

3. Walker, C. D., Strain-Fatigue Properties of Some Steels at 905 Degrees F With a Hold in the Tension Part of the Cycle. Joint Inst. Conf. on Creep, ASME and Inst. of Mech. Eng., 3-49 (1963).

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5. Krempl, E. and Walker, C. D., The Effect of Creep-Rupture Ductility and Hold-Time on the 1000°F Strain Fatigue Behavior of a 1CR-1Mo-0.25V Steel. ASTM STP 459 (1969).

6. Manson, S. S., Freche, J. C. and Ensign, C. R., Application of a Double Linear Damage Rule to Cumulative Fatigue, ASTM STP 415, 384-412 (1967).

Key words: Creep; creep analysis; cyclic creep; cyclic loads; design; fatigue life; fatigue properties; high temperature; high temperature environments; Palmgren-Miner rule; stainless steels; strain rate; stress relaxation.

CALCULATION OF THERMAL-FATIGUE LIFE BASED ON ACCUMULATED CREEP DAMAGE

Spera, D. A. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

NASA-TN-D-5489

This report presents a method for predicting the onset of thermal-fatigue cracking in high temperature components under service conditions. Starting from basic material properties, life is calculated by considering two distinct failure modes, (1) cyclic creep-rupture, using a modification of the well-known life-fraction rule proposed by Robinson and Taira, and (2) conventional, time-dependent, low-cycle fatigue, using empirical equations of the method of universal slopes by Manson. The method is illustrated by using Glenny-type thermal fatigue data on the nickel-base alloy nimonic 90. In 24 of the 28 cases analyzed cyclic creep rupture was the dominant failure mode.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 82).

COMBINED LOW-CYCLE FATIGUE AND STRESS RELAXATION OF ALLOY 800 AND TYPE 304 STAINLESS STEEL AT ELEVATED TEMPERATURES

Jaske, C. E., Mindlin, H. and Perrin, J. S. (Battelle Columbus Labs, OH)

Fatigue At Elevated Temperatures, ASTM STP 520, 365-376 (August 1973)

A detailed analysis was made of data from low-cycle fatigue tests of solution-annealed, nickel-iron-chromium Alloy 800 at 538°C, 649°C, and 760°C of Type 304 austenitic stainless steel at 538°C and 649°C with holdtimes at maximum tensile strain. A single equation was found to approximate the cyclically stable stress relaxation curves for both alloys at these temperatures. This equation was then used in making a linear time fraction creep damage analysis of the stable stress relaxation curves, and a linear life fraction rule was used to compute fatigue damage. Creep-fatigue damage interaction was evaluated for both alloys using the results of these damage computations. Strain range was found to affect the damage interaction of Type 304 stainless steel but not for Alloy 800. With increasing holdtime, both creep and total damage increased for the Alloy 800 and decreased for the Type 304 stainless steel, and fatigue damage decreased for both alloys. A method was developed to relate length of holdtime and fatigue life to total strain range. This method provides a simple and reasonable way of predicting fatigue life when tensile holdtimes are present.

Important References:

1. Coles, A., Hill, G. J., Dawson, R. A. T. and Watson, J. S., The High Strain Fatigue Properties of Low-Alloy Creep Resisting Steels, Proc. Int. Conf. on Thermal and High-Strain Fatigue, The Metals and Metallurgy Trust, London, England, 270-294 (1967).

2. Hill, G. J., In Proc. Int. Conf. on Thermal and High-Strain Fatigue, The Metals and Metallurgy Trust, London, England, 312-327 (1967).

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5. Smith, G. V., An Evaluation of the Yield, Tensile, Creep, and Rupture Strengths of Wrought 304, 316, 321, and 347 Stainless Steels at Elevated Temperatures, ASTM Data Series DS-552 (February 1969).

6. Halford, G. R., Cyclic Creep-Rupture Behavior of Three High-Temperature Alloys, NASA TN-D-6309 (May 1971).

Key words: Analysis methods; cyclic loads; damage; fatigue (materials); fatigue life; high temperature; high temperature environments; life prediction; low-cycle fatigue; stainless steels; stress relaxation; tensile stress; thermal fatigue.

TEMPERATURE EFFECTS OF STRAINRANGE PARTITIONING APPROACH FOR CREEP FATIGUE ANALYSIS
Halford, G. R., Hirschberg, M. H. and Manson, S. S. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)
Fatigue at Elevated Temperatures, ASTM STP 520, 658-669 (August 1973).

Examination is made of the influence of temperature on the strainrange partitioning approach to creep fatigue. Results for 2.25Cr-1Mo steel and Type 316 stainless steel show that four partitioned strainrange-life relationships to be temperature insensitive to within a factor of two on cyclic life. Monotonic creep and tensile ductilities were also found to be temperature insensitive to within a factor of two. The approach provides bounds of cyclic life that can be readily established for any type of inelastic strain cycle. Continuous strain cycling results obtained over a broad range of high temperatures and frequencies are in excellent agreement with bounds provided by the approach.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 79).

DUCTILITY EXHAUSTION MODEL FOR PREDICTION OF THERMAL FATIGUE AND CREEP INTERACTION
Polhemus, J. F., Spaeth, C. E. and Vogel, W. H. (Pratt and Whitney Aircraft, East Hartford, CT)
Fatigue at Elevated Temperatures, ASTM STP 520, 625-636 (August 1973)

Extensive laboratory testing of typical alloys used in gas turbine blading has shown that there is a strong interaction of the thermal fatigue and creep damage modes which is nonlinear in nature. Consequently, a model for cumulative damage analysis was developed using an exhaustion of ductility concept in which the total available ductility is derived from baseline thermal fatigue tests or, alternatively, estimated from stress-rupture tests. A cycle-by-cycle reckoning of ductility used and remaining is made with the use of a digital computer program, and cracking is ultimately predicted at the point where the remaining ductility is insufficient to complete another cycle. The developed analysis is shown to correlate with laboratory test results. The understanding and design procedure developed make it possible to simulate complex service conditions in digital computer programs and evaluate designs and materials in simulated "fly-offs".

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 84).

THE INTERACTION OF CREEP AND FATIGUE FOR A ROTOR STEEL
Leven, M. M. (Westinghouse Astronuclear Lab, Pittsburgh, PA.)
Exp. Mech. 353-372 (September 1973)

Twenty tests were performed on a 1Cr-1Mo-1/4V rotor steel at 1000°F (538°C) to determine the interaction of creep and low-cycle fatigue. These tests involved five different types of strain-controlled cycling: creep at constant tensile stress; linearly varying strain at different frequencies; and hold periods at maximum compressive strain, maximum tensile strain, or both.

The experimental data were then used to characterize the interaction of creep and fatigue by the:

(1) Frequency-modified strainrange approach of Coffin;

(2) Total time to fracture versus the time of one cycle relation as proposed by Conway and Berling;

(3) Total time to fracture versus the number of cycles to fracture characterization of Ellis and Esztergar;

(4) Summation of damage fractions obtained from tests using interspersed creep and fatigue as proposed by the Metal Properties Council;

(5) Strainrange-partitioning method of Manson, Halford, and Hirschberg.

In order to properly assess the strainrange-partitioning approach, seven additional tests were performed at the NASA Lewis Research Center.

Visual, ultrasonic, and acoustic-emission methods of crack-initiation, determination were unsuccessful. An approximate indication of crack initiation was obtained by finding the cycle where the stress-cycle curve first deviated from a constant slope.

Predictive methods (based on monotonic tests) for determining the fatigue life in the creep range were examined and found deficient, though they may still be useful for preliminary comparison of materials and temperatures.

The extension of the frequency-modified strainrange approach to notched members was developed and the results of notched-bar tests were shown to corroborate this approach, when crack initiation for the plain and notched bars was compared.

Comment:

This review paper does an excellent job of characterizing the techniques employed to explain creep and fatigue behavior. In addition it shows the drawbacks and limitations of these approaches and points the way to further work required.

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1. Manson, S. S., Halford, G. R. and Hirschberg, M. H., Creep-Fatigue Analysis by Strainrange Partitioning, Proc. Symp. Design for Elevated Temp. Environ., ASME, 12-24 (May 1971).

2. Coffin, Jr., L. F., The Effect of Frequency on the Cyclic Strain and Low Cycle Fatigue of Cast Udimet 500 at Elevated Temperature, Met. Trans. 12, B105-B113 (November 1971).

3. Conway, J. B. and Berling, J. T., A New Correlation of Low-Cycle Fatigue Data Involving Hold Periods, Met. Trans. 1, No. 1, 324-325 (January 1970).

4. Ellis, J. R. and Esztergar, E. P., Considerations of Creep-Fatigue Interaction in Design Analysis, Symp. on Design for Elevated Temperature Environment, ASME, 29-33 (May 1971).

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8. Berling, J. T., Conway, J. B., A New Approach to the Prediction of Low-Cycle Fatigue Data, Met. Trans. 1, No. 1, 805-809 (April 1970).

Key words: Crack initiation; crack propagation; creep; fatigue (materials); fracture analysis; life prediction; partitioning concepts; testing methods.

III - Fatigue of Materials

MECHANISMS OF HIGH-TEMPERATURE FATIGUE
Gell, M. and Leverant, G. R. (Pratt and Whitney Aircraft, East Hartford, Conn)
ASTM STP 520, 37-67 (August 1973)

A review is presented of high-temperature fatigue mechanisms, with emphasis on nickel-base superalloys. Elevated temperature fatigue fracture can be intergranular or transgranular. The rate of crack initiation and propagation is much faster when it occurs intergrandularly than when it occurs transgranularly. It is, therefore, important to be able to predict the mode of failure for given service conditions. If failure is transgranular, then it can occur in one of two modes; the stage I mode is along slip planes and is in directions of high shear stress and the stage II mode is noncrystallographic and normal to the principal stress direction. It is presently possible to predict under certain circumstances whether transgranular cracking will occur in the stage I or stage II modes, but the more significant transition from transgranular to intergranular cracking requires additional work. The transition from transgranular to intergranular fracture and the rate of intergranular cracking can be related to the creep component and the amount of oxidation occurring in the fatigue cycle. Increasing the creep component and the oxidation promotes intergranular cracking. The creep component is dependent on the temperature, frequency, holdtime, and mean stress. Cracking often starts in the form of cavities or microvoids at the surface of nonmetallic precipitates in grain boundaries. It has been demonstrated that such cavity formation occurs more easily in the presence of a fatigue stress than for the case of simple creep. Oxidation attack also promotes intergranular cracking because grain boundaries and their environs are zones of chemical segregation and precipitation that have poor oxidation resistance. The preferential oxide penetration along a grain boundary is equivalent to a notch of the same depth. Perhaps the most success to date has been in relating the slip character and transgranular fracture mode of a material to conditions of temperature and frequency. Planar slip is favored by low temperatures, small strains, and high frequencies in materials of low stacking fault energy. It has been demonstrated in nickel-base superalloys that stage I fracture occurs when planar slip is generated at a stress concentration or at a crack tip and that stage II fracture occurs when wavy or homogeneous slip is generated. The conditions of temperature and strain rate for generation of each type of deformation have been determined. These concepts of slip character, creep component, oxidation, and fracture mode have been used in a qualitative manner to explain the common phenomenological observations made in investigations of high-temperature fatigue.

Important References:

1. Wells, C. H. and Sullivan, C. P., Low-Cycle Fatigue of Udimet 700 at 1700°F, Trans. Quart. ASM 61, 149-155, (1968).

2. Leverant, G. R., Gell, M. and Hopkins, S. W., Effect of Strain Rate on the Flow Stress and Dislocation Behavior of a Precipitation Hardened Nickel-Base Alloy, Mater. Sci. Eng. 8, No. 3, 125-133 (1971).

3. Organ, F. E. and Gell, M., The Effect of Frequency on the Elevated Temperature Fatigue Behavior of a Nickel-Base Superalloy, Met. Trans. 2, 943-952 (April 1971).

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6. Duquette, D. J. and Gell, M., The Effect of Environment on the Elevated Temperature Fatigue Behavior of Nickel-Base Superalloy Single Crystals, Met. Trans. 3, 1899-1905 (July 1972).

Key words: Coatings; crack initiation; crack propagation; creep; environmental effects; failure mechanism; fatigue (materials); fractures (materials); frequency effects; heat resistant alloys; microstructures; nickel alloys; oxidation; stainless steels; temperature effects.

LOW CYCLE FATIGUE AND CYCLIC STRESS-STRAIN BEHAVIOR OF INCOLOY 800
Conway, J. B., Berling, J. T. and Stentz, R. H. (Mar-Test Inc., Cincinnati, OH)
Met. Trans. 3, 1633-1637 (June 1972)

Strain-controlled low-cycle fatigue tests of solution-annealed Incoloy 800 were performed at temperatures of 538°C, 649°C, 704°C, and 760°C using axial strain rates of 4×10^{-3} and 4×10^{-4} seconds. A few hold time tests were also performed to indicate a noticeable reduction in fatigue life at hold times of 10 and 60 minutes. A comparison of these fatigue data with similar results for AISI 304 stainless steel indicates essentially identical behavior. An extensive study was made of the cyclic stress-strain behavior of Incoloy 800 and the relationship between the cyclic strain-hardening exponent and fatigue behavior was confirmed. Exponents on N_f in the elastic and plastic strain range terms of the total strain range equation are identified and compared with those used in the universal slopes equation.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 143).

STRAIN RATE AND HOLDTIME SATURATION IN LOW-CYCLE FATIGUE: DESIGN-PARAMETER PLOTS
Conway, J. B., Berling, J. T. and Stentz, R. H. (Mar-Test, Inc., Cincinnati, OH)
Fatigue at Elevated Temperatures, ASTM STP 520, 637-647 (August 1973)

A detailed study was made of the effect of strain rate and hold periods on the low-cycle fatigue behavior of AISI 304 stainless steel at 650°C. Data are presented in terms of a logarithmic plot of cycles to fracture versus cycle time to reveal several important regimes. At very small cycle times the fatigue life is independent of strain rate. As the strain rate is decreased the fatigue life is reduced and finally a saturation effect is noted at a strain rate close to 4×10^{-4} per second. In the region prior to saturation, strain rate and hold periods have the same effect on fatigue life as long as they are compared at the same cycle time. Hold-period effects also exhibit a saturation effect, but this occurs at a fatigue life lower than that corresponding to the strain rate saturation level. For hold periods in tension only the holdtime effect is shown to be dependent upon the strain rate employed in that portion of the cycle exclusive of the hold period. Design-parameter plots are introduced to provide an extensive presentation of fatigue data and a graphical solution for the fatigue life at a given temperature once values for strain range, strain rate, and hold period are selected.

Important References:

1. Manson, S. S. and Halford, G. R., A Method of Estimating High-Temperature Low-Cycle Fatigue Behavior of Materials, Proc. Int. Conf. on Thermal and High Strain Fatigue. The Metals and Metallurgy Trust, London, England, 154-170 (1967).

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3. Coffin, Jr., L. F., Predictive Parameters and Their Application to High Temperature, Low-Cycle Fatigue, Fracture 1969, Proc. Int. Conf. Fract., 2nd Chapman and Hall, London, England (1969).

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6. Berling, J. T. and Slot, T., Effect of Temperature and Strain Rate on Low-Cycle Fatigue Resistance of AISI 304, 316 and 348 Stainless Steel, ASTM STP 459, 3-30 (1969).

Key words: Cyclic loads; fatigue (materials); fatigue life; fatigue tests; high temperature; high temperature environments; load cycles; load rest periods; low-cycle fatigue; stainless steels; strain; strain rate.

A COMPREHENSIVE CHARACTERIZATION OF THE HIGH TEMPERATURE FATIGUE BEHAVIOR OF A286

Henry, M. F., Solomon, H. D. and Coffin, Jr., L. F. (General Electric Co., Schenectady, NY)

ASTM, ASME, IME, Int. Conf. Creep and Fatigue in Elevated Temperature Applications, 182.1-182.7, Philadelphia, PA (23-28 September 1973), and Sheffield, England (1-5 April 1974).

The high strain behavior of A286 at 593°C is examined in a multi-faceted program. The program includes phenomenological studies on life prediction in smooth bars and on crack propagation in single-edge-notched specimens. It is shown that the life-prediction equations can be used to account for frequency, wave shape (including hold times) and notches, environment is shown to have a strong effect on the fatigue life when cyclic frequency is varied. Studies from a metallurgical viewpoint are presented on fatigue crack nucleation and propagation. Nucleation and propagation mechanisms are found to be transgranular and intergranular at high and low frequencies respectively. It is shown that the strain range partitioning concept is inapplicable for A286 at 593°C, due most probably to the strong environmental interaction. Key areas are pointed out where information is still lacking.

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Key words: Crack initiation; crack propagation; cracks; cyclic loads; edge crack specimens; environmental effects; failures (materials); fatigue (materials); fatigue life; frequency effects; high temperature; life prediction; load rest periods; low-cycle fatigue; microstructures; stainless steels; strain.

FATIGUE AT ELEVATED TEMPERATURES: A REVIEW OF TEST METHODS
Carden, A. E. (Alabama Univ., Univ. AL)
Fatigue at Elevated Temperatures, ASTM STP 520, 195-223 (August 1973)

The study of fatigue at elevated temperature requires the evaluation of material response to several load-time profiles in specified thermal-chemical-nuclear-electric fields. This review of test methods emphasizes the relationships between pure low-cycle fatigue and tensile, fracture toughness, creep, cyclic-creep, creep fatigue (interspersion), fatigue-cycle with hold, dynamic creep, fatigue crack growth, and high-cycle fatigue testing. The thermal and environmental control is discussed. Special attention is given to isothermal-uniaxial, bending, torsion, and combined stress tests. Cyclic thermal testing is reviewed. Strain measurement, signal conditioning, computer utilization, fatigue crack growth, vacuum and fractography are reviewed as they pertain to fatigue at elevated temperature. Specimen design, gripping, and testing machine characteristics are also discussed.

There is no one test that will characterize a material response to displacement or load cycling when time and environment are left undefined. The principle variables of fatigue are the load-displacement cycle, the thermal-chemical-nuclear-electric fields, the specimen's geometrical response to load (buckling, ratchetting, crack growth, and terminal fracture), and the chronological arrangement of the stress or strain at the point that will lead eventually to failure. Test methods and understanding of the processes of fracture by fatigue are dependent mutually on the other for further development. The log(t) versus log (N_f) plane is recommended as a good coordinate reference for categorization of the effects of time (or frequency) and of the creep-fatigue interaction relationship. The results of different test methods lie in different regions of this coordinate map yet bear a relationship to neighboring data. An appeal is made for improved methods and more economical ways of obtaining data, better utilization of facilities, utilization of the computer and electronic technologies in the performance of tests and reduction of data, of statistical analysis of data, and of some additional contributions on the design of experiments. Prototype and fullscale testing seems to be an area of continuing development.

Comment:

This very well documented review of test methods as related to fatigue at elevated temperatures provides an excellent base for present understanding and future work.

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12. Johnston, J. R. and Ashbrook, R. L., Oxidation and Thermal Fatigue Cracking of Nickel-and Cobalt-Base Alloys in a High Velocity Gas Stream, NASA TN-D-5376 (August 1969).

Key words: Crack growth rate; creep tests; cyclic creep; cyclic loads; design; dynamic tests; fatigue (materials); fatigue tests; high temperature tests; S-N diagrams; test equipment design; test specimen; testing methods; thermal fatigue.

A METHOD OF ESTIMATING HIGH-TEMPERATURE LOW-CYCLE FATIGUE BEHAVIOR OF MATERIALS
Manson, S. S. and Halford, G. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)
Proc. Int. Conf. Thermal and High Strain Fatigue, The Metals and Metallurgy Trust, London, England, 154-170 (1967).

A method is described whereby static-tensile and creep-rupture properties can be used to estimate lower bound, average, and upper bound low-cycle fatigue behavior in the creep range. The approach is based primarily on the method of universal slopes previously developed for estimating room-temperature fatigue behavior, and in part on a highly simplified creep-rupture-fatigue analysis. Reasonable agreement is obtained when the estimates are compared with total strain range/life data for numerous engineering alloys. Included in the study are coated and uncoated nickel-base alloys, a cobalt-base alloy, low-and high-alloy steels, and stainless steels tested under laboratory conditions over a wide range of temperatures and cyclic rates.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 92).

MATHEMATICAL TECHNIQUES APPLYING TO THE THERMAL FATIGUE BEHAVIOUR OF HIGH TEMPERATURE ALLOYS
Howe, P. W. H. (National Gas Turbine Establishment, Pyestock, England)
Aeron.Q.13, Pt. 4, 368-396 (November 1962)

The high temperature thermal fatigue of Nimonic alloys can be analyzed using short-time creep deformation data and cyclic stress endurance data. Experimental and calculated thermal fatigue endurances have been correlated in magnitude and over ranges of temperature, strain, and strain-rate. Transient temperatures in turbine blades can be calculated for a wide range of conditions using Biot's variational method. Combining the thermal strain obtained from Biot's method with a simplified mathematical description of high temperature material behavior leads to a differential equation for thermal stress, whcih can be solved for a wide range of conditions. The correlation of experimental and theoretical thermal fatigue endurances provides an example of these methods, and supports their more general application.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 99).

CALCULATION OF THERMAL-FATIGUE LIFE BASED ON ACCUMULATED CREEP DAMAGE
Spera, D. A. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)
NASA-TN-D-5489

This report presents a method for predicting the onset of thermal-fatigue cracking in high temperature components under service conditions. Starting from basic material properties, life is calculated by considering two distinct failure modes, (1) cyclic creep-rupture, using a modification of the well-known life-fraction rule proposed by Robinson and Taira, and (2) conventional, time-dependent, low-cycle fatigue, using empirical equations of the method of universal slopes developed by Manson. The method is illustrated by using Glenny-type thermal fatigue data on the nickel-base alloy Nimonic 90. In 24 of the 28 cases analyzed cyclic creep rupture was the dominant failure mode.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 82).

OBSERVATIONS AND INTERPRETATION OF CRACK PROPAGATION UNDER CONDITIONS OF TRANSIENT THERMAL STRAIN
Mowbray, D. F. and Woodford, D. A. (General Electric Co., Schenectady, NY)
ASTM, ASME, IME, Int. Conf. Creep and Fatigue in Elevated Temperature Applications, 179.1-179.11. Philadelphia, PA (23-28 September 1973), and Sheffield, England (1-5 April 1974)

Tapered disk thermal fatigue tests have been conducted on one nickel (Rene 77) and one cobalt (FSX 414) base alloy. Measurements of crack length as a function of number of thermal cycles were made on cracks growing from notches machined on the specimen periphery. The effect on crack propagation of peripheral radius (strain range), maximum temperature between 1093°K and 1343°K, and hold time at maximum temperature between 1 and 60 minutes is reported. Responses of both alloys showed identical trends in that increasing hold time or maximum temperature first caused an increase in the measured crack growth rate, but then showed a decrease at long hold times or high temperatures. It is proposed that in both alloys there are two competing processes occurring, namely a cycle dependent creep/environmental damage at the crack tip and a time-dependent microstructural change resulting in enhanced crack propagation resistance with accumulated time at temperature. The measured effect of hold times at temperature and the observed microstructural features point to the major crack advance occurring during the heating shock and holding period rather than at the maximum tensile stress which develops during the cooling shock. This conclusion is supported by a non-linear analysis of the disk periphery which shows that, because of reversed plastic flow, a tensile stress develops at or near the highest temperature in the cycle.

Comment:

The basic information in this paper should be of value in developing improved resistance to heat checking on vanes in gas turbine engines.

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6. Spera, D. A., The Calculation of Thermal Fatigue Life Based on Accumulated Creep Damage, NASA TM-X-52558 (1969).

Key words: Cobalt alloys; crack growth rate; crack initiation; crack propagation; cracks; creep; cyclic loads; fatigue (materials); gas turbine engines; high temperature; load cycles; load rest periods; microstructures; nickel alloys; notched specimens; strain; thermal cycles; thermal fatigue; thermal shock; thermal stresses; turbine blades.

COMPARISON OF EXPERIMENTAL AND THEORETICAL THERMAL FATIGUE LIVES FOR FIVE NICKEL-BASE ALLOYS

Spera, D. A. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

Fatigue at Elevated Temperatures. ASTM STP 520, 648-657 (August 1973)

Alloys investigated were Nimonic 90, IN-100, coated IN-100, B-1900, coated B-1900, MAR M200, and MAR M200DS (directionally solidified). Maximum temperatures ranged from 770°C to 1200°C. Specimen geometries included tapered disks, double-edge wedges, and cambered airfoils. The disks and wedges were heated and cooled in fluidized beds. The airfoil specimens were heated by a Mach 1 natural gas burner and rapid air-cooled, with and without spanwise loading. Life calculations included two distinct failure modes: conventional low-cycle fatigue and cyclic creep. Required material properties were limited to conventional thermal, tensile, and creep-rupture data. The complete life calculation system included the calculation of transient temperature distributions, thermal strains, stresses, creep damage, fatigue damage, and finally cycles to first crack. Calculated lives were within a factor of two for the 76 of the 86 data points analyzed. Cyclic creep accounted for 80 percent of all the calculated damage.

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Key words: Analysis methods; crack initiation; creep properties; cyclic creep; experimental data; failure mode; fatigue (materials); fatigue life; high temperature; low-cycle fatigue; nickel alloys; stress analysis; thermal fatigue; thermal stresses.

THERMAL-FATIGUE RESISTANCE OF 15 HIGH-TEMPERATURE ALLOYS DETERMINED BY THE FLUIDIZED-BED TECHNIQUE

Spera, D. A., Howes, M. A. H. and Bizon, P. T. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH; ITT Research Institute, Chicago, IL)

NASA TM-X-52975 (March 1971)

Thermal-fatigue tests were conducted on B-1900, IN-100, IN-100DS (directionally solidified), MAR M200, MAR M200DS, IN-162, IN-713C, M22, TAZ 8A, U-700 (wrought and cast), TD NiCr, X-40, WI-52, and MAR M302. Alloys B-1900, IN-100 and IN-100DS were also tested with aluminide coating. Among the 18 materials tested, cycles to cracking differed by more than two orders of magnitude. Coating and directional solidification were a definite benefit. However, the directionally solidified alloys suffered considerable weight loss through oxidation. Cycles to cracking calculated theoretically for IN-100 and B-1900, coated and uncoated, were in agreement with the data.

Comment:

These tests in the IITRI fluidized bed provide a technique for qualitative evaluation of engine materials. They noted a progression from intergranular cracking at low shock cycles to transgranular at high cycles, which is significant in terms of optimum structures for turbine blades.

Important References:

1. Spera, D. A., The Calculation of Elevated-Temperature Cyclic Life Considering Low-Cycle Fatigue and Creep, NASA TN-D-5317 (1969).

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Key words: Aluminide coatings; coatings; cobalt alloys; crack initiation; crack propagation; cracks; cyclic loads; directional solidification; fatigue (materials); gas turbine engines; heat resistant alloys; high temperature environments; load cycles; nickel alloys; oxidation; oxidation resistance; protective coatings; thermal cycles; thermal fatigue; thermal stresses.

OXIDATION AND THERMAL FATIGUE CRACKING OF NICKEL-AND COBALT-BASE ALLOYS IN A HIGH VELOCITY GAS STREAM

Johnston, J. R. and Ashbrook, R. L. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

NASA-TN-D-5376 (August 1969).

An investigation was conducted to determine the resistance to oxidation of typical gas turbine alloys exposed alternately to high and low temperature, high velocity gas streams. A natural gas-compressed air burner was used to produce velocities up to Mach 1 and specimen temperatures up to 2000°F (1093°C). The materials tested included six nickel-base alloys: IN-100, B-1900, MAR M-200, TAZ-8A, Hastelloy X, and TD-NiCr, and four cobalt-base alloys: L-605, X-40, MAR M-509A, and WI-52.

In a standard test of 100 cycles of 1 hour at temperature in a Mach 1 gas stream followed by rapid colling to room temperature, the nickel-base alloys as a class experienced less weight loss than the cobalt-base alloys. The average values of weight loss varied widely from 216 to 23,700 milligrams after 100 hours at 2000°F (1093°C). Of the cobalt-base alloys, X-40 had the lowest weight loss, which was only slightly less than that of MAR M-200. The latter alloy had the highest weight loss of all of the nickel alloys. Of all the alloys tested, the cast cobalt-base alloy, WI-52, was the least resistant to weight loss. After 100 hours, surface recession paralleled weight loss and ranged from 0.3 to 50 mils (0.008 to 1.3 mm).

Cast cobalt-base alloys were more resistant to thermal fatigue cracking than conventionally cast nickel-base alloys. However, directionally solidified and single grain MAR M-200 castings and wrought Hastelloy X had no cracks even after 100 cycles at 2000°F (1093°C).

At 2000°F (1093°C) under simulated steady-state operation (10-hour cycles with free air cooling to room temperature) the average weight loss was less for the six alloys so tested than at standard conditions. Cobalt alloys showed more improvement in oxidation resistance from the change in cycle than the nickel-base alloys. No cracking was observed in any alloy under these conditions. When the lower temperature during a 2000°F (1093°C) test was restricted to 1200°F (649°C), the propensity toward cracking was unchanged for IN-100, and B-1900, but substantially reduced for WI-52. However, weight loss decreased substantially for all alloys so tested.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 115).

THE STATIC AND CYCLIC CREEP PROPERTIES OF THREE FORMS OF A CAST NICKEL ALLOY
Harrison, G. F. and Tilly, G. P. (National Gas Turbine Establishment, Farnsborough, England)
Proc. ASTM, ASME, IME, Int. Conf. Creep and Fatigue in Elevated Temperature Applications, Sheffield, England, 222.1-222.9 (1-5 April 1974).

The static and cyclic creep properties of conventionally cast, directionally solidified and single crystal forms of a cast nickel superalloy, MAR M246, have been evaluated at 850°C and 900°C. Tensile and compressive creep curves have been obtained at constant stress and the results analyzed using power law creep terms. Typically, directionally solidified specimens have tensile lives twice those of comparable conventionally-cast materials, and rupture strains three or four times greater. Increase in specimen size raised the life of conventionally cast material but had no effect on single crystals. Differences between tensile and compressive creep properties were accentuated in the tertiary stages of deformation. No improvement in compressive creep resistance was obtained using directionally solidified or single crystal specimens. Equations developed previously from strain hardening theory gave an accurate estimate of behavior under cyclic tension. This theory has been extended to include push-pull loading and is shown to give a satisfactory correlation with the data.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 31).

THE FATIGUE CHARACTERISTICS OF UNIDIRECTIONALLY SOLIDIFIED Al-Al_3Ni EUTECTIC ALLOY

Hoover, W. R. and Hertzberg, R. W. (Lehigh Univ., Bethlehem, PA)

Trans. Amer. Soc. Metals <u>61</u>, 769-776 (1968)

Unidirectional solidification of the Al-Al_3Ni eutectic alloy produces an aligned microstructure consisting of discontinuous Al_3Ni wiskers in an Al matrix which behaves as a fiber-reinforced composite material. The fracture mechanism of this composite under cyclic loading is examined macroscopically, metallographically and fractographically. It is observed that at high stress amplitudes the fracture is controlled by the rupture of the Al_3Ni whiskers. At low stress amplitudes where the stress concentration at the crack tip is insufficient to cause whisker rupture, the fracture is controlled by the fatigue resistance of the matrix, the crystallographic orientation of the matrix and the strength of the Al_3Ni whisker-Al matrix interfacial bond. At these low stress amplitudes, the fatigue crack is found to be deflected by the Al_3Ni whiskers and is observed to propagate through the Al matrix parallel to the loading axis. Evidence is presented to show that the two phases of this composite material undergo unequal amounts of strain during cyclic loading.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 163).

THE INFLUENCE OF SPECIMEN GEOMETRY ON THERMAL-FATIGUE BEHAVIOUR

Glenny, R. J. E. (National Gas Turbine Establishment, Pyestock England)

The Metals and Metallurgy Trust, London, England (1967).

Thermal-fatigue tests on six high-temperature nickel alloys were conducted to determine the influence of changes in specimen geometry on thermal endurance, by means of the fluidized-bed technique. The tests involved alternate rapid heating and rapid cooling between 20°C and 920°C. The results on tapered disks and airfoils showed that a decrease in the size of geometrically similar specimens did not lead to progressive increases in endurance, because of the opposing effects of mass and edge radius. Changes in geometry resulting from surface damage produced mechanically, e.g., by machining or by impact, or chemically, e.g., by oxidation, can drastically lessen the number of cycles to initiate thermal-fatigue cracks and to propagate such cracks to a significant size.

Comment:

This paper is a summary of an extensive test program conducted over a ten year period at the National Gas Turbine Establishment in England. The experimental data developed has been employed in the development of subsequent life prediction techniques.

Key words: Crack growth rate; cracks; damaged structure life; edge crack specimens; failures (materials); fatigue (materials); gas turbine engines; geometric effects; heat resistant alloys; high temperature environments; load cycles; notch sensitivity; notches; stress; stress concentration; thermal cycles; thermal fatigue; thermal stresses; turbine blades.

IIIC - Thermal/Mechanical Fatigue

THERMAL STRESS AND LOW-CYCLE FATIGUE
Manson, S. S. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)
McGraw-Hill Book Co., New York, NY (1966)

This book is an outgrowth of several compilations by the author of the state of knowledge in two major fields of current engineering interest: thermal stress and low-cycle fatigue. Chapters in the book include: elastic stresses; plastic flow and creep; behavior of materials under stress and strain cycling; cyclic plasticity; thermal-stress fatigue of ductile materials; thermal shock; choice of materials; and mitigation of thermal stresses by design configuration. Different methods for solutions are described, each having their advantages and limitations. A number of methods that have been effectively applied for determining thermal stresses in the elastic range are presented. Some of these methods are: the beam-analysis approach, which leads most simply to the determination of the most significant stresses; various energy methods, such as Heldenfils and Roberts; the method of self-equilibrating polynomials; and direct method of applying station function and collocation to the solution of ordinary and partial differential equations. The true significance of thermal stresses in ductile materials cannot be assessed unless consideration is given to the plastic range. In general, fracture by thermal stress fatigue involves consideration of plastic flow on a macroscopic level. Methods are given for computing stress distribution when the yield point of the material is exceeded.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 16).

LOW-CYCLE FATIGUE OF THREE SUPERALLOYS UNDER CYCLIC-EXTENSION AND CYCLIC-TEMPERATURE CONDITIONS
Carden, A.E., Kyzer, R.D. and Vogel, W. H. (University of Alabama, and Pratt and Whitney Aircraft, East Hartford, CT)
ASME Paper 67-MET-19 (1967)

A new test method is described which is versatile and offers great flexibility in programming strain for stress and temperature independently and synchronously. Also a unique strain measurement system allows the direct recording of the mechanical component of strain independent of the thermal component. The results of tests of two nickel- and one cobalt-base superalloys are presented as an example of the utility of the test method. These tests were performed on coated tubular specimens. The temperature was programmed to cycle between 250°C and 982°C in phase with an extension cycle program. The test results show the effect of hold time at constant extension (relaxation cycling) of the three alloys.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 139).

THERMAL-MECHANICAL FATIGUE CRACK PROPAGATION IN NICKEL-AND COBALT-BASE SUPERALLOYS UNDER VARIOUS STRAIN-TEMPERATURE CYCLES

Rau, Jr., C. A., Gemma, A. E. and Leverant, G. R. (Pratt and Whitney Aircraft, Middletown, CT).

Fatigue at Elevated Temperatures, ASTM STP 520, 166-178 (1973)

Crack propagation rates under isothermal and thermal fatigue cycling have been determined for a conventionally-cast cobalt-base superalloy, and conventionally-cast and directionally-solidified nickel-base superalloys. Linear elastic fracture mechanics, where the crack growth rates under different strain ranges or for various crack lengths depend only on the strain intensity factor range, was found to be applicable over the range of crack growth rates of most practical importance. A comparison of crack growth rates is made for thermal fatigue under various strain-temperature cycles and isothermal low-cycle fatigue, and the influence of coatings and superimposed creep is discussed.

Based on the experimental effort the following conclusions are drawn.

1. Linear elastic fracture mechanics can be applied to thermal fatigue crack propagation of nickel-and cobalt-base superalloys under conditions of small plastic strains.

2. For crack growth rates less than 10^{-4} in/cycle, the growth rate depends only on ΔK_E and is independent of strain range, mean strain, and mean stress (for the range of mean strains and strain ranges investigated).

3. Cycle I* thermal fatigue crack propagation rates are more rapid than low temperature isothermal low cycle fatigue crack growth rates where the fracture mode is the same and slightly more rapid than Cycle II thermal fatigue.

4. Cycle I crack growth rates increased slightly with increasing maximum temperature.

5. Directionally solidified nickel-base superalloy has a markedly slower crack growth rate than a conventionally cast nickel-base superalloy of similar microstructure.

6. Coatings have no effect on growth rates of through-the-thickness cracks with one exception. Thin-walled specimens tested with the peak tensile strain in the temperature range where the coating is relatively brittle show an accelerated crack growth rate.

* Cycle I is defined as that cycle which produces the maximum tensile strain at the minimum temperature.

Cycle II is a similar cycle where the tensile strain peaked at the maximum temperature.

Comment:

This paper examines the fatigue crack propagation in superalloys under thermal/mechanical cycling designed to approximate turbine engine conditions. The data developed is useful in characterizing materials in terms of materials selection but should be employed with caution for design purposes because of the more complex conditions existing in engines.

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6. McEvily, Jr., A. J., Fatigue Crack Growth and the Strain Intensity Factor, AFFDL-TR-70-144, 451-459 (September 1970).

Key words: Cobalt alloys; crack propagation; cyclic loads; fatigue (materials); fractures (materials); nickel alloys; protective coatings; thermal cycles; thermal fatigue.

VACUUM THERMAL-MECHANICAL FATIGUE TESTING OF TWO HIGH TEMPERATURE ALLOYS
Sheffler, K. D. (TRW Equipment Labs., Cleveland, OH).
NASA-CR-134524 (January 31, 1974).

Ultrahigh vacuum elevated temperature low cycle fatigue and thermal fatigue tests of 304 stainless steel and A-286 alloy have shown significant effects of frequency and combined temperature-strain cycling on fatigue life. At constant tmeperature, the cycle life of both alloys was lower at lower frequencies. Combined temperature - strain cycling reduced fatigue life with respect to isothermal life at the maximum temperature of the thermal cycle. Life reductions with in-phase thermal cycling (tension at high temperature, compression at low temperature) were attributed to grain boundary cavitation caused by unreversed tensile grain boundary sliding. A specific mechanism for out-of-phase (tension at low temperature, compression at high temperature) life reductions could not be established in the 304 stainless steel test material because of geometric instabilities which occurred as a result of the thermal-mechanical cycling. In the A-286 alloy, where out-or-phase geometric instabilities were not observed, the out-or-phase life reductions were attributed to grain boundary cavitation. The proposed mechanism for out-of-phase cavity generation involved accumulation of unreversed compressive grain boundary displacements which could not be geometrically accomodated by intragranular deformation in the low-ductibity A-286 alloy.

Important References:

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5. Sheffler, K. D. and Doble, G. S., Influence of Creep Damage on the Low Cycle Thermal-Mechanical Fatigue Behavior of Two Tantalum Base Alloys, NASA-CR-121001 (May 1, 1972).

Key words: Creep; cumulative damage; cyclic creep; cyclic testing; fatigue (materials); grain boundaries; heat resistant alloys; high temperature tests; life prediction; microstructures; strainrange partitioning; thermal fatigue.

THE PARTITIONED STRAINRANGE FATIGUE BEHAVIOR OF COATED AND UNCOATED MAR-M-302 AT 1000°C (1832°F) IN ULTRAHIGH VACUUM
Sheffler, K. D. (TRW) Equipment Labs., Cleveland, OH).
NASA-CR-134626 (June 1974).

Elevated temperature (1000°C) vacuum fatigue tests have been conducted on uncoated and aluminide (PWA 45) coated cobalt-base MAR-M-302 alloy with the four different types of thermal-mechanical reversed inelastic strain cycles (wave shapes) defined by the method of strainrange partitioning. Results of these tests indicated two major conclusions. First, there was no significant influence of the aluminide coating on the thermal-mechanical fatigue life of the MAR-M-302 alloy. Second, variations in the type of thermal-mechanical fatigue cycle applied caused significant variations of fatigue life for both coated and uncoated material. the longest lives were achieved with E_{pp} type cycling, while the E_{cc} cycle caused a reduction of fatigue life of about 1/2 order of magnitued with respect to the Epp life. The E_{cp} type cycle caused a life reduction of between 1-1/2 and 2 orders of magnitude relative to the Epp life, while the E_{pc} type cycle provided a fatigue life which appeared to be comparable to that generated by the E_{cc} cycles.

Important References:

1. Manson, S. S., Halford, G. R. and Hirschberg, H. M., Creep-fatigue Analysis by Strainrange Partitioning, Design for Elevated Temperature Environment, ASME, 12-24 (1971).

2. Sheffler, K. D. and Doble, G. S., Influence of Creep Damage on the Low Cycle Thermal-Mechanical Fatigue Behavior of Two Tantalum Base Alloys, NASA-CR-121001 (May 1, 1972).

3. Manson, S. S., The Challenge to Unify Treatment of High Temperature Fatigue - A Partisan Proposal Based on Strainrange Partitioning, ASTM STP 520, 744-782 (1973).

Key words: Aluminide coatings; cobalt alloys; creep; creep rupture; fatigue (materials); fatigue life; heat resistant alloys; high temperature environments; life prediction; low-cycle fatigue; protective coatings; strainrange partitioning; stress rupture; thermal fatigue.

OBSERVATIONS AND INTERPRETATION OF CRACK PROPAGATION UNDER CONDITIONS OF TRANSIENT THERMAL STRAIN
Mowbray, D. F. and Woodford, D. A. (General Electric Co., Schenectady, NY)
ASTM, ASME, IME, Int. Conf. Creep and Fatigue in Elevated Temperature Applications, 179.1-179-11, Philadelphia, PA (23-28 September 1973), and Sheffield, England (1-5 April 1974).

Tapered disk thermal fatigue tests have been conducted on one nickel (Rene 77) and one cobalt (FSX 414) base alloy. Measurements of crack length as a function of number of thermal cycles were made on cracks growing from notches machined on the specimen periphery. The effect on crack propagation of peripheral radius (strain range), maximum temperature between 1093°K and 1343°K, and hold time at maximum temperature between 1 and 60 minutes is reported. Responses of both alloys showed identical trends in that increasing hold time or maximum temperature first caused an increase in the measured crack growth rate, but then showed a decrease at long hold times or high temperatures. It is proposed that in both alloys there are two competing processes occurring, namely a cycle dependent creep/environmental damage at the crack tip and a time-dependent microstructural change resulting in enhanced crack propagation resistance with accumulated time at temperature. The measured effect of hold times at temperature and the observed microstructural features point to the major crack advance occurring during the heating shock and holding period rather than at the maximum tensile stress which develops during the cooling shock. This conclusion is supported by a nonlinear analysis of the disk periphery which shows that, because of reversed plastic flow, a tensile stress develops at and near the highest temperature in the cycle.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 56).

EXPERIMENTS ON THE NATURE OF THE FATIGUE CRACK PLASTIC ZONE
Hahn, G. T., Sarrate, M. and Rosenfield, A. R. (Battelle Memorial Institute, Columbus, OH)
AFFDL-TR-70-144, 425-450 (September 1970).

The experimental work described in this report deals with the plastic zone of a growing fatigue crack and its relation to the zone of a monotonically loaded, stationary crack. The study examines ways of applying two techniques: etch pitting and interferometry, to reveal the plastic zones produced by fatigue cracks under plane strain and plane stress conditions. Preliminary results are reported and these indicate that the plastic deformation generated by each loading cycle is similar to the zone of a stationary crack loaded monotonically. On this basis, theoretical treatments of the monotonically loaded crack are tentatively extended to the fatigue crack problem. Simplified formulations of the plastic blunting and damage accumulation are obtained in this way. The efficiency of the blunting mechanism and the number of plastic strain cycles experienced by material in front of the crack is estimated. This shows that both mechanisms can account for the value of the stress intensity exponent, observed in Regime No. 1 (the high cycle-low stress portion of the crack growth spectrum). While neither mechanism easily accounts for the invariance of crack growth rates in regime No. 1, the existing observations are more easily rationalized in terms of blunting. A possible explanation is offered for the higher values and growth rates of Regime No. 2 (the low cycle-high stress range). Implications with respect to the metallurgical origins of the cyclic crack growth resistance and the prospects of improving it are discussed.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 102).

EFFECT OF LOAD SEQUENCES ON CRACK PROPAGATION UNDER RANDOM AND PROGRAM LOADING
Schijve, J. (National Aerospace Lab., Amsterdam, Netherlands)
Eng. Fract. Mec. 5, 269-280 (1973)

Crack propagation was studied in 2024-T3 Alclad sheet specimens under two types of random loading and under program loading with very short period (40 cycles) and program loading with a longer period (40,000 cycles). In the program test, lo-hi, lo-hi-1 and hi-lo sequences were employed. The loads were based on a gust spectrum. The crack rates were about the same under random loading and program loading with the short period. Under program loading with the longer period the crack rates were 2.5 times slower on the average, while a significant sequence effect was observed in these tests. Fractographic observations indicated different cracking mechanisms for the random tests and program tests with a short period on the one hand and the program tests with the longer period on the other hand. Implications for fatigue tests in practice are discussed.

The results have shown that the crack propagation life is not very sensitive to the sequence of load cycles provided that the variation of the amplitude does not occur slowly. If this variation is slow, as it is in a classic program test, the life may be much longer than for random loading and this was conformed in the present tests. This is a regrettable result from a practical point of view. Actually it implies that nature does not allow us to simplify load sequences if we want to obtain relevant information on fatigue life and crack propagation. In other words, in a test on an aircraft component or a full-scale structure a classically programmed sequence of the fatigue loads cannot guarantee that realistic information will be obtained. It may produce unconservative data. Flight simulation loading should be employed in such a test.

A second remark is concerned with our understanding of the trends observed. Despite our qualitative knowledge of the various aspects related to fatigue damage accumulation it has to be admitted that an explanation for the present sequence effect cannot be given without speculative arguments. Nevertheless, the qualitative knowledge is sufficent to tell us that systematic sequence effects have to be expected. The fractographic observations have confirmed their existence.

Comment:

This paper presents very significant test data showing the effects of random and programmed load cycles on the fatigue life of materials. The observation that programmed loading may be unconservative in terms of random or flight profile loading has broad implications for testing of structure.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 132).

SOME ASPECTS OF ENVIRONMENT-ENHANCED FATIGUE-CRACK GROWTH
Wei, R. P. (Lehigh University, Bethlehem, PA)
Eng. Fract. Mech. 1, No. 4, 633-651 (1970).

A review of the effects of test environment, load profile, test frequency, test temperature and specimen thickness of the rate of fatigue-crack growth in high-strength metal alloys has been made. It was found that the effects of many of these variables depend strongly on the material-environment system involved.

Experimental information is most complete on the aluminum-water (or water vapor) system. The results indicate that water or water vapor has a strong effect on the rate of fatigue-crack growth in these alloys, increasing the rate of fatigue-crack growth up to a factor of ten over that obtained in a reference environment. The effect depends on the partial pressure of water vapor in the atmosphere, and exhibits a transition zone that depends strongly on the test frequency. This frequency effect has been attributed to the requirement of a definite amount of surface contamination to achieve full environmental effect by Bradshaw and Wheeler. These results suggest that the most probable mechanism for water-enhanced fatigue-crack growth in the aluminum alloys is that of the pressure mechanism for hydrogen embrittlement suggested by Broom and Nicholson, and requires the synergistic action of fatigue and water-metal surface reaction. The rate controlling process appears to be that of the creation of fresh crack surfaces by fatigue. A mild frequency dependence for these alloys tested in the fully humid environment or in distilled water (reflected by some 50 percent increase in growth rate for nearly a factor of 30 reduction in test frequency) has been attributed to a small contribution from sustained-load crack growth associated with the increased "time-at-load" at the lower test frequencies. Environment sensitivity is reduced at the higher K levels, and appears to result from a reduction in the effectiveness of the pressure mechanism of hydrogen embrittlement associated with plane-strain to plane-stress fracture mode transition.

Only a limited amount of data are available on the titanium alloys and high-strength steels regarding the influences of these same variables. Available data on a titanium-salt water system and steel-water vapor systems indicate the behavior is quite different for that of the aluminum-water system, and suggest that the environment-enhanced fatigue-crack growth in these systems may be simply regarded as a superposition of environment-enhanced crack growth under sustained loads (SCC) on fatigue. No significant synergistic effect of fatigue and "corrosion" was evident in the experimental results considered. If proven, such a simple model could be used to predict the effects of mean load and test frequency when crack-growth-rate data for fatigue in a reference environment and for sustained-load in the appropriate test environment are obtained. Experimental work to verify this model, as well as comprehensive studies, similar to those reported for the aluminum alloys, should be carried out for specific material-environment systems. Mechanistic studies are also needed.

On the basis of this review it is clear that the present fatigue-crack growth laws could not account for the influence of environments and its related effects. This is, of course, not surprising, since these laws do not specifically incorporate environment effects. Their value in predicting the rate of fatigue-crack growth from basic mechanical properties of materials have already been questioned by Wei, etal. As empirical laws for engineering applications, their validity must be re-established on the basis of comparisons with data obtained in well-controlled reference test environments, and they must be modified to account for environmental and other related effects, bearing in mind that these effects will likely depend on the nature of the operative embrittlement mechanism.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 124).

EFFECT OF ENVIRONMENT ON FATIGUE CRACKS
Achter, M. R. (Naval Research Lab., Washington DC)
Fatigue Crack Propagation, ASTM STP 415, 181-202 (1967)

In this review of the fatigue of metals in controlled gaseous environments, particular emphasis is placed on the mechanism of crack propagation as it is affected by the test variables. The crack growth rates of some metals are accelerated more by oxygen than by water vapor, while for others the reverse is true. Increases of cyclic frequency and of stress decrease the magnitude of the effect of environment. It is generally agreed that the mechanism is more an increase of the rate of crack propagation than of crack initiation. Of the two explanations proposed, the process of corrosive attack of the crack tip is favored over that of the prevention of rewelding of crack surfaces by the formation of oxide layers. Curves of fatigue life, or of crack growth rate versus gas pressure show regions of little or no dependence, connected by a transition region of steep slope. In a quantitative treatment of the shape of the curve, the significance of the location of the transition region is discussed.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 122).

EFFECTS OF FREQUENCY AND ENVIRONMENT ON FATIGUE CRACK GROWTH IN A286 AT 1100°F
Solomon, H. D. and Coffin, L. F. (General Electric Company, Schenectady, NY)
Fatigue at Elevated Temperatures, ASTM STP 520, 112-122 (August 1973).

Previous low-cycle fatigue tests on A286, which covered a frequency range of 5 to 0.1 CPM, have shown a pronounced frequency dependence when the tests were run in air. In contrast, tests run in a vacuum did not show such a frequency effect. This led to the conclusion that, in this frequency range, environmental effects were responsible for the frequency dependence. Air crack propagation tests have also shown a strong frequency dependence. At frequencies below .02 CPM the air crack propagation tests showed a stronger frequency dependence than was observed at higher frequencies and resulted in pure time dependent, cycle independent failure. In order to explain this behavior and to see if it could be observed in low frequency vacuum tests, measurements of the crack propagation rate at 593°C were made in a 10^{-8} Torr vacuum. These vacuum crack propagation results substantiated the assertion that at 593°C, air produces a strong influence on the failure life or crack propagation rate. Additionally, these tests have shown that below .02 CPM the pure time dependent failure noted in air persisted in the vacuum. The vacuum results could be interpreted on the basis of a linear superposition model. Where at low frequency the behavior was a purely time dependent failure; at high frequencies, purely cycle dependent; and at intermediate frequencies, that of a linear superposition of these phenomena. In air this linear superposition model was not applicable because of the additional environmental interaction.

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5. Coffin, Jr., L. F., The Effect of Frequency on High Temperature, Low Cycle Fatigue, AFFDL-TR-70-144, 301-312 (September 1970).

6. Solomon, H. D. and Coffin, Jr., L. F., The Effects of Frequency and Environment on Fatigue Crack Growth in A236 at 1100F, General Electric Report 72CDR101 (1972).

Key Words: Crack propagation; cyclic loads; cyclic testing; edge crack specimens; environmental effects; fatigue (materials); fatigue tests; frequency effects; high temperature; low-cycle fatigue; metallic materials; notched specimens; stainless steels.

SUBCRITICAL CRACK GROWTH CRITERIA FOR INCONEL 718 AT ELEVATED TEMPERATURES
Popp, H. G. and Coles, A. (General Electric Co., Evandale, OH)
AFFDL-TR-70-144, 71-86 (September 1970)

The purpose of this investigation was to determine if fracture mechanics methods are suitably accurate to predict the defect tolerance of Inconel 718 welds at temperatures up to 1200°F in the cyclic conditions typically encountered in jet engine frames and caseings. It was shown that elastic fracture mechanics methods can be applied to temperatures in the creep regime with reasonable accuracy for Inconel 718. In addition, a fracture mechanics model was developed to predict the residual cyclic life of Inconel 718 weldments containing surface defects. Cases of axial and combined axial and bending stress fields were treated. Also, the utility of a time-temperature parameter to predict cyclic crack growth rates at a particular stress intensity was demonstrated. The parameter $P = (T + 460)\ (10 + \mathrm{Log}(TH)\ )$ provided reasonably accurate description of crack growth rate data for temperatures ranging from 70°F to 1200°F and peak stress hold times of from one second to two hours.

Important References:

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4. Energy, A. F., Kobayashi, A. S. and Smith, F. W., Stress Intensity Factors for Penny Shaped Cracks, ASME Paper 67-WA/APM-2 (November 1967).

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Key words: Center crack specimens; crack propagation; cyclic loads; fatigue (material); high temperature; random load cycles; stress intensity factor.

AN EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF VACUUM ENVIRONMENT ON THE FATIGUE LIFE, FATIGUE-CRACK-GROWTH BEHAVIOR, AND FRACTURE TOUGHNESS OF 7075-T6 ALUMINUM ALLOY
Hudson, C. M. (North Carolina State Univ., Raleigh, NC)
PhD Thesis, Department of Materials Engineering (1972)

A series of axial-load fatigue life, fatigue-crack growth, and fracture toughness tests were conducted on 0.090-inch thick specimens made of 7075-T6 aluminum alloy. The fatigue life and fatigue crack-propagation experiments were conducted at a stress ratio of 0.02. The maximum stresses in the fatigue-life experiments ranged from 33 to 60 ksi, and from 10 to 40 ksi in the gas pressures of 760, 5 x 10^{-1}, 5 x 10^{-2}, 5 x 10^{-4}, and 5 x 10^{-8} Torr. Fatigue-crack-growth and fracture toughness experiments were conducted at gas pressures of 760 and 5 x 10^{-8} Torr. Residual stress measurements were made on selected specimens to determine the effect of residual stresses on fatigue behavior. These measurements were made using x-ray diffraction techniques. Fracture surfaces of typical specimens were examined using scanning and transmission electron microscopes to study fracture modes in vacuum and air.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 158).

FRACTURE AND FATIGUE-CRACK-PROPAGATION CHARACTERISTICS OF 1/4-INCH MILL ANNEALED TI-6AL-4V TITANIUM ALLOY PLATE
Feddersen, C. E. and Hyler, W. S. (Battelle Columbus Labs, OH)
Battelle Report No. G-9706 (November 1971)

The fracture and fatigue-crack-propagation behavior of central through-the-thickness cracks has been evaluated for one thickness of mill-annealed titanium alloy plate. The influence of crack aspect ratio on the fracture or residual strength of three panel widths has been determined. The fatigue-crack-propagation rates for various maximum stresses, stress ratios, and panel widths have also been evaluated. It has been observed that elastic fractures in the presence of central through-cracks do not occur in panels of this material less than 18 inches wide. Uniform and regular fatigue-crack-propagation behavior is noted in this material on the basis of a stress-intensity factor range, ΔK, analysis. A fatigue-crack-propagation threshold is evident below 3 or 4 ksi-in ½. Power law modeling of rate data, crack life prediction, and interpretive discussions are also considered.

From the data the crack behavior of mill-annealed Ti-6Al-4V titanium alloy in 1/4-inch thickness appears to be consistent and predictable. The material is quite tough with no elastic fracture instabilities noted in panels less than 18 inches wide. However, slow stable tear (or stable crack extension) in the rising load test is noted at net section stresses about 40 ksi. The fatigue-crack-propagation ratios, (2c)/n, are very consistent when evaluated on a ΔK basis. However, there is an additional distinct effect of stress ratio, R, over and above that reflected in ΔK.

A threshold stress-intensity factor range is evident and varies with stress ratio. The lowest ΔK level at which propagation was noted was about 3.5 ksi-in ½.

It is evident that the crack propagation models currently used need to be modified for threshold effect and for improved accumulation of stress ratio, R. This is a definite necessity in order to obtain a more reliable predictive tool for design purposes.

This experimental program has characterized this particular thickness of the subject titanium alloy quite well. A parallel, but more selective, program at other thickness is recommended.

A very critical issue, now that consistent FCP rates have been demonstrated is a study on environmental effects wherein significantly lower frequencies are applied for much longer time periods.

Comments:

This paper provides an effective characterization of 1/4-inch thick mill-annealed Ti-6Al-4V titanium alloy and is a guide for similar required efforts at other thicknesses with other alloys of interest.

Important References:

1. Feddersen, C. E. and Hyler, W. S., Fracture and Fatigue-Crack Propagation Characteristics of 7075-T7351 Aluminum Alloy Sheet and Plate, Final Report from Battelle Columbus Laboratories to Naval Air Development Center, Contract No. N00156-68-C-1344 (March 1970).

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4. Paris, P. C., The Growth of Cracks Due to Variations in Loads, PhD Thesis, Lehigh University , Bethlehem, PA (1962).

Key words: Crack propagation; fatigue (materials); fractures (materials); residual strength; stress intensity factor; structural reliability; titanium alloys.

IV - Creep and Fatigue Damage Phenomena

FATIGUE DAMAGE ACCUMULATION AND TESTING FOR PERFORMANCE EVALUATION
Freudenthal, A. M. (George Washington Univ., Washington DC)
AFML-TR-71-50 (April 1971)

The effects of mean stress and of stress amplitude on the various stages of the fatigue process is discussed in light of recent research on fatigue mechanisms with the purpose of assessing the relevance of fatigue testing processes under constant and under random loading as well as of the application of linear fracture mechanics in the prediction of the fatigue life of airframes. It is concluded that fatigue tests based on a mission-determined representative flight-by-flight loading spectrum will produce the closest approximation of service conditions and should be used both for life prediction of structures and for materials evaluation for fatigue performance.

Comment:

This paper discusses the philosophy of fatigue and fatigue testing and comes to the not unsurprising conclusion that the closer the test fatigue spectrum simulates the actual service experience the more accurate will be the fatigue life prediction.

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2. Schijve, J., Analysis of Random Load Time Histories, in Fatigue of Aircraft Structures, W. Barris, Ed., MacMillan Co., New York, NY (1963).

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Key words: Cumulative damage; fatigue (materials); fatigue life; fracture mechanics; structural reliability; testing methods.

CUMULATIVE DAMAGE IN FATIGUE, A STEP TOWARDS ITS UNDERSTANDING
Brook, R. H. W. and Parry J. S. C. (Rolls-Royce, Told., Derby England, Bristol Univ., England)
J. Mech. Eng. Sci. 11, No. 3, 243-255 (June 1969)

A method is described which uses change of apparent dynamic modulus and damping during fatigue cycling for estimating accurately the fatigue lives of stainless steel specimens. This technique for estimating well in advance of failure the fatigue lives of individual specimens avoids the usual difficulties caused by scatter of fatigue results, and has enabled a more precise quantitative investigation to be made of cumulative fatigue damage than would have been possible using conventional experimental methods. By estimating the remaining life of a specimen at one stress amplitude before measuring the equivalent remaining life at a second stress amplitude by cycling to failure, it was possible to determine lines of equal damage on a plot of stress amplitude versus remaining fatigue life. These lines of equal damage were used to predict the fatigue lives of specimens subjected to programs of multi-level loading, and the accuracy of these estimates, when compared with the subsequent experimental results, is much better than has been achieved hitherto. Depending on the stressing program chosen, Miner's linear damage rule is shown to be very good, rather pessimistic, or very dangerous.

Comment:

This approach offers an excellent technique for monitoring and predicting fatigue life. It has been developed for a particular specimen and material, although it appears to have wider application.

However, a great deal of work needs to be done to correlate and apply it to other than well characterized laboratory fatigue specimens.

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Key words: Analysis methods; cumulative damage; fatigue (materials); fatigue life; life prediction; linear damage rule; modulus of elasticity; stainless steels.

THE CHALLENGE TO UNIFY TREATMENT OF HIGH TEMPERATURE FATIGUE - A PARTISAN PROPOSAL BASED ON STRAINRANGE PARTITIONING

Manson, S. S. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

Fatigue at Elevated Temperatures. ASTM STP 520 744-782 (August 1973)

An overview lecture summarizing the 1972 international symposium on fatigue at elevated temperatures held at Storrs, Connecticut, is presented. Starting with the observation of the diversity of subjects covered and lack of unaminity of approaches used, it becomes clear that there exists an urgent need for a unifying framework around which the many facets can be coherently structured. It is proposed that the strainrange partitioning concept had the potential of serving as such a framework. The method divides the imposed strain into four basic ranges involving time-dependent and time independent components. It is shown that some of the results presented at the symposium can be better correlated on the basis of this concept than by alternative methods. It is also suggested that methods of data generation and analysis can be helpfully guided by this approach. Potential applicability of the concept to the treatment of frequency and holdtime effects, environmental influence, crack initiation and growth, thermal fatigue, and code specifications are then considered briefly. A required experimental program is outlined.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 89).

TEMPERATURE EFFECTS OF STRAINRANGE PARTITIONING APPROACH FOR CREEP FATIGUE ANALYSIS

Halford, G. R., Hirschberg, M. H., and Manson, S. S. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

Fatigue at Elevated Temperatures. ASTM STP 520, 658-669 (August 1973)

Examination is made of the influence of temperature on the strainrange partitioning approach to creep fatigue. Results for 2.25Cr-1Mo steel and type 316 stainless steel show the four partitioned strainrange-life relationships to be temperature insensitive to within a factor of two on cyclic life. Monotonic creep and tensile ductilities were also found to be temperature insensitive to within a factor of two. The approach provides bounds of cyclic life that can be readily established for any type of inelastic strain cycle. Continuous strain cycling results obtained over a broad range of high temperatures and frequencies are in excellent agreement with bounds provided by the approach.

Important References:

1. Manson, S. S., Halford, G. R., and Hirschberg, M. H., Creep-Fatigue Analysis by Strain-Range Partitioning, Proc. Symp. Design for Elevated Temp. Environ. ASME, 12-24 (1971).

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Key words: Analysis methods; creep; creep analysis; creep properties; cyclic creep; ductility; failure analysis; failures (materials); fatigue (materials); heat resistant alloys; life prediction; load cycles; metallic material; plastic properties; stainless steels; strain; strainrange partitioning; temperature effects; thermal cycles.

APPLICATION OF A DOUBLE LINEAR DAMAGE RULE TO CUMULATIVE FATIGUE

Manson, S. S., Freche, J. C. and Ensign, C. R. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

Fatigue Crack Propagation, ASTM STP 415 384-412 (1967)

The validity of a previously proposed method of predicting cumulative fatigue damage in smooth 1/4 in. diameter specimens based upon the concept of a double linear damage rule is investigated. This method included simplified formulas for determining the crack initiation and propagation stages and indicated that each of these stages could be represented by a linear damage rule. The present study provides a critical evaluation of the earlier proposal, further illuminates the principles underlying cumulative fatigue damage, and suggests a modification of the original proposal. Data was obtained in two stress level tests with maraged 300 CVM and SAR 4130 steels in rotating bending. Two strain level tests were conducted in axial reversed strain cycling with maraged 300 CVM steel. The investigation showed that in most cases the double linear damage rule when used in conjunction with originally proposed equations for determining crack initiation and propagation predicted fatigue life with greater or equal accuracy than the conventional linear damage rule. An alternate viewpoint of the double linear damage rule is suggested. This requires that a limited number of simple two-stress level tests to be run to establish effective fatigue curves for what may be defined as Phases I and II of the fatigue process. These fatigue curves may then be used in the analysis of any spectrum of loads involving as loading extremes then two stresses used for their determination. Only limited verification of the new method has been obtained to date, and it must presently be limited to the study of smooth, 1/4-inch diameter specimens. However, it may be considered as a first step in the direction of eventually predicting the effect of a complex loading history on the life of more complex geometrical shapes.

Comment:

This effort provides interesting correlation between relatively simple tests and fatigue life behavior. Its application to more complex specimens and loading histories has been found to be considerably more difficult. Many of the techniques such as this one work fine for simple specimens but the application to more complex systems and spectrums become more difficult than an actual life or accelerated life test.

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1. Manson, S. S., Nachtigall, A. J., Ensign, C. R., and Freche, J. C., Further Investigation of a Relation for Cumulative Fatigue Damage in Bending. Trans. ASME (February 1965).

2. Manson, S. S., Interfaces Between Fatigue, Creep, and Fracture, (March 1966) Int. J. Fract. Mech. 2, No. 1, 327-363.

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Key words: Analysis methods; crack initiation; crack propagation; cracks; cumulative damage; cumulative effects; fatigue (materials); fatigue life; fatigue tests; life prediction; linear damage rule; load cycles; maraging steel; steels.

DAMAGE ACCUMULATION DURING STRAIN CYCLING AT DIFFERENT TEMPERATURES AND STRAIN RATES

Abdel-Raouf, H., Topper, T. H. and Plumtree, A. (Waterloo Univ., Ontario, Canada)

ASTM, ASME, IME, Int. Conf. Creep and Fatigue in Elevated Temperature Applications, 185.1-185.8 Philadelphia, PA (23-28 September 1973) and Sheffield, England (1-5 April 1974).

The effects of temperature (-75°C to 760°C) and cyclic strain rate (2×10^{-4} per sec to 4×10^{-1} per sec) on the fracture mechanism were investigated using OFHC copper and Type 304 stainless steel under strain control. It was found that time dependent fracture predominates at high temperatures and low strain rates. However, at high strain rates the life was insensitive to temperature. The role of grain boundary migration on the fracture process was investigated. Grain boundary migration was found to be dependent on the strain rate for copper whereas the Type 304 stainless steel, grain boundary migration was inhibited at high temperature (760°C) due to the presence of precipitates at the grain boundaries. During strain cycling of OFHC copper and Type 304 stainless steel, creep damage can not be summed to the fatigue damage to give a total damage of unity for failure, if only a single deformation and fracture mechanism is operating. The sense of the damage accumulation does not affect these findings.

In general, the amount of previous damage has no influence on the damage accumulation which follows, if it is not of the same kind.

Important References:

1. Abdel-Raouf, H., Plumtree, A. and Topper, T. H., Effects of Temperature and Deformation Rate on Cyclic Strength and Fracture of Low-Carbon Steel, ASTM STP 519, 28-57 (May 1973).

2. Coffin, Jr., L. F., The Effect of Vacuum on the High Temperature, Low Cycle Fatigue Behavior of Structural Metals, General Electric Report TIS 71-C-108 (1971).

3. Manson, S. S., Halford, G. R. and Spera, D. A., The Role of Creep in High-Temperature Low-Cycle Fatigue, Advances in Creep Design, A. E. Johnson Memorial Vol., Appl. Sci. Publishers Ltd., London, England, 229-249 (1971).

4. Conway, J. B., Berling, J. T. and Stentz, R. H., A Brief Study of Cumulative Damage in Low-Cycle Fatigue Testing of AISI 304 Stainless Steel at 650°C, Met. Trans. 1, 2034 (1970).

5. Topper, T. H., Sandor, B. I. and Morrow, J., Cumulative Damage Under Cyclic Strain Control, J. Mater. 4, No. 1 (1969).

6. Cocks, G. J. and Toplin, D. M. R., The Influence of Grain Boundary Migration on the Fatigue Life of OFHC Copper and Copper Alloy at 490°C, Int. Conf. Fract., 3rd, Munich, Germany (April 1973).

Key words: Creep; cumulative damage; cyclic loads; damage; fatigue (materials); fractures (materials); grain boundaries; high temperature; load cycles; low temperature; stainless steels; strain; strain rate; temperature effects; thermal stresses.

CALCULATION OF THERMAL-FATIGUE LIFE BASED ON ACCUMULATED CREEP DAMAGE
Spera, D. A. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)
NASA-TN-D-5489

This report presents a method for predicting the onset of thermal-fatigue cracking in high temperature components under service conditions. Starting from basic material properties, life is calculated by considering two distinct failure modes, (1) cyclic creep-rupture, using a modification of the well-known life-fraction rule proposed by Robinson and Taira, and (2) conventional, time-dependent, low-cycle fatigue, using empirical equations of the method of universal slopes developed by Manson. The method is illustrated by using Glenny-type thermal fatigue data on the nickel-base alloy Nimonic 90. In 24 of the 28 cases analyzed cyclic creep rupture was the dominant failure mode.

Important References:

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2. Howe, P. W. H., Mathematical Techniques Applying to the Thermal Fatigue Behavior of High Temperature Alloys, Aeron. Quart. 13, Pt. 4, 368-396 (November 1962).

3. Taira, S., Lifetime of Structures Subjected to Varying Load and Temperature, Creep in Structures, Nicholas J. Hoff, Ed., Academic Press, New York, NY, 96-124 (1962).

4. Manson, S. S. and Halford, G., A Method of Estimating High-Temperature Low-Cycle Fatigue Behavior of Materials, Thermal and High Strain Fatigue, The Metals and Metallurgy Trust, London, England, 154-170 (1967).

Key words: Crack initiation; crack propagation; creep; creep analysis; failure mode; heat resistant alloys; high temperature; linear damage rule; nickel alloys; structural safety; thermal fatigue; yield strength.

A SPECIALIZED MODEL FOR ANALYSIS OF CREEP-RUPTURE DATA BY THE MINIMUM COMMITMENT, STATION-FUNCTION APPROACH

Manson, S. S. and Ensign, C. R. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)
NASA-TM-X-52999

The use of minimum commitment, station-function approach for correlating creep-rupture data is discussed. A hypothesized time-temperature-stress relation is taken in sufficiently general form to include all commonly used parameters. The functional forms involved in the relation are not taken in analytical form; rather they are defined as "station functions" - their numerical value at selected station values of the independent variable. Using station functions not only avoids "forcing" the pattern of the data, but provides an incidental benefit in avoiding illconditioning of the system of resulting equations, which are computer-solved for the optimum data representation. This feature also contributes to the objectiveness of the method, and gives each time-temperature parameter consistant with the model an equal chance to demonstrate itself as the correct one.

Comment:

As the authors indicate, this method produces correct predictions if the basic data conform to one of the commonly used time-temperature parameters, and when the input data is plentiful and given to a high degree of accuracy. Additional effort is needed to delineate the best uses of this method and its limitations.

Important References:

1. Manson, S. S., Time-Temperature Parameters - A Re-Evaluation and Some New Approaches, ASM Pub. D8-100 (January 1970).

Key words: Analysis methods; creep; creep rupture; high temperature; life prediction; stress; theories.

DUCTILITY EXHAUSTION MODEL FOR PREDICTION OF THERMAL FATIGUE AND CREEP INTERACTION

Polhemus, J. F., Spaeth, C. E. and Vogel, W. H. (Pratt and Whitney Aircraft, East Hartford, CT).

Fatigue at Elevated Temperatures, ASTM STP 520, 625-636 (August 1973)

Extensive laboratory testing of typical alloys used in gas turbine blading has shown that there is a strong interaction of the thermal fatigue and creep damage modes which is nonlinear in nature. Consequently, a model for cumulative damage analysis was developed using an exhaustion of ductility concept in which the total available ductility is derived from baseline thermal fatigue tests or, alternatively, estimated from stress-rupture tests. A cycle-by-cycle reckoning of ductility used and remaining is made with the use of a digital computer program, and cracking is ultimately predicted at the point where the remaining ductility is insufficient to complete another cycle. The developed analysis is shown to correlate with laboratory test results. The understanding and design procedure developed make it possible to simulate complex service conditions in digital computer programs and evaluate designs and materials in simulated "fly-offs".

Important References:

1. Vogel, W. H. and Carden, A. E., Thermal Mechanical Fatigue of Some Superalloys, Presented at Nat. Metal Cong., Cleveland, OH (1967).

2. Ohji, K., Miller, W. R. and Martin, J., Cumulative Damage and Effect of Mean Strain in Low-Cycle Fatigue of 2024-T351 Aluminum Alloy, Winter Annu. Meet. Chicago, IL, (7-11 November 1965).

3. Manson, S. S., Thermal Stress and Low-Cycle Fatigue. McGraw-Hill, New York, NY (1966).

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Key words: Cracking (fracturing); creep; creep properties; creep rupture strength; cumulative damage; cyclic loads; ductility; failures (materials); fatigue (materials); fatigue tests; gas turbine engines; high temperature; high temperature environments; life prediction; low-cycle fatigue; metallic materials; stress rutpure; thermal cycles; thermal fatigue; turbine blades.

A STUDY OF CYCLIC PLASTIC STRESSES AT A NOTCH ROOT

Crews, Jr., J. H. and Hardrath, H. F. (National Aeronautics and Space Administration, Langley Research Center, Langley Station, VA)

J. SESA 6, No. 6, 313-320 (1966)

An experimental study is presented for cyclic plastic stresses at notch roots in specimens under constant-amplitude repeated tension and reversed loading. Edge-notched, K_t equals 2, 2024-T3 aluminum-alloy sheet specimens with a K_t value of 2 were cycled until local stress conditions stabilized. Local stress histories

were determined by recording local strain histories during cycling and reproducing these histories in simple, unnotched specimens. The fatigue lives for these notched specimens were estimated using stabilized local stresses and an alternating versus mean stress diagram for unnotched specimens of the local material. In addition, an expression is presented for calculating local first-cycle plastic stresses. An acceptable correlation is shown between predicted stresses and experimental data.

Important References:

1. Neuber, H., Theory of Notch Stresses, Principles for Exact Calculation of Strength with Reference to Structural Form and Material, J. W. Edwards, Ann Arbor, MI (1946).

2. Illg, W., Fatigue Tests on Notched and Unnotched Sheet Specimens of 2024-T3 and 7075-T6 Aluminum Alloys and of SAE 4130 Steel with Special Consideration of the Life Range from 2 to 10,000 Cycles, NACA TN-3866 (1956).

3. Grover, H. J., Bishop, S. M. and Jackson, L. R., Fatigue Strengths of Aircraft Materials, Axial-Load Fatigue Tests on Notched Sheet Specimens of 24S-T3 and 24S-T6 Aluminum Alloys and of SAE 4130 Steel with Stress-Concentration Factors of 2.0 and 4.0, NACA-TN-2389 (1951).

Key words: Aluminum alloys; cyclic loads; fatigue properties; fatigue tests; load cycles; notch sensitivity; plastic strain; residual stress; S-N diagrams; strain accumulation; stress; stress ratio.

MECHANICS OF CRACK TIP DEFORMATION AND EXTENSION BY FATIGUE
Rice, J. R. (Brown Univ., Providence, RI)
Fatigue Crack Propagation, ASTM STP 415, 247-309 (1967)

Crack propagation is viewed primarily as a problem in continuum mechanics. Part I surveys the elastic and elastic-plastic stress analyses of cracked bodies, with emphasis on the plasticity. In addition to well-known results based on models of perfectly plastic anti-plane shearing and discrete surfaces of tensile yielding or slip (equivalently, continuous dislocation arrays), some recently obtained results on work-hardening and anisotropic perfect plasticity are summarized, and methods are presented for the modeling of plane strain yielding. Emphasis is placed on the common result of all plasticity analyses that the coefficient of a characteristic singularity in elastic solutions determines the plastic deformation in situations of small scale yielding. The influence of hardening behavior, finite width effects, and large scale yielding are illustrated and the predictions of various models compared.

Part II considers the mechanics of fatigue crack propagation. Elastic-plastic responses to cyclic loading are determined for perfectly plastic and a type of stable hardening behavior. Effectively, the yield stress is double so that cyclic

flow zones and variations in plastic deformations are smaller than for monotonic loading. Crack tip blunting by large deformations and related effects are treated approximately. General features of fatigue crack growth are surveyed, and the extensive evidence is cited supporting a primary conclusion of continuum analyses: that crack growth rates are determined by elastic stress intensity factor variations or the small scale yielding situation common in low-stress high-cycle fatigue. Results pertaining to mean load, sheet thickness, and mode transition effects, delays in crack extension due to overloads, growth under bending loads, and growth by random applied loads are also noted and interpreted in continuum terms. Theories of crack growth relating continuum considerations to "damage" accumulation and material separation are examined. Further progress requires better continuum analysis, incorporating crack blunting by deformation and clearer ideas of separation mechanics.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT SEE PAGE 100).

PREDICTIVE TESTING IN ELEVATED TEMPERATURE FATIGUE AND CREEP: STATUS AND PROBLEMS
Coffin, Jr., L. F. and Goldhoff, R.M. (General Electric Co., Schenectady, NY)
Testing for Prediction of Materials Performance in Structures and Components
ASTM STP 515 22-74 (October 1972)

Two well recognized problem areas of high temperature material behavior, namely, creep and fatigue, are considered with those factors which contribute to the prediction and useful service life of the component. The information available is obtained almost entirely in a laboratory environment, in which simplified load conditions and specimen geometries and controlled environments are employed for material evaluation. Consideration is not given to transferring this information to actual design, other than to identify the importance of such problems as the analytical determination of stresses and strains in the structure, the effect of highly complex loading, or the behavior in a complex environment, but on several practical problems occurring in high temperature power generating machinery will be employed as examples of the topics for discussion; namely, creep, fatigue, and creep-fatigue interaction. The topics of creep and fatigue are considered separately, the discussion being built around three central topics: (1) real problems in prediction, (2) complicating instabilities including the effects of environment, deformation, and microstructure; and (3) some current predictive methods. Consideration of the less well defined problem of creep fatigue interactions is also included.

Figure IV-B presents a simple schematic overview of the creep-rupture problem while introducing complicating factors. In the area of analysis every design will be based on limits imposed by creep or rupture, and a prediction as to whether stress or strain criteria apply must be made.

Comment:

This paper effectively summarizes the state of the art of predictive testing at elevated temperature including a lucid presentation of the accepted governing equations. It is a basic review which can bring someone effectively and quickly up to date in this area. Also included are guidelines for future research and development in the related areas of creep and rupture and of high temperature fatigue. The 125 references are also an effective bibliography of this particular area.

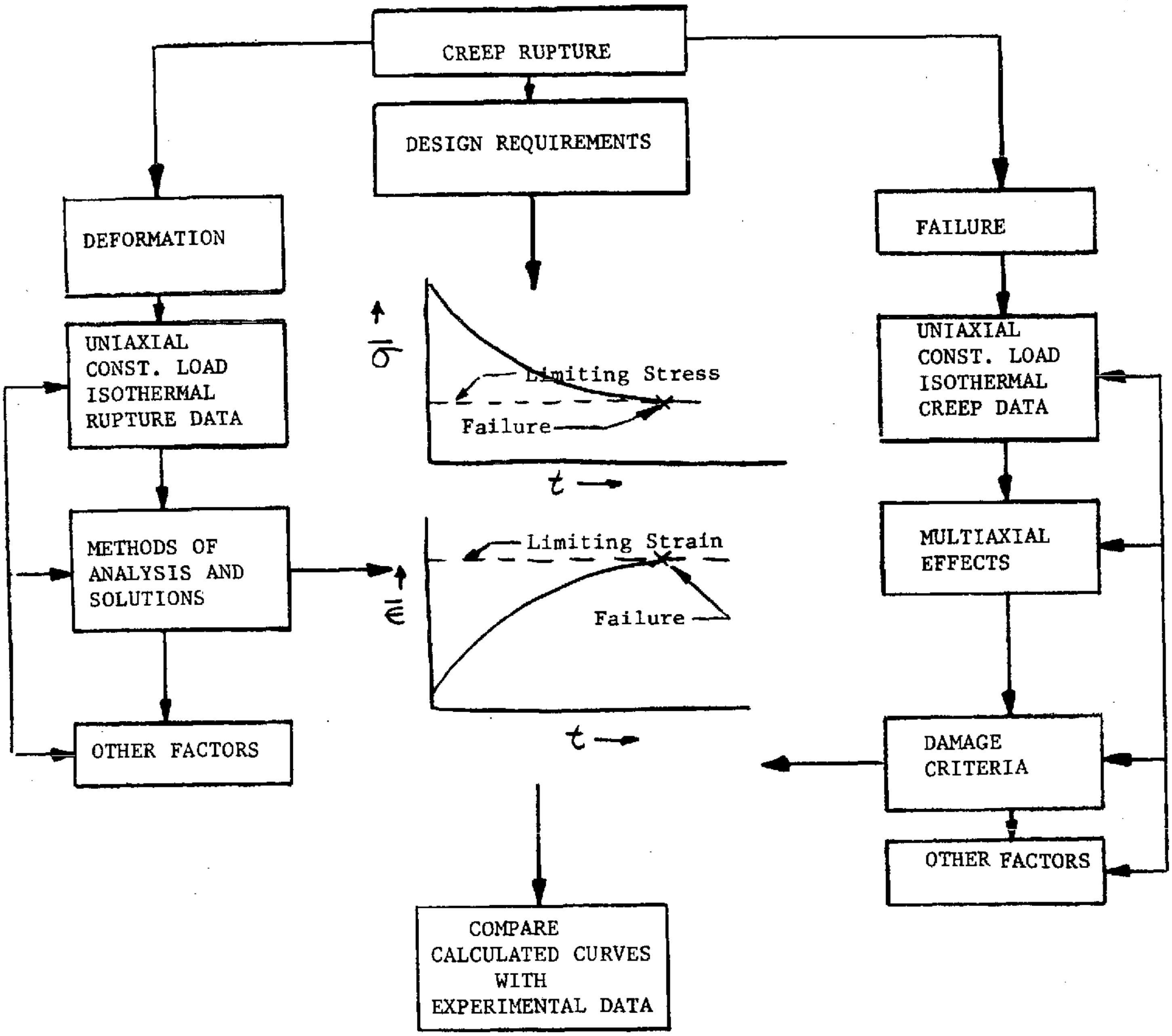

FIGURE IV-B CREEP RUPTURE PROBLEM ELEMENTS

Important References:

1. Dorn, J. E., Mechanical Behavior of Materials at Elevated Temperature, McGraw Hill, New York, NY (1961).

2. Manson, S. S., Time-Temperature Parameters - A Re-Evaluation and Some New Approaches, Amer. Soc. Met. Pub. D8-100, 1 (1968).

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4. Coffin, Jr., L.F., Achievement of High Fatigue Resistance in Metals and Alloys, ASTM STP 467, 53 (1970).

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7. Manson, S. S., Thermal Stress and Low Cycle Fatigue, McGraw-Hill, New York, NY (1966).

8. Spera, D. A., The Calculation of Elevated-Temperature Cyclic Life Considering Low Cycle Fatigue and Creep, NASA TN-D-5317 (1969).

Key words: Crack initiation; crack propagation; creep rupture strength; environmental effects; fatigue (materials) fatigue properties; grain boundaries; high temperature; life prediction; microstructures; notch sensitivity; strain; stress.

THE CHALLENGE TO UNIFY TREATMENT OF HIGH TEMPERATURE FATIGUE - A PARTISAN PROPOSAL BASED ON STRAINRANGE PARTITIONING

Manson, S. S. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

Fatigue at Elevated Temperatures, ASTM STP 520, 744-782 (August 1973)

This paper was presented as an overview lecture summarizing the 1972 International Symposium on Fatigue at Elevated Temperatures held at Storrs, Connecticut. Starting with the observation of the diversity of subjects covered and lack of unanimity of approaches used, it becomes clear that there exists an urgent need for a unifying framework around which the many facets can be coherently structured. It is proposed that the strainrange partitioning concept had the potential of serving as such a framework. The method divides the imposed strain into four basic ranges involving time-dependent and time independent components. It is shown that some of the results presented at the symposium can be better correlated on the basis of this concept than by alternative methods. It is also suggested that methods of data generation and analysis can be helpfully guided by this approach. Potential applicability of the concept to the treatment of frequency and holdtime effects, environmental influence, crack initiation and growth, thermal fatigue, and code specifications are then considered briefly. A required experimental program is outlined.

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1. Halford, G. R., Hirschberg, M. H. and Manson, S. S., Temperature Effects on the Strainrange Partitioning Approach for Creep Fatigue Analysis, ASTM STP 520, 658-669 (August 1973).

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3. Manson, S. S. and Halford, G. R., A Method of Estimating High-Temperature Low-Cycle Fatigue Behavior of Materials, Proc. Int. Conf. Thermal and High-Strain Fatigue, The Met. and Metal. Trust, London, England, 154-170 (1967).

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6. Campbell, R. D., Creep/Fatigue Interaction for 304 Stainless Steel Subjected to Strain Controlled Cycling with Holdtimes at Peak Strain, Nat. Cong. Pressure Vessels and Piping, 1st., ASME Paper No. 71-PVP-6, San Francisco, CA (May 1971).

Key words: Analysis methods; crack propagation; creep; creep analysis; cyclic creep; cyclic loads; deformation; ductility; failure analysis; fatigue (materials); fatigue life; high temperature; strain; strainrange partitioning; thermal fatigue.

PREDICTIVE PARAMETERS AND THEIR APPLICATION TO HIGH TEMPERATURE, LOW CYCLE FATIGUE

Coffin, Jr., L. F. (General Electric Co., Schenectady, NY)

Proc. Int. Conf. on Fracture, 2nd., Brighton, England, 56/1 - 45/12 (13-18 April, 1969)

Existing predictive methods for determining high temperature, low cycle fatigue life are re-examined, based on experiments on 'A' nickel. The relationship

$N_f^{\alpha} \cdot \Delta E_p = C$ is found to exist, where α is the function of strain rate and temperature. Assuming $\Delta E_p = \Delta E_f$ at $N_f = 1/4$, as for low temperature, where E_f is the tensile ductility, this point falls well below the fatigue curve. The present results and those of other investigators are shown to be expressible in the form $C_1^{\beta} \cdot \Delta E_p = C_2$ where C_1 is a quantity defined as the frequency-modified fatigue life and β and C_2 depend only on temperature for a given material. The frequency-modified fatigue life, defined as $\nu^{\kappa} \cdot t$ where ν is the frequency and t the time to failure, has applicability to the prediction of long hold-time fatigue life from short time tests. Fatigue crack propagation was both transgranular and intergranular and this bi-modal failure process is self-consistent with the concept of a frequency-modified fatigue life, and with the dependence of β on temperature. An upper bound fatigue curve is predicted for very low lives where crack propagation is by ductile, transgranular fracture. It employs the tensile ductility and assumes $\alpha = \beta = 1/2$. The curve intersects with the bi-modal curve at very low cycle life, and a method for predicting this intersection is suggested, based on experimental observation.

Comments:

This paper shows that certain formulas may adequately describe high temperature, low cycle fatigue behavior when modified by applicable empirical constants.

Important References:

1. Manson, S. S. and Halford, G., A Method of Estimating High-Temperature Low-Cycle fatigue Behavior of Materials, Thermal and High-Strain Fatigue, Met. and Metal. Trust, London, England, 154-170 (1967).

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3. Forrest, P. G., The Use of Strain Cycling Tests for Assessing Thermal Fatigue Resistance, Appl. Mater. Res. 4, 239 (1965).

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6. Coles, A., Hill, G. J., Dawson, R. A. T., and Watson, S. J., The High Strain Fatigue Properties of Low-Alloy Creep Resisting Steels, Proc. Int. Conf. on Thermal and High Strain Fatigue, The Metals and Metal. Trust, 270 (1967).

Key words: Analysis methods; fatigue life; fatigue (materials); fracture analysis; high temperature; low-cycle fatigue; microstructures.

A METHOD OF ESTIMATING HIGH-TEMPERATURE LOW-CYCLE FATIGUE BEHAVIOR OF MATERIALS

Manson, S. S. and Halford, G. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

Int. Conf. Thermal and High Strain Fatigue, The Metals and Metallurgy Trust, Londong, England 154-170 (1967)

A method is described whereby static-tensile and creep-rupture properties can be used to estimate lower bound, average, and upper bound low-cycle fatigue behavior in the creep range. The approach is based primarily on the method of universal slopes previously developed for estimating room-temperature fatigue behavior, and in part on a highly simplified creep-rupture-fatigue analysis. Reasonable agreement is obtained when the estimates are compared with total strain range/life data for numerous engineering alloys. Included in the study are coated and uncoated nickel-base alloys, a cobalt-base alloy, low-and high-alloy steels, and stainless steels tested under laboratory conditions over a wide range of temperatures and cyclic rates.

Comment:

The authors checked the method by comparing the estimates with elevated temperature strain-controlled laboratory fatigue data on numerous materials. Without excluding data scatter arising from the diverse testing techniques of different laboratories, the results obtained still indicate that the estimates at high temperature can be made with about the same degree of confidence as for room temperature behavior by the method of universal slopes.

Important References:

1. Manson, S. S., Interfaces Between Fatigue, Creep and Fracture, Int. J. Fract. Mech. 2, No. 1, 327-363 (March 1966).

2. Manson, S. S., Fatigue: A Complex Subject - Some Simple Approximations, Exp. Mech. 5, No. 7, 193-226 (July 1965).

3. Manson, S. S., Thermal Stress and Low-Cycle Fatigue, McGraw-Hill Book Co. New York, NY (1966)

Key words: Analysis methods; cobalt alloys; creep; creep rupture; cyclic loads; fatigue life; high temperature; life prediction; low-cycle fatigue; nickel alloys; steels; strain; universal slopes.

APPLICATION OF A METHOD OF ESTIMATING HIGH-TEMPERATURE LOW-CYCLE FATIGUE BEHAVIOR OF MATERIALS

Halford, G. R. and Manson, S. S. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

Trans. Amer. Soc. Metals 61, 94-102 (1968)

Further study is made of a recently proposed method whereby tensile and stress-rupture properties may be used to estimate low-cycle, strain fatigue behavior in the creep range. The method is based primarily on the equation of universal slopes previously developed for predicting room-temperature fatigue

behavior, and on a straightforward linear damage analysis of combined fatigue and stress-rupture. Fatigue life estimates are presented and compared with a large quantity of fatigue data for nickel-base alloys, high-and low-alloy steels, stainless steels, and aluminum-base alloys tested under laboratory conditions over a wide range of temperatures and cycling frequencies.

The method proposed affords a simple way of estimating elevated temperature, low-cycle fatigue behavior of materials from tensile and stress-rupture properties. Fatigue life estimates based upon the method have been compared with over 75 sets of high-temperature fatigue data on a variety of materials tested over a wide range of test conditions. The method provided lower bound fatigue lives for about 85 percent of the data, upper bound lives for approximately 95 percent of the data, and nearly 80 percent of the data fall within a factor of three on either side of the estimated average lives. The favorable agreement between the estimates and observed behavior suggests that it may be applied with confidence to other materials and test conditions. Such fatigue life estimates can be very useful, particularly in the early stages of design and materials selection. It is not intended, however, for these estimates to eliminate the need for further experimental evaluation of the low-cycle fatigue behavior of materials at elevated temperatures. Rather, they are best suited for quick, approximate answers, and not for final design purposes.

Comment:

The method embodied in this paper can be very useful if applied in accordance with the cautions indicated in the paper.

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1. Manson, S. S. and Halford, G. R., A Method of Estimating High-Temperature, Low Cycle Fatigue Behavior of Materials, Proc. Int. Conf. on Thermal and High-Strain Fatigue, Metals and Metallurgy Trust, London, England, 154-170 (1967).

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Key words: Analysis methods; fatigue (materials); fatigue life ; high temperature; linear damage rule; low-cycle fatigue.

NEUBERS RULE APPLIED TO FATIGUE OF NOTCHED SPECIMENS

Topper, T. H., Wetzel, R. M. and Morrow, J. (Illinois Univ., Urbana, IL.)

J. Mater. 4, No. 1, 200-209 (March 1969)

A method is presented for predicting the fatigue life of notched members from smooth specimen fatigue data. Inelastic behavior of the material at the notch root is treated using Neubers rule, which states that the theoretical stress concentration factor is equal to the geometric mean of the actual stress and strain concentration factors. This rule provides indexes of equal fatigue damage for notched and unnotched members. Experimental results for notched aluminum alloy plates subjected to one or two levels of completely reversed loading are compared with predictions based on these indexes. Measured notched fatigue lives and lives predicted from smooth specimens agree within a factor of two.

Comment:

The technique demonstrated in the paper is shown to be applicable to notched aluminum alloy plates subjected to completely reversed bending. The application to wider classes of alloys and loadings is not demonstrated and is the subject of further investigations.

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4. Wetzel, R. M., Smooth Specimen Simulation of the Fatigue Behavior of Notches, J. Mater. 3, 646-657 (September 1968).

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Key words: Aluminum alloys; analysis methods; cumulative damage; cyclic testing; fatigue (materials); fatigue life; fatigue tests; notch sensitivity; stress concentration.

PREDICTION OF FATIGUE LIFETIME BY COMBINED FRACTURE MECHANICS AND ACOUSTIC EMISSION TECHNIQUES

Harris, D. O., Dunegan, H. L., and Tetelman, A. S. (California Univ., Livermore, Lawrence Radiation Lab., California Univ., Los Angeles CA)

AFFDL TR-70-144, 459-471 (September 1970)

The following are the major conclusions to be drawn from the results of the investigation reported in this paper:

1. The use of acoustic emission in conjunction with periodic proof stressing provides a means of detecting the presence and growth of fatigue cracks.

2. The technique of periodic proofing can be used to detect impending failure by two methods: observation of increasing number of counts during loading between the working and proofing loads; and observation of acoustic emission while holding at the proof load.

3. This technique provides ample and early warning of impending failure, and would therefore be of value in practical applications.

4. Good agreement was observed between experimental results and theoretical predictions made from a model for analysis of fatigue crack growth with intermittent proofing and acoustic emission monitoring.

5. Acoustic emission from a penny-shaped crack can not be directly related to the stress intensity factor, but reference must be made to the flaw size. This differs from the case of through cracks, for which the acoustic emission can be directly related to the stress intensity factor.

6. The optimum number of cycles between proofing can be calculated if the crack growth law, K variation with crack length, the minimum K for emission during hold and K_{IC} are known.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 107).

A RELIABILITY APPROACH TO THE FATIGUE OF STRUCTURES

Payne, A. O. (Aeronautical Research Labs., Melbourne Australia)

Probabilistic Aspects of Fatigue, ASTM STP 511, 106-155 (July 1972)

A method of assessing structural safety in fatigue is proposed in which a statistical model for the fatigue process is used to carry out a reliability analysis, enabling the probability of failure to be estimated at any stage of the life. The statistical variability in crack-propagation rate and residual strength of the cracked structure is included together with the effect of any prescribed inspection procedure. The method is applied to a structure of high strength steel typifying a "safe-life" structure and to a redundant aluminum alloy structure representative of the "fail-safe" construction. It is concluded that the reliability analysis can be applied to both fail-safe and safe-life structures and provides a quantitative basis for ensuring safe operation, including the planning of an inspection procedure if feasible. In this regard the method represents an advance on the existing procedures but inherent in the quantitative approach it employs is the adoption of an acceptable safety level. The most appropriate way of defining safety level is discussed and a suitable measure is proposed. An extensive amount of data is required in applying the procedure but it is suggested that in the case of aircraft structures this difficulty can be overcome by using results from the comprehensive structural testing program normally carried out, together with relevant data from similar structures.

Comment:

This approach treats failure as a statistical phenomena, ignoring the mechanics of the failure. It is a useful approach for such things as predicting time between overhauls based on an increasing data base of experience. The author's attempt to extrapolate this technique to complex aircraft structure will be only as successful as the accuracy and representative nature of the data.

Important References:

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5. Ingham, J. and Grandage, J. M., Investigations into the Probability Distribution of the Crack Propagation Rate in Fabricated Structures, Aeronautical Research Labs., Melbourne, Australia (Feburary 1967).

Key words: Aircraft structures; aluminum alloys; analysis methods; crack growth rate; crack propagation; cracks; critical flaw size; fail-safe design; failure analyses; failures (materials); fatigue (materials); fatigue life; reliability; residual strength; statistical analysis; steels; structural safety.

A CRITICAL ASSESSMENT OF THE LIFE FRACTION RULE FOR CREEP-RUPTURE UNDER NONSTEADY STRESS OF TEMPERATURE

Woodford, D. A. (General Electric Co., Schenectady, NY)

ASTM, ASME, IME, Int. Conf. Creep and Fatigue in Elevated Temperature Applications, 180.1-180.6 Philadelphia, PA (23-28 September 1973) and Sheffield, England (1-5 April 1974).

Under conditions of incremental stress or temperature changes, the life fraction rule predicts that failure will occur when the sum of the fractions of life equals unity. Experimental data on ferritic steels are used to show that although this rule may be reasonable for temperature changes, it is inconsistent with material response to stress changes. The reasons for these differences are considered in terms of the phenomenology of creep damage. There is a strong sensitivity to stress history resulting in a loading sequence effect on cumulative life fraction at failure. On the other hand, for temperature changes, the apparent insensitivity to temperature history is shown to be consistent with the generality of time-temperature parametric representations of rupture life. These characteristics are revealed by a new analysis involving the generation of constant damage curves in terms of remaining life for both stress and temperature changes. It is shown how families of these curves may, in principle, be used to predict failure for multiple stress and temperature changes. Some possible limitations and restrictions in the use of this approach are considered.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS, AND A DUPLICATE ABSTRACT, SEE PAGE 35).

ROLE OF THE STRAIN-HARDENING EXPONENT IN LIFE-PREDICTION IN HIGH-TEMPERATURE LOW CYCLE FATIGUE

Saheb, R. E. and Bui-Quoc, T. (Ecole Polytechnique, Montreal, Quebec, Canada)

ASTM, ASME, IME, Int. Conf. Creep and Fatigue in Elevated Temperature Applications, 186.1-186.7 Philadelphia, PA (23-28 September 1973) and Sheffield, England (1-5 April 1974).

Results are reported of fatigue tests with controlled axial strain on an annealed 304 stainless steel at 650^{o}C using either of two modes of strain measurement: axial and diametral. Expressions are suggested for determining the plastic and elastic components of the strain range in terms of the number of cycles to failure, using the strain hardening exponent together with other tensile properties as predictive parameters. The resulting equation is then compared with experimental data on stainless steels.

Important References:

1. Dubuc, J. and Biron, A., Effect of Creep in Low-Cycle Fatigue of Pressure Vessel Steel, J. Eng. Ind. 92, 67-73 (1970).

2. Saheb, R. E., A Study of the Interaction Between Creep and Fatigue for an Austenitic Stainless Steel at High Temperature, DSc Thesis, Ecole Polytechnique, Montreal, Canada (July 1973).

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5. Coffin, Jr., L. F., A Note on Low-Cycle Fatigue Laws, J. Mater. 6, 348-402 (1971).

6. Berling, J. T. and Slot, T., Effect of Temperature and Strain Rate on Low Cycle Fatigue Resistance of AISI 304, 316 and 348 Stainless Steel, ASTM STP 459, 3-30 (1969).

Key words: Cyclic loads, experimental data; failures (materials); fatigue (material); fatigue tests; high temperature; life prediction; load cycles ; low-cycle fatigue; plastic strain; stainless steels; strain; strain hardening; tensile stress.

A PARAMETRIC APPROACH TO IRREGULAR FATIGUE PREDICTION

Erismann, T. H. (Federal Lab for Testing Materials and Research, Dubendorf, Switzerland)

NASA SP-309, 429-436 (1971)

The method proposed consists of two parts: empirical determination of certain characteristics of a material by means of a relatively small number of well-defined standard tests, and arithmetical application of the results obtained to arbitrary loading histories. The following groups of parameters are thus taken into account: the variations of the mean stress, the interaction of these variations and the superposed oscillating stresses, the spectrum of the oscillating-stress amplitudes, and the sequence of the oscillating-stress amplitudes. It is pointed out that only experimental verification can throw sufficient light upon possibilities and limitations of this (or any other) prediction method.

Comment:

The parametric approach presented in this paper rests on certain simplifying assumptions which may or may not be true for a given fatigue/material system. These include an application of Miner's rule which may not be accurate. If, however, the Miner's rule application holds for a particular system this technique could lead to reduced test complexity and cost.

Important References:

1. Erismann, T. H., Fatigue-Life Prediction Under Irregular Stress Conditions, J. Strain Anal. 5, 207 (1970).

Key words: Analysis methods; cumulative damage; fatigue life; fatigue (materials); fatigue tests; linear damage rule; load cycles; Palmgren-Miner rule; testing methods.

MATHEMATICAL TECHNIQUES APPLYING TO THE THERMAL FATIGUE BEHAVIOR OF HIGH TEMPERATURE ALLOYS
Howe, P. W. H. (National Gas Turbine Establishment, Pyestock, England)
Aeron. Q. 13, Pt. 4, 368-396 (November 1962).

The high temperature thermal fatigue of Nimonic alloys can be analyzed using short-time creep deformation data and cyclic stress endurance data. Experimental and calculated thermal fatigue endurances have been correlated in magnitude and over ranges of temperature, strain, and strain-rate. Transient temperatures in turbine blades can be calculated for a wide range of conditions using Biot's variational method. Combining the thermal strain obtained from Biot's method with a simplified mathematical description of high temperature material behavior leads to a differential equation for thermal stress, which can be solved for a wide range of conditions. The correlation of experimental and theoretical thermal fatigue endurances provides an example of these methods, and supports their more general application.

Comment:

The author has divided a complicated material problem into several pieces of mathematics, for each of which logical deductions can be made from start to finish. It was demonstrated that Fourier analysis can be applied to material behavior at high temperatures, with stress dependencies realistically described.

Important References:

1. Glenny, R. J. E. and Taylor, T. A., A Study of the Thermal Fatigue Behavior of Metals, The Effect of Test Conditions on Nickel-Base High-Temperature Alloys, J. Inst. Metals 88, No. 11, 449 (July 1960).

Key words: Analysis methods; cracks; creep; cyclic loads; deformation; fatigue (materials); gas turbine engines; heat resistant alloys; high temperature; plastic strain; thermal cycles; thermal fatigue; thermal stresses; turbine blades.

MECHANICS OF CRACK TIP DEFORMATION AND EXTENSION BY FATIGUE
Rice, J. R. (Brown Univ., Providence, RI)
Fatigue Crack Propagation, ASTM STP 415, 247-309 (1967)

Crack propagation is viewed primarily as a problem in continuum mechanics. Part I surveys the elastic and elastic-plastic stress analyses of cracked bodies, with emphasis on the plasticity. In addition to well-known results based on models of perfectly plastic anti-plane shearing and discrete surfaces of tensile yielding or slip (equivalently, continuous dislocation arrays), some recently obtained results on work-hardening and anisotropic perfect plasticity are summarized, and methods are presented for modeling of plane strain yielding. Emphasis is placed on the common result of all plasticity analyses that the coefficient of a characteristic singularity in elastic solutions determines the plastic deformation in situations of small scale yielding are illustrated and the predictions of various models compared.

Part II considers the mechanics of fatigue crack propagation. Elastic-plastic responses to cyclic loading are determined for perfectly plastic and a type of stable hardening behavior. Effectively, the yield stress is doubled so that cyclic flow zones and variations in plastic deformations are smaller than for monotonic loading. Crack tip blunting by large deformations are smaller than for monotonic loading. Crack tip blunting by large deformations and related effects are treated approximately. General features of fatigue crack growth are surveyed, and the extensive evidence is cited supporting a primary conclusion of continuum analyses: that crack growth rates are determined by elastic stress intensity factor variations for the small scale yielding situation common in low-stress high-cycle fatigue. Results pertaining to mean load, sheet thickness, and mode transition effects, delays in crack extension due to overloads, growth under bending loads, and growth by random applied loads are also noted and interpreted in continuum terms. Theories of crack growth relating continuum considerations to "damage" accumulation and material separation are examined. Further progress requires better continuum analysis, incorporating crack blunting by deformation and clearer ideas of separation mechanics.

Comment:

This excellent "state of the art" paper established the continuum mechanics approach to crack tip deformation analysis under fatigue conditions. The paper cites a number of instances where the continuum approach is instructive of the basic mechanics of the system.

Important References:

1. Paris, P. C. and Erdogan, F., A Critical Analysis of Crack Propagation Laws, Trans. ASME 85, No. 4 (1963).

2. Rice, J. R., Stresses Due to a Sharp Notch in a Work Hardening Elastic-Plastic Material Loaded by Longitudinal Shear, J. Appl. Mech. 34, 287-298 (1967).

3. Hahn, G. T. and Rosenfield, A. R., Local Yielding and Extension of a Crack Under Plane Stress, Acta Met. . 13, No. 3 (1965).

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9. Coffin, Jr., L. F., Low-Cycle Fatigue - A Review, Appl. Mater. Res. 1, No. 3, (1962).

Key words: Analysis methods; crack propagation; crack tip plastic zone; fatigue (materials); fracture mechanics; stress concentration; stress intensity factor.

A STUDY OF CYCLIC PLASTIC STRESSES AT A NOTCH ROOT

Crews, Jr., J. H. and Hardrath, H. F. (National Aeronautics and Space Administration Langley Research Center, Langley Station, VA)

J. of SESA 6, No. 6, 313-320 (1966)

An experimental study is presented for cyclic plastic stresses at notch roots in specimens under constant-amplitude repeated tension and reversed loading. Edge-notched 2024-T3 aluminum-alloy sheet specimens with a K_t value of 2 were cycled until local stress conditions **stabilized**. Local stress histories were determined by recording local strain histories during cycling and reproducing these histories in simple, unnotched specimens. The fatigue lives for these notched specimens were estimated using stabilized local stresses and an alternating versus mean stress diagram for unnotched specimens of the local material. In addition, an expression is presented for calculating local first-cycle plastic stresses. An acceptable correlation is shown between predicted stresses and experimental data.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 84).

AVOIDANCE, CONTROL, AND REPAIR OF FATIGUE DAMAGE

Manson, S. S. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

Metal Fatigue Damage - Mechanism, Detection, Avoidance, and Repair
ASTM STP 495, 254-346 (1971)

A number of approaches are outlined for improving the fatigue life of materials. The principal aspects that must be considered involve: (1) proper choice by the designer of materials or material-combinations that give the best possible fatigue resistance; (2) avoidance of strain concentrations in design, fabrication, and service; (3) provision for surface protection against inadequate design, rough handling, and pernicious environments; (4) introduction of beneficial residual compressive stresses by various means taking into account factors such as design, fabrication, and usage requirements that have a bearing on the ability of the material to retain these stresses during service; (5) property conditioning and restoration such as reheat treatment, surface husking and any other procedure which can restore fatigue resistance once damage has been incurred; and (6) fail-safe design approach together with the concept of continuous surveillance. A few potentially rewarding areas for future research are discussed. These include: further development of controlled solidification techniques; thermomechanical processing as a means of improving fatigue resistance; improving the compatibility of coatings and substrate and in particular metalliding. In addition sophisticated application of fracture mechanics as an analytical tool to establish limits of permissible crack growth promises to augment the practicality of the fail-safe design philosophy. It is shown that the range of fatigue life involved in the application is important, what is good for low-cycle fatigue life range may not be good for the high-cycle-fatigue life range, and vise versa. In all cases it is important to take into consideration the type of loading, the part geometry, the basic behavior of the material, environmental effects, reliability requirements, and a host of other factors that govern fatigue life.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 102).

EXPERIMENTS ON THE NATURE OF THE FATIGUE CRACK PLASTIC ZONE

Hahn, G. T., Sarrate, M. and Rosenfield, A. R. (Battelle Memorial Inst., Columbus, OH)

AFFDL-TR-70-144, 425-450 (September 1970)

The experimental work described in this report deals with the plastic zone of a propagating fatigue crack and its relation to the zone of a monotonically loaded, stationary crack. The study examines ways of applying two techniques: etch pitting and interferometry, to reveal the plastic zones produced by fatigue cracks under plane strain and plane stress conditions. Preliminary results are reported and these indicate that the plastic deformation generated by each loading

cycle is similar to the zone of a stationary crack loaded monotonically. On this basis, theoretical treatments of the monotonically loaded crack are tentatively extended to the fatigue crack problem. Simplified formulations of the plastic blunting and damage accumulation are obtained in this way. The efficiency of the blunting mechanism and the number of plastic strain cycles experienced by material in front of the crack is estimated. This shows that both mechanisms can account for the value of the stress intensity exponent, observed in Regime No. 1 (the high cycle-low stress portion of the crack growth spectrum). While neither mechanism easily accounts for the invariance of crack growth rates in Regime No. 1, the existing observations are more easily rationalized in terms of blunting. A possible explanation is offered for the higher values and growth rates of Regime No. 2 (the low cycle-high stress range). Implications with respect to the metallurgical origins of the cyclic crack growth resistance and the prospects of improving it are discussed.

Comment:

The two experimental techniques employed offer potential for further illumination of the metallurgical processes involved in cyclic fatigue and monotonic crack growth. This illumination can lead to structurally based crack growth mechanisms which will enable both better life predictions and approaches to improving the metallurgical structure. This improved structure can result in improved fatigue lives.

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2. Hall, L. R., Plane Strain Cyclic Flaw Growth in 2014-T62 Aluminum and 6AL-4V Titanium, NASA-CR-72396 (1968).

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Key words: Crack initiation; crack tip plastic zone; cracks; cumulative damage; cyclic loads; fatigue (materials); fracture tests; plane strain; plane stress; strain accumulation; stress concentration; stress intensity factor.

ACOUSTIC EMISSION FROM LOW-CYCLE HIGH-STRESS INTENSITY FATIGUE

Hartbower, C. E., Morais, C. F., Reuter, W. G., and Crimmins, P. P.
(Aerojet Solid Propulsion Co., Sacramento, CA)
Eng. Fract. Mech. 5, 765-789 (1973)

This paper presents the findings of an Advanced Research Projects Agency study, the overall objective of which was to develop a nondestructive testing technique to determine flaw criticality based on Acoustic emission. The research included an evaluation of sensors and instrumentation systems, using several materials and material conditions loaded in low-cycle, high stress-intensity fatigue.

The materials used for the study were D6AC steel tempered at 600°F and 1100°F, annealed and solution-treated-and-aged 6Al-4V titanium and 7075-T6 aluminum. The test specimen was the precracked, single-edge-notch tension specimen; macrocracking was detected by crack-opening-displacement (COD) gage and microcracking by acoustic emission. The acoustic-emission system utilized 400 and 1000 KHz bandpass filtering at 100 db gain. The output signals of the totalizer and the COD gage were recorded on a single strip chart using a dual-pen recorder. The specimens were subjected to low-cycle, high-stress-intensity fatigue at 6 cpm. In some tests, cycling was begun in air and finished in water.

Acoustic emission was demonstrated to be highly effective as a non-destructive test method for following crack growth in low-cycle high-stress-intensity fatigue; acoustic emission confirmed the existence of periods of dormancy punctuated by periods of active fatigue crack growth. Using a dual-pen, strip-chart recorder displaying both crack-opening-displacement and stress-wave count on the same chart, it was a simple matter not only to observe if there was crack growth in each individual cycle but also where in the cycle it occurred. Moreover, the process of stress-corrosion cracking during low-cycle, high-stress-intensity fatigue was readily detected by a marked increase in the stress-wave count rate.

The utility of acoustic emission as a precursor of failure was demonstrated for low-cycle, high-stress-intensity fatigue as well as for the case of environmentally assisted fatigue. Plots of cumulative stress-wave count versus cycle number consistently showed a marked increase in count rate several (10-20 or more) cycles before fracture.

Comment:

In this well documented experimental effort the acoustic emission effect is related to fatigue failure for a specific set of experimental conditions. It is demonstrated that significant acoustical phenomena preceed fracture and that this may be an excellent fatigue failure monitoring technique when developed for more complex systems and applications.

Important References:

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Key words: Crack propagation; cracks; fatigue (materials); fractures (materials); low-cycle fatigue; NDE; stress concentration; stress corrosion; ultrasonic tests.

PREDICTION OF FATIGUE LIFETIME BY COMBINED FRACTURE MECHANICS AND ACOUSTIC EMISSION TECHNIQUES

Harris, D. O., Dunegan. H. L, and Tetelman, A. S. (California Univ., Livermore, Lawrence Radiation Lab., California Univ., Los Angeles CA)

AFFDL-TR-60-144, 459-471 (September 1970).

The following are the major conclusions to be drawn from the results of the investigation reported in this paper.

1. The use of acoustic emission in conjunction with periodic proof stressing provides a means of detecting the presence and growth of fatigue cracks.

2. The technique of periodic proofing can be used to detect impending failure by two methods: observation of increasing number of counts during loading between the working and proofing loads; and observation of acoustic emission while holding at the proof load.

3. This technique provides ample and early warning of impending failure, and would therefore be of value in practical applications.

4. Good agreement was observed between experimental results and theoretical predictions made from a model for analysis of fatigue crack growth with intermittent proofing and acoustic emission monitoring.

5. Acoustic emission from a penny-shaped crack can not be directly related to the stress intensity factor, but reference must be made to the flaw size. This differs from the case of through cracks, for which the acoustic emission can be directly related to the stress intensity factor.

6. The optimum number of cycles between proofing can be calculated if the crack growth law, K variation with crack length, the minimum K for emission during hold and K_{IC} are known.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 107).

PREDICTION OF FATIGUE LIFETIME BY COMBINED FRACTURE MECHANICS AND ACOUSTIC EMISSION TECHNIQUES

Harris, D. O., Dunegan, H. L., and Tetelman, A. S. (California Univ., Livermore, Lawrence Radiation Lab., California Univ., Los Angeles CA)

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Key words: Crack growth rate; cyclic loads; fatigue (materials); fatigue life; fracture mechanics; fracture tests; stress intensity factor; ultrasonic tests.

AN APPLICATION OF FRACTURE CONCEPTS TO THE PREDICTION OF CRITICAL LENGTH OF FATIGUE CRACKS

Davis, S. O. (Air Force Materials Lab, Wright-Patterson AFB, OH)

AFML-TR-70-202, Parts I, II, III, IV and V (1971)

This report synthesizes technological concepts of fracture by making a historical review of the literature from 1913 up to the present (1970). The relevant concepts of linear elastic fracture mechanics derivatives were delineated and summarized for the prediction of the critical length of fatigue cracks. There is no available theory for correlating the many variables affecting fatigue failure and for successfully predicting failure. The application of linear elastic fracture mechanics and the thermodynamics of fracture to the crack propagation facet of fatigue is proposed as an approach to the prediction of critical lengths of stable fatigue cracking and unstable fracturing before failure. Thermodynamic energy approach is used to develop a unified theory of fracture relative to mechanical response of metals and alloys as a function of the atomic and metallurgical structures and the phenomenological aggregate levels collectively. The Irwin fracture criteria and Boyle mechanical compliance analysis were used to predict critical crack lengths of stable fatigue cracks in 7075-T7351 aluminum plates. The Boyd hypothesis was also used to predict the velocity of unstable cracks in these plates. The technological significance of fracture mechanics in practice was validated with a 96 percent accuracy by deducing the operational stress and calculating the critical crack length based upon a known value of K_{IC} and . This validated the practicality of the fracture mechanics approach in predicting the critical crack length stress for a given crack length and that failure will occur after a crack reaches a specified length and the stress reaches a critical magnitude.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 173).

FATIGUE AND FRACTURE

Hardrath, H. F. (National Aeronautics and Space Administration, Langley Research Center, Langley Station, VA)

NASA SP-292, 209-224 (November 1971)

Designing against fatigue and fracture in any vehicle subjected to repeated loadings requires consideration of a host of parameters that interact synergistically. Formal analysis procedures are far from adequate to accomplish the task by calculations alone. Furthermore, considerable scatter in the load experience in a given fleet of vehicles and in the fatigue response to a given set of load experiences, and the extreme complexity of a representative aircraft structure make the analytical task more formidable. Because aerospace vehicles must be made as light as possible for economic and performance reasons, the designer is forced to reduce margins of safety to the minimum. The next decade of development in civil aviation should see improvements in structural integrity. Damage-tolerant designs will and should be employed whenever practical to provide good safety. Improved fatigue-load monitoring devices should be employed, particularly in vehicles subjected to wide variations in load experience. The NASA Langley Reserach Center has started a 10-year plan of systematic research that should enhance the design of safe and efficient aircraft structures.

Important References:

1. Coleman, T. L., Trends in Repeated Loads on Transport Airplanes, NASA TN-D-4586 (1968).

Key words: Aluminum alloys; damage tolerance; design; fatigue (materials); fiber reinforced composites; fractures (materials); life (durability); materials selection; steels; structural reliability; structural safety; titanium alloys.

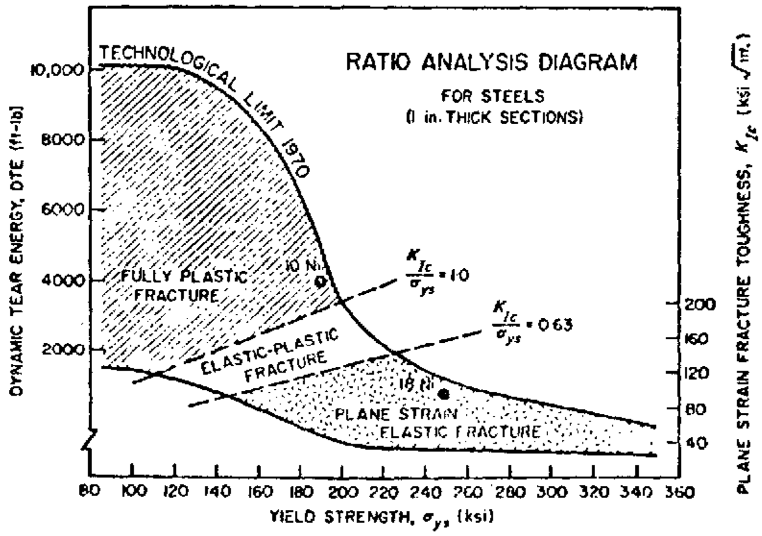
THE ROLE OF FRACTURE TOUGHNESS IN LOW-CYCLE FATIGUE CRACK PROPAGATION FOR HIGH-STRENGTH ALLOYS

Crooker, T. W. (Naval Research Lab., Washington, DC)

Eng. Fract. Mech. 5, 35-43 (1973).

Under the repeated application of high stresses imposed on high strength alloys, undetected cracks remaining from fabrication will rapidly grow in low-cycle fatigue. To guard against failures caused by cracks propagating to terminal fracture, high-strength structural alloys which also possess high levels of fracture resistance have been developed in recent years. This paper describes the principal fatigue crack propagation characteristics which are derived from high fracture toughness and discusses the potential benefits available through the use of high-toughness alloys in cyclically-loaded structures.

Structural designers now have available considerable choice in making yield strength/fracture toughness trade-offs among competing alloys. The Naval Research Laboratory Ratio Analysis Diagram (RAD) provides a graphical means of quantitatively illustrating these effects. The figure shows the RAD characteristics for steels in 1 inch thick section sizes. Since thickness has a powerful effect on fracture, certain details of these diagrams which are influenced by through-thickness restraint will vary for thicknesses thicker or thinner than 1 inch. The RAD is a cumulative plot, by alloy family, of fracture toughness versus yield strength for the full spectrum of high and intermediate yield strength levels. The upper portions of the diagram have been compiled from Dynamic Tear (DT) tests, and the lower portions of the diagram have been compiled from valid plane strain fracture toughness tests. One of the important functions of the RAD is to illustrate the yield strength/fracture trade-offs which can be made over a given yield strength range or the increases in fracture toughness available at a specific strength level through improvement of metal quality and thus guide the materials selection process out of the hazardous domain of plane-strain brittle fracture.



Ratio Analysis Diagram showing the upper and lower limits of fracture toughness for 1 inch thick steels over the yield strength range from 80 to 360 ksi.

Comment:

This paper illuminates the critical area of low cycle fatigue with high-amplitude cycling and demonstrates the critical need for definitive work in this area. It demonstrates that the margin of safety lies in the application of high toughness alloys in structures exposed to possible high-amplitude cycling.

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1. Pellini, W. S., Criteria for Fracture Control Plans, Naval Research Laboratory Report, Int. J. Fract. Mech. 8, 7406, (1972).

2. Paris, P. and Erdogan, F., A Critical Analysis of Crack Propagation Laws, ASME Trans. 85, Series D, 528 (1963).

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8. Crooker, T. W., Crack Propagation in Aluminum Alloys Under High-Amplitude Cycle Load, NRL-7286 (July 1971).

Key Words: Crack propagation; fatigue (materials); fracture strength; fracture tests; high strength alloys; structural safety.

ON THE APPLICABILITY OF FRACTURE MECHANICS TO ELEVATED TEMPERATURE DESIGN
McEvily, Jr., A. J. and Wells, C. H. (Connecticut Univ., Storrs; Pratt and Whitney Aircraft, Middletown, CN)
ASTM, ASME, IME, Int. Conf. Creep and Fatigue in Elevated Temperature Applications, 230.1-230.7 Philadelphia, PA (23-28 September 1973), and Sheffield, England (1-5 April 1974).

In recent years, consideration has been given to the extension of fracture mechanics to safe design in the creep range. This paper reviews the experimental work which has been carried out at elevated temperatures within the fracture mechanics framework. Most of these studies deal with the rate of fatigue crack growth as a function of stress intensity factor, with temperature, frequency, and environment being the principal test variables. It is concluded that although the approach is still in an early stage of development it has considerable potential as a design procedure within certain limitations. The nature of these limitations is discussed.

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1. James, L. A., Hold-Time Effects on the Elevated Temperature Fatigue - Crack Propagation of Type 304 Stainless Steel, Nucl. Technol. 16, 521-530 (1972).

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6. Wells, C. H., Sullivan, C. P. and Gell, M., Mechanisms of Fatigue in the Creep Range, ASTM STP 495, 61-122 (1971).

Key words: Analysis methods; crack propagation; crack tip plastic zone; cracks; creep; fail-safe design; failure analyses; fatigue (materials); fracture mechanics; frequency effects; high temperature; stress corrosion cracking; stress intensity factor.

V - Factors Affecting Creep and Fatigue

OXIDATION AND THERMAL FATIGUE CRACKING OF NICKEL-AND COBALT-BASE ALLOYS IN A HIGH VELOCITY GAS STREAM
Johnston, J. R. and Ashbrook, R. L. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)
NASA-TN-D-5376 (August 1969)

An investigation was conducted to determine the resistance to oxidation of typical gas turbine alloys exposed alternately to high and low temperature, high velocity gas streams. A natural gas-compressed air burner was used to produce velocities up to Mach 1 and specimen temperatures up to 2000°F (1093°C). The materials tested included six nickel-base alloys: IN-100, B-1900, MAR M200, TAZ-8A, Hastelloy X, and TD-NiCr, and four cobalt-base alloys: L-605, X-40, MAR M509A, and WI-52.

In a standard test of 100 cycles of 1 hour at temperature in a Mach 1 gas stream followed by rapid cooling to room temperature, the nickel-base alloys as a class experienced less weight loss than the cobalt-base alloys. The average values of weight loss varied widely from 216 to 23,700 milligrams after 100 hours at 2000°F (1093°C). Of the cobalt-base alloys, X-40 had the lowest weight loss, which was only slightly less than that of MAR M200. The latter alloy had the highest weight loss of all of the nickel alloys. Of all the alloys tested, the cast cobalt-base alloy, WI-52, was the least resistant to weight loss. After 100 hours, surface recession paralleled weight loss and ranged from 0.3 to 50 mils (0.008 to 1.3 mm).

Cast cobalt-base alloys were more resistant to thermal fatigue cracking than conventionally cast nickel-base alloys. However, directionally solidified and single grain MAR M200 castings and wrought Hastelloy X had no cracks even after 100 cycles at 2000°F (1093°C).

At 2000°F (1093°C) under simualted steady-state operation (10-hour cycles with free air cooling to room temperature) the average weight loss was less for the six alloys so tested than at standard conditions. Cobalt alloys showed more improvement in oxidation resistance from the change in cycle than the nickel-base alloys. No cracking was observed in any alloy under these conditions. When the lower temperature during a 2000°F (1093°C) test was restricted to 1200°F (649°C), the propensity toward cracking was unchanged for IN-100, and B-1900, but substantially reduced for WI-52. However, weight loss decreased substantially for all alloys so tested.

Comment:

This study presents a compilation of experimental data, including micro-structural information on a number of turbine blade alloys in simulated high temperature environments. This data will be useful in both materials selection and as a guide for future alloy development.

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1. Piearcey, B. J., Kear, B. H. and Smashey, R. W., Correlation of Structure with Properties in a Directionally Solidified Nickel-Base Superalloy, Trans. ASM 60, No. 4, 634-645 (December 1967).

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5. Waters, W. J. and Freche, J. C., Investigation of Columbium-Modified NASA TAZ-8 Superalloy, NASA-TN-D-3597 (1966).

Key words: Cobalt alloys; crack initiation; fatigue life; heat resistant alloys; nickel alloys; oxidation; thermal fatigue.

OXIDATION AND HOT-CORROSION CHARACTERISTICS OF SEVERAL RECENTLY DEVELOPED NICKEL-BASE SUPERALLOYS

Dapkunas, S. J., Wheatfall, W. L., and Hammond, B. L. (Naval Ship Research and Development Center, Annapolis, MD)

NSRDC Report No. 3925 (March 1973)

Oxidation and hot corrosion tests were conducted on six recently developed nickel-base superalloys (cast Udimet 710, wrought Udimet 710, IN-738, IN-792, MAR M421, and MAR M432) to determine the surface stability characteristics of the materials. In addition to optical measurements, oxidized alloys were analyzed by x-ray microprobe techniques to determine the redistribution of alloying elements after oxidation in pure oxygen for 210 hours at 900°C and 955°C. In general, the new alloys had reasonably good oxidation and hot corrosion resistance when compared to older alloys such as Udimet 500 and Alloy 713C. Udimet 710 (cast and wrought) had the best overall hot-corrosion resistance of any of the six recently developed alloys, and wrought Udimet 710 had the best oxidation resistance. For the most part, the x-ray microprobe analyses of oxidized alloys correlated fairly well with the optical measurements. Physical and mechanical properties and structural stability characteristics of each alloy are included in the appendixes to provide additional information for comparing the alloys. Appendix C includes 104 figures of microprobe results.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 119).

"BLACK PLAGUE" CORROSION OF AIRCRAFT TURBINE BLADES

Belcher, P. R., Bird, R. J. and Wilson, R. W. (Shell Research Ltd., Chester, England)

Hot Corrosion Problems Associated with Gas Turbines, ASTM STP 421, 123-145 (1967)

"Black Plague" is the name given to a particular type of high temperature corrosion encountered on certain nickel-rich alloys used for turbine blades. Metallurgical examination of corroded blades shows that black plague corrosion has certain distinctive characteristics and that it is not a special form of internal oxidation ("green rot") or sulfide attack. Rig tests were carried out in which the combustion products from artificially contaminated fuels were passed over new and used blades at 850°C to 950°C. The results showed that contamination with tetraethyl-lead, chlorine, sulfur, or residual fuel does not cause accelerated corrosion. However, black plague was reproduced. In all tests, used blades corroded more than new blades, and it was shown that the prolonged preheating of new blades in air at elevated temperatures renders them more susceptible to corrosion. Corroded blades from test rigs and from service have been examined by metallorgraphic, x-ray, and electron probe techniques. From these investigations it appears that black plague should be regarded as an oxidation phenomenon.

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1. Schirmer, R. M., Communication of Hot Corrosion Workshop, Paper Presented at Gas Turbine Panel of ASTM-ASME, Lafayette, Inc. (June 1965).

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4. Imai, Y. and Nishi, Y., Effect of Molybdenum Upon the High-Temperature Oxidation and the V205 Attack on Ni-Cr-Base alloys, Sci. Rep. of Res. Inst. 14, No. 6, 347-362 (1962).

Key words: Corrosion; corrosion resistance; creep strength; electron microscopy; gas turbine engines; heat resistant alloys; high temperature environments; high temperature tests; hot corrosion; metallography; nickel alloys; oxidation; oxidation resistance; turbine blades; x-ray diffraction.

HOT CORROSION OF GAS TURBINE ALLOYS
Bergman, P. A. (General Electric Co., Lynn, MA)
Corrosion 23, No. 3, 72-81 (March 1967)

Types of hot corrosion encountered in aircraft gas turbines operating in marine environments were reproduced in laboratory tests. Nickel and cobalt-base alloys were tested in the products of combustion of JP-5 and 0, 2, and 200 PPM sea salt between 1600°F and 2000°F. Higher chromium alloys were generally (but not always) more resistant to hot corrosion. Attack was caused by sodium sulfate, corrosion occurring only in the temperature range in which sodium sulfate was deposited in a molten state. Microstructural changes were studied by metallographic techniques and chemical compositional changes and sulfide were identified by electron microprobe analyses. The nature of attack is discussed and some concepts of the hot ocrrosion mechanism postulated. Apparently, depletion of chromium in surface zones through the formation of oxides and sulfides reduce the corrosion resistance of depleted zones, thereby promoting severe hot corrosion.

Comment:

The authors, by utilizing an imaginative hot corrosion test stand have characterized the hot corrosion of several nickel base superalloys in typical aircraft fuels with and without sea water addition. This information has been employed in the successful development of hot corrosion resistant superalloy compositions.

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3. Davis, A. and Courtsouradis, D., Dry Corrosion of Cobalt, Chromium and Co-Cr, Ni-Cr and Fe-Cr Alloys in Hydrogen Sulfide Atmospheres, Cobalt 17, 23-26 (December 1962).

Key words: Analysis methods; cobalt alloys; corrosion; environmental effects; gas turbine engines; hot corrosion; microstructures; nickel alloys; oxidation.

OXIDATION AND HOT-CORROSION CHARACTERISTICS OF SEVERAL RECENTLY DEVELOPED NICKEL-BASE SUPERALLOYS

Dapkunas, S. J., Wheatfall, W. L. and Hammond, B. L. (Naval Ship Research and Development Center, Annapolis, MD)

NSRDC Report No. 3925 (March 1973)

Oxidation and hot-corrosion tests were conducted on six recently developed nickel-base superalloys (cast Udimet 710, wrought Udimet 710, IN-738, IN-792, MAR M421, and MAR M432) to determine the surface stability characteristics of the materials. In addition to optical measurements, oxidized alloys were analyzed by x-ray microprobe techniques to determine the redistribution of alloying elements after oxidation in pure oxygen for 210 hours at 900°C and 955°C. In general, the new alloys had reasonably good oxidation and hot corrosion resistance when compared to older alloys such as Udimet 500 and Alloy 713C. Udimet 710 (cast and wrought) had the best overall hot corrosion resistance of any of the six recently developed alloys, and wrought Udimet 710 had the best oxidation resistance. For the most part, the x-ray microprobe analyses of oxidized alloys correlated fairly well with the optical measurements. Physical and mechanical properties and structural stability characteristics of each alloy are included in the appendixes to provide additional information for comparing the alloys. Appendix C includes 104 figures of microprobe results.

Important References:

1. Kaufman, M. and Wasielewski, G. E., Development of Hot-Corrosion-Resistant Alloys for Marine Gas Turbine Service, NSRDC/A Report 8-613 (1 July 1970).

2. Wheatfall, W. L. and Schwab, R. C., Hot-Corrosion Behavior of Several Newly Developed Nickel-Base Superalloys, NSRDC/A R&D Report 3199 (February 1970).

3. Lund, C. H. and Wagner, H. J., Oxidation of Nickel- and Cobalt-Base Superalloys, DMIC Report 214 (1 March 1965).

Key words: Gas turbine engines; heat resistant alloys; high temperature; high temperature environments; high temperature tests; mechanical properties; metallography; nickel alloys; oxidation; oxidation resistance; turbine blades; x-ray diffraction.

ENVIRONMENT-ASSISTED FRACTURE IN ENGINEERING ALLOYS, PART 1 - MONOTONIC LOADING
McMahon, Jr., C. J. (Pennsylvania Univ., Philadelphia PA)
J. Eng. Mater. Tech. 133-141 (July 1973)

ENVIRONMENT-ASSISTED FRACTURE IN ENGINEERING ALLOYS, PART 2 - CYCLIC LOADING AND FUTURE WORK
McMahon, Jr., C. J. (Pennsylvania Univ., Philadelphia PA)
J. Eng. Mater. Tech., 142-149 (July 1973)

These reports cover a study commissioned by the Metal Properties Council Inc., to analyze the problem of environment-assisted crack growth with regard to: (1) its present status, (2) the nature and reliability of presently available data which might be of direct use to materials engineers, and (3) the steps that could be taken in the near future to increase the supply of useful and reliable data. Only minor attention is paid to work on the mechanistic aspects of stress corrosion cracking and corrosion fatigue since this appears to have little to offer for the immediate practical needs of engineers. Instead, the major emphasis is placed on the needs of engineers for information on which they could base decisions about material selection, component design and inspection, life prediction, and periodic inspection and overhaul procedures. Basically, engineers must estimate when failure starts, how fast it proceeds, and when the catastrophic stage becomes imminent. Hence, there is a need to determine, first the forms of data that would be most suitable, and then to design tests that will provide these data in a reproducible and generally applicable way. Monotonic loading effects will be discussed in Part I of this paper, and the effects of cyclic loading will be dealt with in Part II.

The traditional approach of measuring time or number of cycles to failure as a function of applied stress in static or cyclic tests has provided a wealth of general information about, and many insights into, the mechanisms of stress corrosion cracking and corrosion fatigue. In general, however, the smooth specimen data are not suitable for direct application by materials engineers in a number of important areas. The present study concludes that the kinds of data now available that best fill the needs of engineers are: (1) reliable measurements of K_{ISCC} in the environments of interest, (2) rates of growth of statically loaded cracked specimens in various media as a function of K, and (3) rates of growth in cyclically loaded cracked specimens in various media as a function of K, K_{max}, and frequency. It is important to use data for tests of the particular alloys in the particular environments to be encountered, with due regard for the effects of variations of alloy and environment composition which may occur, since such variations may have significant influence on the K_{ISCC} values and on cracking rates.

These kinds of data are not sufficient for all purposes, however, because it is often necessary to know the time required for crack initiation and rates of early crack growth for initially crack-free alloys in various conditions of stress and environment. It is suggested that this be carried out by standard metallographic techniques of sectioning to observe crack profiles and that this be made a part of routine materials evaluation.

Comment:

This two part paper on environment assisted fracture presents an accurate picture of the state of the art. The recommendations for future work are particularly pertinent in proposing a program on the nationwide scale to develop a set of techniques for the evaluation of the resistance of engineering materials to environment assisted cracking. This program could be similar to the type of effort by ASTM Committee E-24 in the evaluation of fracture toughness.

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8. Speidel, M. O., Blackburn, M. J., Beck, T. R., and Feeney, J. A., Corrosion-Fatigue and Stress-Corrosion Crack Growth in High Strength Aluminum Alloys, Magnesium Alloys, and Titanium Alloys, Exposed to Aqueous Solutions, Proc. Int. Conf. on Corrosion Fatigue, University of Connecticut, Storrs, CT (June 1971).

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10. Gallagher, J. P., Corrosion Fatigue Crack Growth Behavior Above and Below K_{ISCC}, NRL Report 7064 (May 28, 1970).

11. Brown, B. F., The Application of Fracture Mechanics to Stress Corrosion Cracking, Metallurgy Rev. 171 (1968).

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Key words: Aluminum alloys; corrosion; environmental effects; fatigue (materials); fracture mechanics; fractures (materials); microstructures; steels; stress corrosion; stress intensity factory; titanium alloys.

EFFECT OF ENVIRONMENT ON FATIGUE CRACKS
Achter, M. R. (Naval Research Lab., Washington DC)
Fatigue Crack Propagation, ASTM STP 415, 181-202 (1967).

In this review of the fatigue of metals in controlled gaseous environments, particular emphasis is placed on the mechanism of crack propagation as it is affected by the test variables. The crack growth rates of some metals are accelerated more by oxygen than by water vapor, while for others the reverse is true. Increases of cyclic frequency and of stress decrease the magnitude of the effect of environment. It is generally agreed that the mechanism is more an increase of the rate of crack propagation than of crack initiation. Of the two explanations proposed, the process of corrosive attack of the crack tip is favored over that of the prevention of rewelding of crack surfaces by the formation of oxide layers. Curves of fatigue life, or of crack growth rate, versus gas pressure show reasons of little or no dependence, connected by a transition region of steep slope. In a quantitative treatment of the shape of the curve, the significance of the location of the transition region is discussed.

Comment:

This paper illuminates the basic mechanisms of gas interaction with the fresh crack surface as a method of accelerating the growth rate. It is shown that the environment may be an overriding factor in crack growth rate measurements and for this reason data reported in the literature is suspect without scrupulous attention to the environmental test conditions.

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Key words: Corrosion; crack initiation; crack propagation; cyclic loads; environmental effects; fatigue (materials); frequency effects; heat resistant alloys; microstructures; oxidation; temperature effects.

FATIGUE AND CORROSION-FATIGUE CRACK PROPAGATION IN INTERMEDIATE-STRENGTH ALUMINUM ALLOYS

Crooker, T. W. (Naval Research Lab., Washington, DC)

J. Eng. Mater. Technol., 150-156 (July 1973)

Fatigue crack propagation in a variety of intermediate-strength aluminum alloys under high-amplitude elastic loading is discussed. Alloys of the 2000, 5000, 6000, and 7000 series with yield strengths from 34 to 55 ksi were investigated using the crack-tip stress-intensity factor range (ΔK) as the primary variable in describing crack growth rates. The ΔK values studies varied from approximately 12 to 50 Ksi-in½. Tests were conducted in both ambient room air and saltwater environments. The results of this study provide a definitive materials characterization and are applicable as basic criteria for fatigue design.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS, AND A COMPLETE ABSTRACT, SEE PAGE 156).

SOME ASPECTS OF ENVIRONMENT-ENHANCED FATIGUE-CRACK GROWTH
Wei, R. P. (Lehigh University, Bethlehem, PA)
Eng. Fract. Mech. 1, No. 4, 633-651 (1970)

A review of the effects of test environment, load profile, test frequency, test temperature and specimen thickness on the rate of fatigue-crack growth in high-strength metal alloys has been made. It was found that the effects of many of these variables depend strongly on the material-environment system involved.

Experimental information is most complete on the aluminum-water (or water vapor) system. The results indicate that water or water vapor has a strong effect on the rate of fatigue-crack growth in these alloys, increasing the rate of fatigue-crack growth up to a factor of ten over that obtained in a reference environment. The effect depends on the partial pressure of water vapor in the atmosphere, and exhibits a transition zone that depends strongly on the test frequency. This frequency effect has been attributed to the requirement of a definite amount of surface contamination to achieve full environmental effect by Bradshaw and Wheeler. These results suggest that the most probably mechanism for water-enhanced fatigue-crack growth in the aluminum alloys is that of the pressure mechanism for hydrogen embrittlement suggested by Broom and Nicholson, and requires the synergistic action of fatigue and water-metal surface reaction. The rate controlling process appears to be that of the creation of fresh crack surfaces by fatigue. A mild frequency dependence for these alloys tested in the fully humid environment or in distilled water (reflected by some 50 percent increase in growth rate for nearly a factor of 30 reduction in test frequency) has been attributed to a small contribution from sustained-load crack growth associated with the increased 'time-at-load' at the lower test frequencies. Environment sensitivity is reduced at the higher K levels, and appears to result from a reduction in the effectiveness of the pressure mechanism of hydrogen embrittlement associated with plane-strain and plane-stress fracture mode transition.

Only a limited amount of data are available on the titanium alloys and high-strength steels regarding the influences of these same variables. Available data on a titanium-salt water system and steel-water vapor systems indicate the behavior is quite different from that of the aluminum-water system, and suggest that the environment-enhanced fatigue-crack growth in these systems may be sustained loads (SCC) on fatigue. (No significant synergistic effect of fatigue and corrosion was evident in the experimental results considered.) If proven, such a simple model could be used to predict the effects of mean load and test frequency when crack-growth-rate data for fatigue in a reference environment and for sustained-load in the appropriate test environment are obtained. Experimental work to verify this model, as well as comprehensive studies, similar to those reported for the aluminum alloys, should be carried out for specific material-environment systems. Mechanistic studies are also needed.

On the basis of this review it is clear that the present fatigue-crack growth 'laws' could not account for the influence of environments and its related effects. This is, of course, not surprising, since these 'laws' do not specifically incorporate environment effects. Their value in predicting the rate of fatigue-crack growth from basic mechanical properties of materials have already been questioned by Wei et al. As empirical 'laws' for engineering applications, their validity must be re-established on the basis of comparisons with data obtained in well-controlled reference test environments, and they must be modified to account for environmental and other related effects, bearing in mind that these effects will likely depend on the nature of the operative 'embrittlement' mechanism.

Comment:

This paper presents a review of the influence of environment on fatigue crack growth. The collection of data into this effective presentation documents the significant effect of environment in accelerating fatigue crack growth.

Important References:

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Key Words: Analysis methods; crack propagation; environmental effects; fatigue (materials); frequency effects; stress corrosion; temperature effects.

SURFACE-SENSITIVE MECHANICAL BEHAVIOR OF METALS
Latanision, R. M., Sedriks, A. J. and Westwood, A. R. C. (Martin Marietta Corp., Baltimore, MD)
RIAS-TR-71-06C (1971)

The effects of surface and environmental conditions on the plastic flow and fracture of metals and alloys are reviewed, with particular emphasis on topics of current controversy. These include the effects of surface films and the hard versus soft surface layer controversy in the plastic deformation of metal monocrystals, and the influence of crack-tip chemistry, cathodically produced hydrogen, brittle films and other parameters in stress-corrosion cracking.

The last two years have seen increasing recognition of the need for a better understanding of the chemistry of the solution within a stress corrosion crack. Several workers have recognized the importance of defining the environment within a crack in terms of the kinetics of mass transport of reactant species, and the need for the development of techniques for the analysis of the extremely small quantities of solution present, and the measurement of potential gradients within crevices simulating stress corrosion cracks, has also been pointed out.

The testing of pre-cracked specimens, often referred to as the "fracture mechanics approach to SCC", has gained in popularity and has had a profound effect on procedures used for evaluating stress-corrosion resistance. This approach has resulted especially in the generation of useful data for the rates of propagation of single cracks. The availability of such data has enabled new analyses to be carried out, and provided an explanation for the extensive variation in the measured activation energies for stress-corrosion cracking. On the other hand, while the fracture mechanics approach has provided design engineers with more reliable estimates of the stress-corrosion resistance of high-strength alloys containing such stress raisers as fatigue cracks, this approach has yet to provide any new insight into stress-corrosion mechanisms.

Among techniques recently applied to studies of stress-corrosion processes, high-voltage microscopy in nickel-base alloys, ellipsometry in titanium alloys and brasses, and acoustic emission in titanium alloys, and steels.

Among novel ways of mitigating stress-corrosion failure two approaches should be mentioned. The first, which could be termed the "composite approach," utilizes composites comprising of alternate laminate of high-strength alloys (susceptible to SCC) and low-strength (nonsusceptible) alloys. To date, composites consisting of alternate layers of maraging steel and Armco iron have been evaluated, with promising results. The second approach involves the utilization of preferred orientation effects to mitigate susceptibility, for example, of high-strength titanium alloys. It has been established that transgranular stress-corrosion cracks in alpha (c.p.h.) titanium alloys select a crack path within 15 degrees of the basal plane. Since alloys such as the high strength Ti-8Al-1Mo-1V exhibit a pronounced texture, in which the basal planes (0001) are aligned parallel to the rolling direction, it would be expected that crack propagation would be difficult in a direction perpendicular to the basal planes. Such behavior has been observed, and this approach may find useful application in the manufacture of hardware.

No conceptually new mechanisms have emerged in the last few years, and the main development has been the emergence of ideas concerning the role of hydrogen in stress-corrosion cracking.

It is evident that the flow and fracture behavior of metals and alloys can be significantly influenced by surface conditions. Although the detailed mechanisms of surface and environment-sensitive mechanical phenomena are still in many cases controversial, a better understanding of this behavior is not only academic but may lead the way to entirely new areas of technology ranging from easier methods of forming and maching modern superalloys, to improve life and reliability of complex and expensive structures in agressive environments.

Comment:

This paper accurately portrays the state of the art of surface sensitive behavior of metals and indicates the recent advances that may lead to significant breakthroughs in the future.

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1. Latanision, R. M. and Westwood, A. R. C., In Advances in Corrosion Science and Technology, M. G. Fontana and R. W. Staehle, Eds., 1, 51, Plenum Press, New York, NY (1970).

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Key Words: Corrosion; crack initiation; dislocations (materials); mechanical properties; microstructures; plastic deformation; stress corrosion; surface layers; surface properties.

ANALYSIS OF MULTIAXIAL FLOW UNDER VARIABLE LOAD AND TEMPERATURE

Rashid, Y. R. (General Electric Co. San Jose, CA)

ASTM, ASME, IME, Int. Conf. Creep and Fatigue in Elevated Temperature Applications, 183.1-183.9 Philadelphis, PA (23-28 September 1973), and Sheffield, England (1-5 April 1974).

A brief overview of creep methods used in the analysis of structures operating in high temperature environments and subjected to variable mechanical and thermal load histories is given. The present discussion is limited to analytical and computational techniques which have been applied to the analysis of large size structural problems through the use of large scale computer programs. The creep constitutive laws are first discussed from fundamental points of view. The basic properties and predictive capabilities of these laws are examined through simple examples. Practical implications of using creep analysis methods in structural design are also discussed.

Important References:

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2. Rashid, Y. R. and Cheng, T. Y., Stress Analysis of Two Dimensional Problems Under Simultaneous Creep and Plasticity, Proc. Int. Conf. Structural Mechanics in Reactor Tech., 1st., 327-340, Berlin, Germany (September 1971).

3. Esztergar, E. P., Creep Fatigue Interaction and Cumulative Damage Evaluations for Type 304 Stainless Steel, ORNL 4757 (June 1972).

4. Blackburn, L. D., Strain-Time Relations During Creep Deformation of Austenitic Stainless Steel, WADCO Report RM-3, Rev. 1 (December 1970).

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Key words: Analysis methods; creep; creep analysis; creep rupture; high temperature; high temperature environments; loads (forces); thermal stresses; variable temperature.

FATIGUE CRACK CLOSURE UNDER CYCLIC TENSION
Elber, W. (Institute Fuer Festigkeit, Mulheim, West Germany)
Eng. Fract. Mech 2, 37-45 (1970)

Results of an investigation are presented which indicate that a fatigue crack, propagating under zero-to-tension loading, may be partially or completely closed at zero load. An analysis of the stress distribution acting on the fracture surfaces shows that the local compressive stress maxima may influence the shape of the striation pattern on the fracture surfaces.

Comment:

The identification of compressive stresses in the region of the crack tip plastic zone in zero to tension cycling is important in predicting cumulative damage mechanisms.

Important References:

1. Rice, J. R., Mechanics of Crack Tip Deformation and Extension by Fatigue, ASTM STP 415, 247 (1967).

Key words: Crack propagation; cracks; cyclic loads; deformation; fatigue (materials); fractures (materials); stress concentration; tensile stress.

INCREASES IN FATIGUE LIFE CAUSED BY THE INTRODUCTION OF REST PERIODS
Miller, K. J. and Hatter, D. J. (Cambridge Univ., England, North East London Polytechnic, Dagenham, England)
J. Strain Anal. 7, No. 1, 69-73 (1972)

Fatigue data are usually derived from uninterrupted laboratory tests although the data may be required for conditions in which components are infrequently cycled. This paper discusses tests that involve rest periods to simulate infrequent cycling. The introduction of rest periods always causes an increase in endurance which approaches a maximum of approximately 100 percent at a critical value of rest. The total rest period appears to be a more important parameter than either the number of rest periods or the position in the lifetime at which rests may be taken.

The introduction of rest periods at zero load during fatigue tests increased the fatigue endurance of the hardened and tempered 2.5 percent Ni-Cr-Mo steel in terms of the number of cycles to failure.

A maximum increase in endurance of approximately 100 percent occurs after a critical rest period of 100 hours. Thereafter the improvement in endurance is not so marked and with rest periods in excess of 200 hours the increase in endurance is approximately constant at 33 percent.

A more comprehensive study needs to be undertaken to determine the role of carbon and nitrogen diffusion, dislocations, the cyclic stress-strain state of the material, straining rate, and the effect of material history.

Comment:

This paper presents data showing that infrequent cyclic stressing gives longer fatigue life than continuous cycling. These results indicate the complexity of the problem of fatigue life prediction.

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Key words: Crack initiation; crack propagation; cyclic loads; ductility; fatigue (materials); fatigue life; fatigue tests; load cycles; load rest periods; steels.

THE EFFECT OF FREQUENCY UPON THE FATIGUE-CRACK GROWTH OF TYPE 304 STAINLESS STEEL AT 1000°F

James, L. A. (Westinghouse Electric Co., Richland, WA)

Stress Analysis and Growth of Cracks, ASTM STP 513, 218-229 (September 1972)

The results of this study may be summarized as follows:

(1) The fatigue-crack growth behavior of solution-annealed Type 304 stainless steel at 1000°F appears to be frequency-dependent at some values of ΔK, and frequency-independent at others. The transition from independent to dependent behavior occurs at higher values of ΔK as the cyclic frequency is decreased.

(2) In the regime where the crack growth behavior is dependent upon frequency, decreasing the frequency results in a significant increase in the fatigue-crack growth rate, da/dN. If the crack extension is characterized on a time basis, da/dt, the above observation is reversed.

(3) The slope of the frequency-dependent portion of the da/dN versus ΔK curves is nearly constant for all frequencies. This allows the behavior to be characterized in terms of a power law of the form $da/dN = A(f)\,[\Delta K]^n$, where n is constant for all frequencies tested. It should be emphasized that this relationship is entirely empirical, and its extension to other material/environment combinations should be approached with caution.

(4) Based on very limited data, it appears that either the average, mean, or root-mean-square frequencies did a satisfactory job in correlating the test data for a condition of non-constant frequency. Additional work, however, is required to determine the most appropriate correlation parameter.

Comment:

The attempt to relate dependent behavior to some empirical power law is successful, however, a more direct relationship might be possible considering the thermodynamic kinetics of the surface reactions in the opening and closing crack.

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1. Popp, H. G. and Coles, A., Subcritical Crack Growth Criteria for Inconel 718 at Elevated Temperatures, AFFDL-TR-70-144, 71-86 (September 1970).

2. James, L. A., The Effect of Elevated Temperature Upon the Fatigue-Crack Propagation of Type 304 Stainless Steel, Nucl. Technol. 14, No. 2, 163-170 (1972).

3. James, L. A., The Effect of Elevated Temperature Upon the Fatigue-Crack Propagation Behavior of Two Austenitic Stainless Steels, Int. Conf. on Mechanical Behavior of Mater., Kyoto, Japan (15-20 August 1971).

4. Coffin, Jr., L. F., Life Prediction of Metals Subjected to High Temperature Fatigue, Int. Conf. on Mechanical Behavior of Mater., Kyoto, Japan (15-20 August 1971).

Key words: Analysis methods; crack propagation; fatigue (materials); frequency effects; stress ratio.

EFFECT OF LOAD SEQUENCES ON CRACK PROPAGATION UNDER RANDOM AND PROGRAM LOADING

Schijve, J. (National Aerospace Lab., Amsterdam, Netherlands)

Eng. Fract. Mech. 5, 269-280 (1973)

Crack propagation was studied in 2024-T3 Alclad sheet specimens under two types of random loading and under program loading with very short period (40 cycles) and program loading with a longer period (40,000 cycles). In the program tests, lo-hi, lo-hi-lo, and hi-lo sequences were employed. The loads were based on a gust spectrum. The crack rates were about the same under random loading and program loading with the short period. Under program loading with the longer period the crack rates were 2.5 times slower on the average, while a significant sequence effect was observed in these tests. Fractographic observations indicated different cracking mechanisms for the random tests and program tests with a short period on the one hand and the program tests with the longer period on the other hand. Implications for fatigue tests in practice are discussed.

The results have shown that the crack propagation life is not very sensitive to the sequence of load cycles provided that the variation of the amplitude does not occur slowly. If this variation is slow, as it is in a classic program test, the life may be much larger than for random loading and this was confirmed in the present tests. This is a regrettable result from a practical point of view. Actually it implies that nature does not allow us to simply load sequences if we want to obtain relevant information on fatigue life and crack propagation. In other words, in a test on an aircraft component or a full-scale structure a classically programmed sequence of the fatigue loads cannot guarantee that realistic information will be obtained. It may produce unconservative data. Flight simulation loading should be employed in such a test.

A second remark is concerned with our understanding of the trends observed. Despite our qualitative knowledge of the various aspects related to fatigue damage accumulation it has to be admitted that an explanation for the present sequence effect cannot be given without speculative arguments. Nevertheless the qualitative knowledge is sufficient to tell us that systematic sequence effects have to be expected. The fractographic observations have confirmed their existence.

Comment:

This paper presents very significant test data showing the effects of random and programmed load cycles on the fatigue life of materials. The observation that programmed loading may be unconservative in terms of random or flight profile loading has broad implications for testing of structure.

Important References:

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2. Schijve, J., Jacobs, F. A. and Tromp, P. J., Crack Propagation in Aluminum Alloy Sheet Material Under Flight-Simulation Loading, NRL TR-68117, Amsterdam, Netherlands (1968).

3. Naumann, E. C., Fatigue Under Random and Programmed Loads, NASA-TN-D-2629 (1965).

4. Jacoby, G., Comparison of Fatigue Lives Under Conventional Program Loading and Digital Random Loading, ASTM STP 436, 89 (1968).

Key words: Aluminum alloys; crack analysis; crack propagation; cracks; cyclic loads; fatigue (materials); fatigue tests; load cycles; random load cycles.

INVESTIGATION OF FATIGUE-CRACK GROWTH UNDER SIMPLE VARIABLE AMPLITUDE LOADING
Hudson, C. M. and Raju, K. N. (National Aeronautics and Space Administration, Langley Research, Langley Station, VA)
NASA-TN-D-5702

Variable amplitude fatigue-crack-growth tests were conducted on simple sheet specimens made of 7075-T6 aluminum alloy. The numbers and the amplitudes of the high-load cycles applied in these tests were systematically varied to study their effects on subject low-load fatigue-crack growth.

The high-load cycles consistently delayed subsequent fatigue-crack growth at lower load levels. For a given low-load level, the higher the preceeding high-load level was, the greater the delay in crack propagation. Furthermore, the delay in crack growth increased with increasing numbers of high-load cycles up to a limit. One high-load cycle caused approximately one-fourth of the maximum delay, and ten high-load cycles caused approximately one-half of the maximum delay. These delays probably resulted from residual compressive stresses generated in the material immediately ahead of the crack tip during the application of the high-load cycles.

Electron fractographic studies showed that at a given stress level, fatigue cracks propagated more slowly immediately after the application of a high-load cycle than they did immediately before its application. This lower crack-growth rate is consistent with the delay in crack growth observed on the macroscopic level.

Comment:

This effort demonstrated the beneficial effects of overstressing on subsequent low amplitude fatigue. These are explained as being the result of residual compressive stresses, but could equally be a form of work hardening. A limitation to this work was the limitation of the experimental effort to one heat treatment of one aluminum alloy and the application to other alloys is problematical.

Important References:

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Key words: Aluminum alloys; crack propagation; cracks; cyclic loads; fatigue (materials); fatigue properties; notched specimens.

AN APPROACH TO THE ANALYSIS OF THE NONLINEAR DEFORMATION AND FATIGUE RESPONSE OF COMPONENTS SUBJECTED TO COMPLEX SERVICE LOAD HISTORIES

Topper, T. H. and Conle, A. (Waterloo University, Ontario, Canada)

AD-763780, AFOSR TR-73-1146 (March 1973)

Successful fatigue designs are currently based on trial and error methods of utilizing experience and empiricism to create a prototype. Validation is done by full-scale testing. The time and expense incurred in using such methods has encouraged basic research which, in turn, has resulted in a recognition of the importance of inelastic deformation, geometric constraints, history effects, and mean stresses. An approach to the treatment of these problems and a unified method of dealing with them in fatigue analysis has been presented in the preceding sections.

A design method for parts which contain highly stressed regions due to stress raisers has been outlined. In this method local plastic strains in nominally elastic components are simulated in a computer program, containing the notch analysis technique, which can model material behavior such as memory, hardening and softening and mean stress relaxation. Sequence effects resulting from the occurrence of plastic strain during the history are accounted for and a damage parameter which accounts for mean stress effects is introduced. Automatic matching of half cycles to form closed loops is then used to determine when the damage is to be summed. Good life predictions are achieved for a randomly loaded notched plate.

This kind of approach to fatigue analysis, which treats fatigue of a notched component as a system composed of components describing the various features of fatigue, and the corresponding mathematical models is now sufficiently sophisticated to achieve good laboratory results. Actual engineering application followed by evaluation and further refinement will constitute the next direction of development. It is the opinion of the authors that the approach outlined will also contribute to fatigue research by fostering a better understanding of the relative importance of the many variables influencing the fatigue process.

Comment:

This paper presents an interesting breakdown of the components of the fatigue process, which will help further the understanding of mechanisms. Application of these insights should improve life prediction in complex service history situations.

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Key words: Aircraft structures; analysis methods; failures (materials); fatigue (materials); fatigue life; low cycle fatigue; metallic materials; notched specimens; plastic strain.

VI - Materials

LOW-CYCLE FATIGUE OF THREE SUPERALLOYS UNDER CYCLIC-EXTENSION AND CYCLIC-TEMPERATURE CONDITIONS

Carden, A. E., Kyzer, R. D. and Vogel, W. H. (University of Alabama, University AL and Pratt and Whitney Aircraft, East Hartford, CT)

ASME Paper 67-MET-19 (1967)

A new test method is described which is versatile and offers great flexibility in programming strain for stress and temperature independently and synchronously. Also a unique strain measurement system allows the direct recording of the mechanical component of strain independent of the thermal component. The results of tests of two nickel-and one cobalt-base superalloys are presented as an example of the utility of the test method. These tests were performed on coated tubular specimens. The temperature was programmed to cycle between 205 and 982°C in phase with an extension cycle program. The test results show the effect of hold time at constant extension (relaxation cycling) of the three alloys.

Important References:

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Key words: Cobalt alloys; compressive loads; cyclic loads; heat resistant alloys; life prediction; low cycle fatigue; nickel alloys; tensile stress; thermal cycles.

DEVELOPMENT OF ALLOY FOR CAST AIR-COOLED TURBINE BLADES
Collins, H. E. and Graham, L. D. (TRW, Inc., Cleveland, OH)
AFML-TR-72-128, AD-744109 (January 1972)

The objective of this program was to develop an alloy for cast air cooled turbine blades, specifically the target goals for the alloy were, intermediate temperature tensile ductility in cast thin sections equivalent to that of high strength superalloys in thick sections, creep-rupture life of 100 hours at 982°C/1400 Kg/cm^2, oxidation and corrosion resistance of 982°C equivalent to that of U-700 at 890°C. Alloy TRW-NASA VIA was selected as the basic composition. Alloy IIIH and IIIK satisfied the stress-rupture life and corrosion resistance target goals, but they fell short of the tensile ductility of the thick selection value of TRW-NASA VIA. Corrosion resistance was good for both alloys. Further alloy development work is suggested.

Comment:

This effort demonstrates that alloy composition variations can be tailored to optimize particular properties such as intermediate temperature tensile ductility.

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Key words: Corrosion resistance; ductility; heat resistant alloys; high temperature environments; high temperature tests; hot corrosion; mechanical properties; nickel alloys; oxidation resistance; stress rupture; turbine blades.

OXIDATION AND THERMAL FATIGUE CRACKING OF NICKEL-AND COBALT-BASE ALLOYS IN A HIGH VELOCITY GAS STREAM
Johnston, J. R. and Ashbrook, R. L. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)
NASA TN-D-5376 (August 1969)

An investigation was conducted to determine the resistance to oxidation of typical gas turbine alloys exposed alternately to high and low temperature, high velocity gas streams. A natural gas-compressed air burner was used to produce velocities up to Mach 1 and specimen temperatures up to 2000°F (1093°C). The materials tested included six nickel-base alloys: IN-100, B-1900, MAR M-200, TAZ-8A, Hastelloy X, and TD-NiCr, and four cobalt-base alloys: L-605, X-40, MAR M-509A, and WI-52.

In a standard test of 100 cycles of 1 hour at temperature in a Mach 1 gas stream followed by rapid cooling to room temperature, the nickel-base alloys as a class experienced less weight loss than the cobalt-base alloys. The average values of weight loss varied widely from 216 to 23,700 milligrams after 100 hours at 2000°F (1093°C). Of the cobalt-base alloys, X-40 had the lowest weight loss, which was only slightly less than that of MAR M-200. The latter alloy had the highest weight loss of all of the nickel alloys. Of all the alloys tested, the cast cobalt-base alloy, WI-52, was the least resistant to weight loss. After 100 hours, surface recession paralleled weight loss and ranged from 0.3 to 50 mils (0.008 to 1.3 mm).

Cast cobalt-base alloys were more resistant to thermal fatigue cracking than conventionally cast nickel-base alloys. However, directionally solidified and single grain MAR M-200 castings and wrought Hastelloy X had no cracks even after 100 cycles at 2000°F (1093°C).

At 2000°F (1093°C) under simulated steady-state operation (10-hour cycles with free air cooling to room temperature) the average weight loss was less for the six alloys so tested than at standard conditions. Cobalt alloys showed more improvement in oxidation resistance from the change in cycle than the nickel-base alloys. No cracking was observed in any alloy under these conditions. When the lower temperature during a 2000°F (1093°C) test was restricted to 1200°F (649°C), the propensity toward cracking was unchanged for IN-100, and B-1900, but substantially reduced for WI-52. However, weight loss decreased substantially for all alloys so tested.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 115).

OXIDATION AND HOT-CORROSION CHARACTERISTICS OF SEVERAL RECENTLY DEVELOPED NICKEL-BASE SUPERALLOYS

Dapkunas, S. J., Wheatfall, W. L. and Hammond, B. L. (Naval Ship Research and Development Center, Annapolis, MD)
NSRDC Report No. 3925 (March 1973)

Oxidation and hot corrosion tests were conducted in six recently developed nickel-base superalloys (cast Udimet 710, wrought Udimet 710, IN-738, IN-792, MAR-M421, and MAR-M432) to determine the surface stability characteristics of the materials. In addition to optical measurements, oxidized alloys were analyzed by x-ray microprobe techniques to determine the redistribution of alloying elements after oxidation in pure oxygen for 210 hours at 900°C and 955°C. In general, the new alloys had reasonably good oxidation and hot corrosion resistance when compared to older alloys such as Udimet 500 and Alloy 713C. Udimet 710 (cast and wrought) had the best overall hot corrosion resistance of any of the six recently developed alloys, and wrought Udimet 710 had the best oxidation resistance. For the most part, the x-ray microprobe analyses of oxidized alloys correlated fairly well with the optical measurements. Physical and mechanical properties and structural stability characteristics of each alloy are included in the appendixes to provide additional information for comparing the alloys. Appendix C includes 104 figures of microprobe results.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 119).

NASA PROGRAMS FOR DEVELOPMENT OF HIGH-TEMPERATURE ALLOYS FOR ADVANCED ENGINES
Freche, J. C. and Hall, R. W. (National Aeronautics and Space Administration, J. Aircraft 6, No. 5, 424-431 (September-October 1969) Lewis Research Center, Cleveland, OH)

An intensive research effort is underway at the NASA Lewis Research Center to provide improved materials for the hot components of advanced aircraft gas turbine engines. Research is being conducted both in-house and under NASA sponsorship to develop advanced materials for such applications as stator vanes, turbine buckets and disks, combustion chamber liners, and the latter compressor stages. Major areas of work deal with the development of nickel and cobalt base alloys, chromium base alloys dispersion strengthened materials, composite materials, and protective coatings. Progress in NASA programs dealing with all these areas is described. Of most immediate importance is the development of an advanced cast nickel base alloy, NASA-TRW-VI-A. This alloy shows approximately a 50°F (28°C) improvement in use temperature over the strongest superalloys currently in use. Even larger improvements over the strengths of currently used superalloys have been achieved in chromium alloys and metal matrix composite materials. However, many problems remain to be solved before the opportunities indicated by these later developments can be utilized in aircraft engines. Foremost among the needs at this time is that for improved oxidation, nitridation, and erosion resistant coatings to permit use of these stronger materials at temperatures consistent with their strength potential.

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1. Freche, J. C., Waters, W. J. and Riley, T. J., A New Series of Nickel-Base Alloys for Advanced-Temperature Applications, Trans ASM 53, 523-537 (1961).

2. Freche, J. C., Progress in Superalloys, NASA TND 2495 (1964).

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4. Freche, J. C., Waters, W. J. and Ashbrook, R. L., Application of Directional Solidification to a NASA Nickel-Base Alloy (TAX-8B), NASA-TN-D-4390 (1968).

5. Collins, H. E., Development of High Temperature Nickel-Base Alloys for Jet Engine Turbine Bucket Applications, NASA-CR-54517 (1967).

6. Sandrock, G. D., Ashbrook, R. L. and Freche, J. C., Effect of Variations in Silicon and Iron Content on Embrittlement of a Cobalt-Base Alloy (L-605), NASA-TN-D-2989.

7. Sandrock, G. D. and Leonard, L., Cold Reduction as a Means of Reducing Embrittlement of a Cobalt-Base Alloy (L-605), NASA-TN-D-3528 (1966).

Key words: Cobalt alloys; creep; creep tests; directional solidification; environmental effects; gas turbine engines; heat resistant alloys; high temperature environments; nickel alloys; protective coatings; stress rupture.

LOW-CYCLE FATIGUE AND CYCLIC STRESS-STRAIN BEHAVIOR OF INCOLOY 800

Conway, J. B., Berling, T. J. and Stentz, R. H. (Mar-Test Inc., Cincinnati, OH)

Met. Trans. 3, 1633-1637 (June 1972)

Strain-controlled low-cycle fatigue tests of solution-annealed Incology 800 were performed at temperatures of 538°C, 649°C, 704°C, and 760°C using axial strain rates of 4 x 10^{-4} seconds. A few hold time tests were also performed to indicate a noticeable reduction in fatigue life at hold-times of 10 and 60 minutes. A comparison of these fatigue data with similar results for AISI 304 stainless steel indicates essentially identical behavior. An extensive study is made of the cyclic stress-strain behavior of Incoloy 800 and the relationship between the cyclic strain-hardening exponent and fatigue behavior is confirmed. Exponents on N_f in the elastic and plastic strain range terms of the total strain range equation are identified and compared with those used in the universal slopes equation.

Important References:

1. Berling, J. T. and Slot, T., Effect of Strain Range on Low-Cycle Fatigue Resistance of AISI 304, 316 and 348 Stainless Steels at Elevated Temperature, ASTM STP 459 (1970).

2. Berling, J. T. and Conway, J. B., Effect of Hold-Time on the Low-Cycle Fatigue Resistance of 304 Stainless Steel at 1200°F, Proc. Int. Conf. on Pressure Vessel Technol., 1st, Delft, Holland (1969).

3. Conway, J. B., Berling, J. T. and Stentz, R. H., New Correlations Involving the Low-Cycle Fatigue and Short-Term Tensile Behavior of Irradiated and Unirradiated 304 and 306 Stainless Steel, Nucl. Applic. Technol. 9, 31 (1970).

4. Conway, J. B., Berling, J. T. and Stentz, R. H., A Temperature Correlation of the Low-Cycle Fatigue Data for 304 Stainless Steel, Met. Trans. 2, 3247 (1971).

Key words: Cyclic loads; cyclic testing; fatigue life; fatigue properties; heat resistant alloys; high temperature; low-cycle fatigue; nickel alloys stainless steels; temperature effects; testing methods.

THE FATIGUE STRENGTH OF NICKEL-BASE SUPERALLOYS

Gell, M., Leverant, G. R. and Wells, C. H. (Pratt and Whitney Aircraft, Middletown, CT) ASTM STP 467, 113-153 (September 1970)

The fatigue behavior of nickel-base superalloys is reviewed and methods for improving their properties are suggested. Low-temperature crack initiation occurs preferentially at microstructural defects such as pores and brittle phases in cast materials and at defects such as brittle phases and annealing in boundaries in wrought materials. The brittle phases may contain inherent cracks or be cracked during working operations or service exposures. Plastic deformation at low temperatures is concentrated in coarse planar bands, and as a result matrix cracking is predominately transgranular and crystallographic. Techniques are discussed for increasing the low-temperature fatigue properties by minimizing the role of microstructural defects and achieving a more homogeneous distribution of deformation. At elevated temperatures, intergranular cracking predominates and methods are discussed for improving fatigue properties through grain size control, the use of columnar-grained and single-crystal materials, and the application of oxidation-resistant and fatigue-resistant coatings.

Important References:

1. Gell, M. and Leverant, G. R., The Fatigue of the Nickel-Base Superalloy MAR-M200 in Single-Crystal and Columnar-Grained Forms at Room Temperature, Trans. Met. Soc. AIME 242, 1869-1879 (September 1968).

2. Leverant, G. R. and Gell, M., Trans. Met. Soc. AIME 245, 1167-1173 (1969).

3. Wells, C. H. and Sullivan, C. P., The Low-Cycle Fatigue Characteristics of a Nickel-Base Superalloy at Room Temperature, ASM Trans. Quart. 57, 841-855, (1964).

4. Gell, M. and Leverant, G. R., The Effect of Temperature on Fatigue Fracture in a Directionally Solidified Nickel-Base Superalloy, Fracture, 1969, Proc. Int. Conf. on Fracture, 2nd, Chapman and Hall, Ltd., London, England, (1969).

5. Fornwalt, D. E. and Boone, D. H., Metallographic Characterization of Phases Associated with Aluminide Coated Udimet 700, Proc. Annu. Meet. Inter. Metallographic Soc., 1st, Denver, CO (1969).

Key words: Crack initiation; crack propagation; environment effects; fatigue (materials); fatigue strength; fracture analysis; fractures (materials); frequency effects; heat resistant alloys; microstructures; nickel alloys; protective coatings; temperature effects.

THERMAL-MECHANICAL FATIGUE CRACK PROPAGATION IN NICKEL-AND COBALT-BASE SUPERALLOYS UNDER VARIOUS STRAIN-TEMPERATURE CYCLES

Rau, Jr., C. A., Gemma, A. E. and Leverant, G. R. (Pratt and Whitney Aircraft, Middletown, CT)

Fatigue at Elevated Temperatures, ASTM STP 520, 166-178 (1973)

Crack propagation rates under isothermal and thermal fatigue cycling have been determined for a conventionally-cast cobalt-base superalloy, and conventionally-cast and directionally-solidified nickel-base superalloys. Linear elastic fracture mechanics, where the crack growth rates under different strain ranges or for various crack lengths depend only on the strain intensity factor range, was found to be applicable over the range of crack growth rates of most practical importance. A comparison of crack growth rates is made for thermal fatigue under various strain-temperature cycles and isothermal low-cycle fatigue, and the influence of coatings and superimposed creep is discussed.

Based on the experimental effort the following conclusions are drawn.

1. Linear elastic fracture mechanics can be applied to thermal fatigue crack propagation of nickel-and cobalt-base superalloys under conditions of small plastic strains.

2. For crack growth rates less than 10^{-4} inch/cycle, the growth rate depends only on ΔK_E and is independent of strain range, mean strain, and mean stress (for the range of mean strains and strain ranges investigated).

3. Cycle I* thermal fatigue crack propagation rates are more rapid than low temperature isothermal low cycle fatigue crack growth rates where the fracture mode is the same and slightly more rapid than Cycle II thermal fatigue.

4. Cycle I crack growth rates increased slightly with increasing maximum temperature.

5. Directionally solidified nickel-base superalloy has a markedly slower crack growth rate than a conventionally cast nickel-base superalloy of similar microstructure.

6. Coatings have no effect on growth rates of through-the-thickness cracks with one exception. Thin-walled specimens tested with the peak tensile strain in the temperature range where the coating is relatively brittle show an accelerated crack growth rate.

* Cycle I is defined as that cycle which produces the maximum tensile strain at the minimum temperature.

Cycle II is a similar cycle where the tensile strain peaked at the maximum temperature.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 63).

SUBCRITICAL CRACK GROWTH CRITERIA FOR INCONEL 718 AT ELEVATED TEMPERATURES
Popp, H. G. and Coles, A. (General Electric Co., Evendale, OH)
AFFDL-TR-70-144, 71-86 (September 1970).

The purpose of this investigation was to determine if fracture mechanics methods are suitably accurate to predict the defect tolerance of Inconel 718 welds at temperatures up to 1200°F in the cyclic conditions typically encountered in jet engine frames and castings. It was shown that elastic fracture mechanics methods can be applied at temperatures in the creep regime with reasonable accuracy for Inconel 718. In addition, a fracture mechanics model was developed to predict the residual cyclic life of Inconel 718 weldments containing surface defects. Cases of axial and combined axial and bending stress fields were treated. Also, the utility of a time-temperature parameter to predict cyclic crack growth rates at a particular stress intensity was demonstrated. The parameter P = (T + 460) (10 + Log(TH)) provided reasonably accurate description of crack growth rate data for temperatures ranging from 70°F to 1200°F and peak stress hold times of from one second to two hours.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 72).

EFFECTS OF FREQUENCY AND ENVIRONMENT ON FATIGUE CRACK GROWTH IN A286 AT 1100°F
Solomon, H. D. and Coffin, L. F. (General Electric Company, Schenectady, NY)
Fatigue at Elevated Temperatures, ASTM STP 520, 112-122 (August 1973)

Previous low-cycle fatigue tests on A286, which covered a frequency range of 5 to 0.1 CPM, have shown a pronounced frequency dependence when the tests were run in air. In contrast, tests run in a vacuum did not show such a frequency effect. This led to the conclusion that, in this frequency range, environmental effects were responsible for the frequency dependence. Air crack propagation tests have also shown a strong frequency dependence. At frequencies below .02 CPM the air crack propagation tests showed a stronger frequency dependence than was observed at higher frequencies and resulted in pure time dependent, cycle independent failure. In order to explain this behavior and to see if it could be observed in low frequency vacuum tests, measurements of the crack propagation rate at 593°C were made in a 10^{-8} Torr vacuum. These vacuum crack propagation results substantiated the assertion that at 593°C, air produces a strong influence on the failure life or crack propagation rate. Additionally, these tests have shown that below .02 CPM the pure time dependent failure noted in air persisted in a vacuum. The vacuum results could be interpreted on the basis of a linear superposition model. Where at low frequency the behavior was a purely time dependent failure; at high frequencies, purely cycle dependent; and at intermediate frequencies, that of a linear suposition of these phenomena. In air this linear superposition model was not applicable because of the additional environmental interaction.

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1. Coffin, Jr., L. F., The Effect of Vacuum on the High Temperature, Low Cycle Fatigue Behavior of Structural Metals, Proc. Int. Conf. Corrosion Fatigue (June 1971); also General Electric Report 71-C-108 (1971).

2. Coffin, Jr., L. F., The Effect of High Vacuum on the Low Cycle Fatigue Law, Met. Trans. 3, 1777-1778 (July 1972).

3. Coffin, Jr., L. F., Predictive Parameters and Their Application to High Temperature Low-Cycle Fatigue, Fracture, 1969, Proc. Int. Conf. Fracture, 2nd, 643, Brighton, England (April 1969).

4. Solomon, H. D., Frequency Modified Low Cycle Fatigue Crack Propagation, Met. Trans. 4, 341-347 (1973).

5. Coffin, Jr., L. F., The Effect of Frequency on High Temperature, Low Cycle Fatigue, Proc. Air Force Conf. Fatigue and Fracture of Aircraft Structure and Materials, AFFDL-TR-70-144 (September 1970).

6. Solomon, H. D. and Coffin, Jr., L. F., The Effects of Frequency and Environment on Fatigue Crack Growth in A286 at 1100°F, General Electric Report 72CDR101 (1972).

Key words: Crack propagation; cyclic loads; cyclic testing; edge crack specimens; environmental effects; fatigue (materials); fatigue tests; frequency effects; high temperature; low-cycle fatigue; metallic materials; notched specimens; stainless steels.

THE STATIC AND CYCLIC CREEP PROPERTIES OF THREE FORMS OF A CAST NICKEL ALLOY
Harrison, G. F. and Tilly, G. P. (National Gas Turbine Establishment, Farnsborough, England)
Proc. ASTM, ASME, IME, Int. Conf. Creep and Fatigue in Elevated Temperature Applications, 222.1-222.9, Philadelphia, PA (23-28 September 1973) and Sheffield, England (1-5 April 1974).

The static and cyclic creep properties of conventionally cast, directionally solidified and single crystal forms of a cast nickel superalloy, MAR M246, have been evaluated at 850°C and 900°C. Tensile and compressive creep curves have been obtained at constant stress and the results analyzed using power law creep terms. Typically, directionally solidified specimens have tensile lives twice those of comparable conventionally-cast materials, and rupture strains three or four times greater. Increase in specimen size raised the life of conventionally cast material but had no effect on single crystals. Differences between tensile and compressive creep properties were accentuated in the tertiary stages of deformation. No improvement in compressive creep resistance was obtained using directionally solidified or single crystal specimens. Equations developed previously from strain hardening theory gave an accurate estimate of behavior under cyclic tension. This theory has been extended to include push-pull loading and is shown to give a satisfactory correlation with the data.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 31).

A COMPRESSIVE CHARACTERIZATION OF THE HIGH TEMPERATURE FATIGUE BEHAVIOR OF A286
Henry, M. F., Solomon, H. D. and Coffin, Jr., L. F. (General Electric Company, Schenectady, NY)
ASTM, ASME, IME, Int. Conf. Creep and Fatigue in Elevated Temperature Applications 182.1-182.7, Philadelphia, PA (23-28 September 1973) and Sheffield, England (1-5 April 1974).

The high strain behavior of A286 at 593°C is examined in a multi-faceted program. The program includes phenomenological studies on life prediction in smooth bars and on crack propagation in single-edge-notched specimens. It is shown that the life-prediction equations can be used to account for frequency, wave shape (including hold times) and notches, environment is shown to have a strong effect on the fatigue life when cyclic frequency is varied. Studies from a metallurgical viewpoint are presented on fatigue crack nucleation and propagation. Nucleation and propagation mechanisms are found to be transgranular and intergranular at high and low frequencies respectively. It is shown that the strainrange partitioning concept is inapplicable for A286 at 593°C, due most probably to the strong environmental interaction. Key areas are pointed out where information is still lacking.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 51).

STRESS RUPTURE BEHAVIOR OF A DISPERSION STRENGTHENED SUPERALLOY
Cairns, R. L. and Benjamin, J. S. (International Nickel Co., Inc., New York, NY)
J. Eng. Mater. 10-14 (January 1973)

A dispersion strengthened nickel-base superalloy, designated IN-853, has been made by a new process called mechanical alloying. This provides a long sought combination of properties typical of dispersion strengthened and precipitation hardened materials. The alloy has flat rupture curves over a wide temperature range. Rupture stress/temperature curves for the alloy show a transition separating the low temperature regime where precipitation hardening controls the strength, and the high temperature range where dispersion strengthening predominates. The slope of a Larson-Miller Plot of stress temperature rupture stress is less sensitive to temperature changes than is the case with conventional nickel-base superalloys. At a fixed stress level the rupture life of the dispersion strengthened superalloy is more sensitive to temperature changes.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 32).

FATIGUE, CREEP, AND STRESS-RUPTURE PROPERTIES OF SEVERAL SUPERALLOYS
Blatherwick, A. A. and Cers, A. E. (University of Minnesota, Minneapolis, MN)
AFML-TR-69-12 (1970)

A fatigue, creep, and stress-rupture testing program was conducted on bar specimens of Rene 41 and Inconel X-750 and on sheet specimens of magnesium alloy HK31A-H24 and titanium alloys, Ti-4Al-3Mo-1V and Ti-6Al-4V. Cyclic stress condition tests were conducted at room temperature and at appropriate elevated temperatures under axial stress conditions and at various combinations of mean and alternating stresses. Notched as well as smooth specimens were tested.

This testing program was undertaken primarily for the purpose of obtaining fatigue and creep design data on these materials. The results, which were presented in the form of S-N diagrams, constant-life diagrams, and creep-strength diagrams, did show some scatter, as is usual. The curves were fitted to the experimental points by eye in an effort to produce a reasonable fit. It is important that users recognize that the curves shown are the best representation of the material properties that could be determined from the data obtained. Because of scatter, however, it should be realized that some points do fall below the curves. No statistical analyses were made, and therefore no confidence levels are shown in the diagrams.

The unusual behavior of Inconel X-750 in which the elevated temperature fatigue strength is higher than at room temperature is significant, and more work should be done to determine the cause. We speculated that metallurgical changes occur through the combination of cyclic stressing and elevated temperature. However, no direct evidence was obtained to support this hyopthesis. Future work should include metallographic studies of this material after various periods of cyclic stressing at selected temperatures.

Important References:

1. Blatherwick, A. A. and Cers, A. E., Fatigue, Creep and Stress Rupture Properties of Ti-13V-11Cr-3Al Titanium Alloy (B120-VCA), AFML-TR-66-293, (September 1966).

2. Blatherwick, A. A. and Cers, A. E., Fatigue, Creep and Stress Rupture Properties of Nicrotung, Super A-286 and Inconel 718, AFML-TR-65-329, (September 1965).

Key words: Creep properties; creep rupture strength; creep strength; creep strength diagrams; creep tests; cyclic loads; fatigue (materials); fatigue properties; fatigue tests; heat resistant alloys; high temperature environments; high temperature tests; mechanical properties; nickel alloys; S-N diagrams; stress rupture; tensile stress; titanium alloys.

COMPARISON OF EXPERIMENTAL AND THEORETICAL THERMAL FATIGUE LIVES FOR FIVE NICKEL-BASE ALLOYS

Spera, D. A. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

Fatigue at Elevated Temperatures, ASTM STP 520, 648-657 (August 1973)

Alloys investigated were Nimonic 90, IN-100, coated IN-100, B-1900, coated B-1900, MAR M200 and MAR M200DS (directionally solidified). Maximum temperatures ranged from 770°C to 1200°C. Specimen geometries included tapered disks, double-edge wedges, and cambered airfoils. The disks and wedges were heated and cooled in fluidized beds. The airfoil specimens were heated by a Mach 1 natural gas burner and rapid air-cooled, with and without spanwise loading. Life calculations included two distinct failure modes: conventional low-cycle fatigue and cyclic creep. Required material properties were limited to conventional thermal, tensile, and creep-rupture data. The complete life calculation system included the calculation of transient temperature distributions, thermal strains, stresses, creep damage, fatigue damage, and finally cycles to first crack. Calculated lives were within a factor of two for the 76 of the 86 data points analyzed. Cyclic creep accounted for 80 percent of all the calculated damage.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 57).

DEVELOPMENT STUDY OF COMPOSITIONS FOR ADVANCED WROUGHT NICKEL-BASE SUPERALLOYS

Kent, W. B. (Cyclops Corp., Bridgefield, PA)

NASA-CR-120934 (January 1972)

Using NASA 11B as a base composition, the effects of five key elements (carbon, tungsten, tantalum, aluminum, and hafnium) on resultant properties were investigated in an effort to optimize the composition and derive new wrought high temperature alloys with improved strength characteristics. A total of nineteen compositions were melted, extruded, and rolled to bar stock using

thermomechanical processing. Both full and partial solution heat treatments were developed for the compositions. Tensile properties from room temperature to 1800°F (982°C), stress and creep rupture properties to 1800°F (982°C), and thermal stability characteristics were evaluated. NASA 11B-7 exhibited the best response to the partial solution heat treatment for optimum properties up to 1200°F (649°C). Another promising composition tested for full solution applications at 1400°F (760°C) and above, is designated NASA 11B-11. An objective of the study was evaluation of the alloys for turbine engine applications. It was concluded that more work needs to be done. Supplementary note added by F. H. Hart, NASA Lewis Research Center.

Important References:

1. Collins, H. E., Development of High Temperature Nickel-Base Alloys for Jet Engine Turbine Bucket Applications, NASA-CR-72011 (June 1967).

2. Phase Occurrance from Compositions in Austenitic Superalloys, Trans. AIME 236, 519-527 (April 1966).

3. Kent, W. B., Wrought Nicke-Base Superalloys, NASA-CR-72687 (March 1970).

Key words: Creep rupture strength; ductility; fatigue (materials); fatigue properties; heat resistant alloys; heat treatment; high temperature tests; mechanical properties; nickel alloys; statistical analysis.

COMBINED LOW-CYCLE FATIGUE AND STRESS RELAXATION OF ALLOY 800 AND TYPE 304 STAINLESS STEEL AT ELEVATED TEMPERATURES

Jaske, C. E. Mindlin, H. and Perrin, J. S. (Battelle Columbus Labs, OH)

Fatigue at Elevated Temperatures, ASTM STP 520, 365-376 (August 1973)

A detailed analysis was made of data from low-cycle fatigue tests of solution-annealed, nickel-iron-chromium Alloy 800 at 538°C, 649°C, and 760°C of Type 304 austenitic stainless steel at 538°C and 649°C with holdtimes at maximum tensile strain. A single equation was found to approximate the cyclically stable stress relaxation curves for both alloys at these temperatures. This equation was then used in making a linear time fraction creep damage analysis of the stable stress relaxation curves, and a linear life fraction rule was used to compute fatigue damage. Creep-fatigue damage interaction was evaluated for both alloys using the results of these damage computations. Strain range was found to affect the damage interaction for Type 304 stainless steel but not for Alloy 800. With increasing holdtime, both creep and total damage increased for the Alloy 800 and decreased for the Type 304 stainless steel, and fatigue damage decreased for both alloys. A method was developed to relate length of holdtime and fatigue life to total strain range. This method provides a simple and reasonable way of predicting fatigue life when tensile holdtimes are present.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 142).

THE FATIGUE BEHAVIOR FOR FINE GRAINED TWO-PHASE ALLOYS
Hayden, H. W. and Floreen, S. (Martin Marietta Corp., Baltimore, MD; International Nickel Co., Inc., New York, NY)
Met. Trans. 4, 561-568 (February 1973)

The fatigue properties of a number of ultrafine grained two-phase alloys have been examined. Compositions and processing treatments were altered to produce volume fractions of the individual phases ranging from 0 to 100 percent along with changes in the grain sizes of the individual phases. In all two-phase alloys in this investigation, the second phase was distributed at grain boundaries rather than within the grains of the primary phase, the fatigue strengths of the two-phase microduplex alloys were generally higher than those of the corresponding single phase alloys. Tension-compression fatigue tests showed that a Coffin law type of fatigue relationship was obeyed in the low cycle fatigue tests. Fatigue crack growth rate studies in tension-tension on IN-744 sheet gave results very comparable to those reported for other steels. Fatigue cracks propagated through both phases without following any obvious crack paths and no indication of delamination or crack blunting was detected. The high cycle fatigue performance of microduplex alloys can be rationalized in terms of a critical crack opening displacement model for fatigue crack initiation.

Comment:

The microduplex structure with grain sizes down to one micron represents a significant approach to increases in the fatigue strength of nickel base superalloy compositions. This is an area which could use additional effort.

Important References:

1. Gibson, R. C., Hayden, H. W. and Brophy, J. H., Properties of Stainless Steels With a Microduplex Structure, Trans. ASM 61, 85-93 (1968).

2. Hayden, H. W. and Floreen, S., The Deformation and Fracture of Stainless Steels Having Microduplex Structures, ASM Trans. 61, 474-488 (1968).

3. Crooker, T. W. and Lange, E. A., How Yield Strength and Fracture Toughness Considerations Can Influence Fatigue Design Procedures for Structural Steels, Weld. Res. Suppl. 49, 488A (October 1970).

4. Frost, N. E., Pook, L. P. and Denton, K., A Fracture Mechanics Analysis of Fatigue Crack Growth Data for Various Materials, Eng. Fract. Mech. 3, 109-126 (August 1971).

5. Hayden, H. W. and Floreen, S., The Influence of Martensite and Ferrite on the Properties of Two-Phase Stainless Steels Having Microduplex Structures, Met. Trans. 1, 1955-1959 (1970).

6. Brown, B. F., The Application of Fracture Mechanics to Stress Corrosion Cracking, Metals Mater. 2, No. 12, 171-183 (1968).
Key words: Crack growth rate; crack initiation; crack propagation; fatigue (materials); fatigue life; heat resistant alloys, microstructures; steels.

THE EFFECT OF FREQUENCY UPON THE FATIGUE-CRACK GROWTH OF TYPE 304 STAINLESS STEEL AT 1000°F

James, L. A. (Westinghouse Electric Co., Richland, WA)
ASTM STP 513, 218-229 (September 1972)

The results of this study may be summarized as follows:

(1) The fatigue-crack growth behavior of solution-annealed Type 304 stainless steel at 1000°F appears to be frequency-dependent at some values of ΔK, and frequency-independent at others. The transition from independent to dependent behavior occurs at higher values of ΔK as the cyclic frequency is decreased.

(2) In the regime where the crack growth behavior is dependent upon frequency, decreasing the frequency results in a significant increase in the fatigue-crack growth rate, da/dN. If the crack extension is characterized on a time basis, da/dt, the above observation is reversed.

(3) The slope of the frequency-dependent portion of the da/dN versus ΔK curves is nearly constant for all frequencies. This allows the behavior to be characterized in terms of a power law of the form $da/dN = A(f)\,[\Delta K]^n$, where n is constant for all frequencies tested. It should be emphasized that this relationship is entirely empirical, and its extension to other material/environment combinations should be approached with caution.

(4) Based on very limited data, it appears that either the average, mean, or root-mean-square frequencies did a satisfactory job in correlating the test data for a condition of non-constant frequency. Additional work, however, is required to determine the most appropriate correlation parameter.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 130).

THE INTERACTION OF CREEP AND FATIGUE FOR A ROTOR STEEL
Leven, M. M. (Westinghouse Astronuclear Lab, Pittsburgh, PA)
Exp. Mech., 353-372 (September 1973)

Twenty tests were performed on a 1Cr-1Mo-1/4V rotor steel at 1000°F (538°C) to determine the interaction of creep and low-cycle fatigue. These tests involved five different types of strain-controlled cycling: creep at constant tensile stress; linearly varying strain at different frequencies; and hold periods at maximum compressive strain, maximum tensile strain, or both.

The experimental data were then used to characterize the interaction of creep and fatigue by the:

(1) Frequency-modified strain-range approach of Coffin;

(2) Total time to fracture versus the time of one cycle relation as proposed by Conway and Berling;

(3) Total time to fracture versus the number of cycles to fracture characterization of Ellis and Esztergar;

(4) Summation of damage fractions obtained from tests using interspersed creep and fatigue as proposed by the Metal Properties Council;

(5) Strain-range-partitioning method of Manson, Halford, and Hirschberg.

In order to properly assess the strain-range-partitioning approach, seven additional tests were performed at the NASA Lewis Research Center.

Visual, ultrasonic, and acoustic-emission methods of crack-initiation, determination were unsuccessful. An approximate indication of crack initiation was obtained by finding the cycle where the stress-cycle curve first deviated from a constant slope.

Predictive methods (based on monotonic tests) for determining the fatigue life in the creep range were examined and found deficient, though they may still be useful for preliminary comparison of materials and temperatures.

The extension of the frequency-modified strain-range approach to notched members was developed and the results of notched-bar tests were shown to corroborate this approach, when crack initiation for the plain and notched bars was compared.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 43).

COMBINED LOW-CYCLE FATIGUE AND STRESS RELAXATION OF ALLOY 800 AND TYPE 304 STAINLESS STEEL AT ELEVATED TEMPERATURES

Jaske, C. E., Mindlin, H. and Perrin, J. S. (Battelle Columbus Labs, OH)
Fatigue at Elevated Temperatures, ASTM STP 520, 365-376 (August 1973)

A detailed analysis was made of data from low-cycle fatigue tests of solution-annealed, nickel-iron-chromium Alloy 800 at 538°C, 649°C, and 760°C of Type 304 austenitic stainless steel at 538°C and 649°C with holdtimes at maximum tensile strain. A single equation was found to approximate the cyclically stable stress relaxation curves for both alloys at these temperatures. This equation was then used in making a linear time fraction creep damage analysis of the stable stress relaxation curves, and a linear life fraction rule was used to compute fatigue damage. Creep-fatigue damage interaction was evaluated for both alloys using the results of these damage computations. Strain range was found to affect the damage interaction of Type 304 stainless steel, but not for Alloy 800. With increasing holdtime, both creep and total damage increased for the Alloy 800 and decreased for the Type 304 stainless steel, and fatigue damage decreased for both alloys. A method was developed to relate length of holdtime and fatigue life to total strain range. This method provides a simple and reasonable way of predicting fatigue life when tensile holdtimes are present.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 42).

PROCEDURES FOR STRESS-CORROSION CRACKING CHARACTERIZATION AND INTERPRETATION TO FAILURE-SAFE DESIGN FOR HIGH-STRENGTH STEELS

Judy, Jr., R. W. and Goode, R. J. (Naval Research Lab, Washington, DC)
NRL Report 6988 (November 1969)

A preliminary analysis of the interpretability of fracture mechanics K_{ISCC} methods to failure-safe design for structures of high-strength steels subjected to salt water stress corrosion cracking is given. Pre-cracked cantilever bend data are used to determine K_{ISCC}. The ratio analysis diagram for steels is used. This provides a simple procedure for engineering interpretation of the fracture toughness characteristics of steel in terms of the expected critical flaw depths for fast fracture.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 170).

FATIGUE AND CORROSION-FATIGUE CRACK PROPAGATION IN INTERMEDIATE-STRENGTH ALUMINUM ALLOYS
Crooker, T. W. (Naval Research Lab., Washington, DC)
J. Eng. Mater. Technol., 150-156 (July 1973)

Fatigue crack propagation in a variety of intermediate-strength aluminum alloys under high-amplitude elastic loading is discussed. Alloys of the 2000, 5000, 6000, and 7000 series with yield strengths from 34 to 55 ksi were investigated using the crack-tip stress-intensity factor range (ΔK) as the primary variable in describing crack growth rates. The ΔK values studied varied from approximately 12 to 50 ksi in. $^{1/2}$. Tests were conducted in both ambient room air and saltwater environments. The results of this study provide a definitive materials characterization and are applicable as basic criteria for fatigue design.

The following conclusions have been reached from this investigation:

1. Log-log plots of fatigue crack growth rate (da/dN) versus stress-intensity factor range (ΔK) data for all of the alloys studied consist of two rectilinear curves meeting at a distinct point of slope transition. For most of the alloys, the point of slope transition agrees very accurately with predictions based on a crack-opening-displacement (COD) model for slope transition behavior.

2. A summary plot of da/dN versus ΔK for all of the alloys investigated shows that the lower branches of the respective curves all fall within a narrow scatterband with no apparent significant differences. However, above the region of slope transition, the upper branches of the curves are more widely separated with the higher-toughness alloys generally exhibiting the greatest crack propagation resistance.

3. Comparisons between the scatterband of da/dN versus ΔK for these aluminum alloys and similar scatterbands for steel and titanium alloys, also obtained under high amplitude cycling, reveal distinct crack propagation characteristics for each family of alloys. The differences in crack propagation behavior among the various families of alloys suggest that efforts to fit all data into a universal crack propagation law can only be accomplished on a very approximate basis in the high amplitude crack propagation regime.

4. Environmental effects of 3.5 percent NaCl saltwater on crack propagation were greatest in a 7000-series, stress-corrosion-cracking sensitive alloy. Environmental effects were modest or nil in the 2000, 5000, and 6000 series alloys examined.

Comment:

This paper presents data on a number of alloys showing the relationship between the fatigue crack growth rate and stress intensity factor range. This data will be useful as discussed in the paper only in terms of the detailed test conditions.

Important References:

1. Boettner, R. C., Laird, C. and McEvily, Jr., A. J., Crack Nucleation and Growth in High Strain-Low Cycle Fatigue, Trans. AIME 233, 379 (1965).

2. Clark, Jr., W. G., Fracture Mechanics and Nondestructive Testing of Brittle Materials, Eng. Ind. 94, No. 1, 291 (February 1972).

3. Judy, Jr., R. W., Goode, R. J. and Freed, C. N., Fracture Toughness Characterization Procedures and Interpretations to Fracture-Safe Design for Structural Aluminum Alloys, NRL Report 6871 (March 31, 1969).

4. Nordmark, G. E. and Kaufman, J. G., Fatigue-Crack Propagation Characteristics of Aluminum Alloys in Thick Sections, Eng. Fract. Mech. 4, No. 2, 193 (June 1972).

5. Feeney, J. A., McMillan, J. C. and Wei, R. P., Environmental Fatigue Crack Propagation of Aluminum Alloys at Low Stress Intensity Levels, Met. Trans. 1, 1741 (1970).

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7. Carman, C. M. and Katlin, J. M., Low Cycle Fatigue Crack Propagation Characteristics of High Strength Steels, J. Basic Eng. 88, No. 4, 792 (December 1966).

Key words: Aluminum alloys; corrosion; crack propagation; fatigue (materials); stress intensity factor.

AN EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF VACUUM ENVIRONMENT ON THE FATIGUE LIFE, FATIGUE-CRACK-GROWTH BEHAVIOR, AND FRACTURE TOUGHNESS OF 7075-T6 ALUMINUM ALLOY

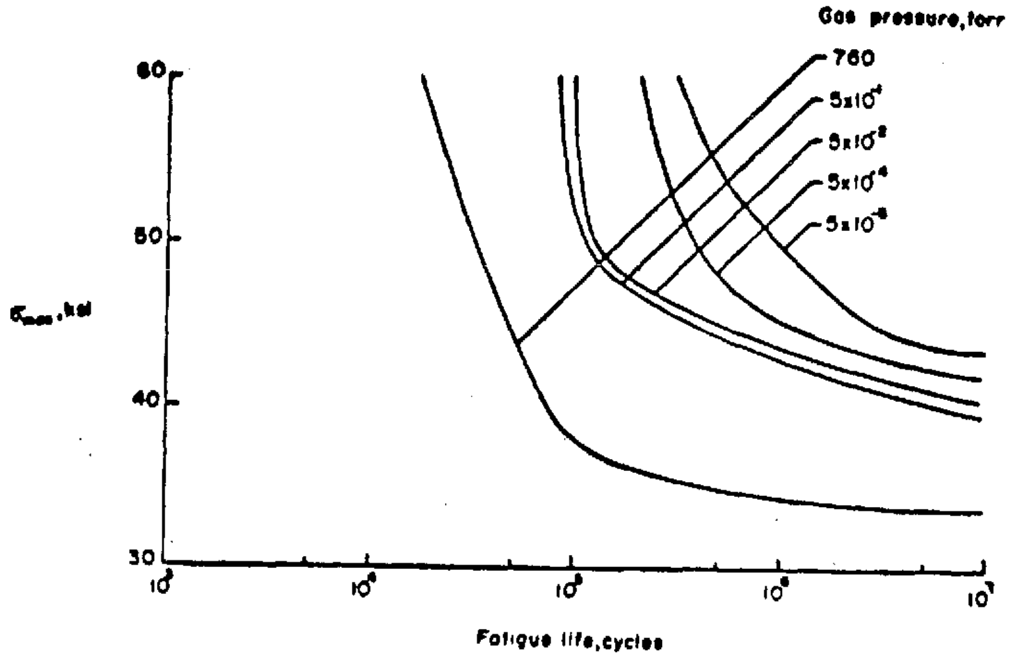
Hudson, C. M. (North Carolina State Univ, Raleigh NC)

PhD Thesis, Department of Materials Engineering (1972)

A series of axial-load fatigue-life, fatigue-crack growth, and fracture toughness tests were conducted on 0.090-inch thick specimens made of 7075-T6 aluminum alloy. The fatigue life and fatigue crack-propagation experiments were conducted at a stress ratio of 0.02. The maximum stresses in the fatigue-life experiments ranged from 33 to 60 ksi, and from 10 to 40 ksi in the fatigue, crack-growth experiments. Fatigue life experiments were conducted at gas pressures of 760, 5×10^{-1}, 5×10^{-2}, 5×10^{-4}, and 5×10^{-8} Torr. Fatigue-crack-growth and fracture toughness experiments were conducted at gas pressures of 760 and 5×10^{-8} Torr. Residual stress measurements were made on selected specimens to determine the effect of residual stresses on fatigue behavior. These measurements were made using x-ray diffraction techniques. Fracture surfaces of typical specimens were examined using scanning and transmission electron microscopes to study fracture modes in vacuum and air.

Comment:

This thesis presents some significant information relating to the effect of environment on fatigue life by showing the increase in life as a function of decreasing gas pressure as shown in the figure.



Combined S-N curves for 7075-T6 obtained at various gas pressures.

Important References:

1. Achter, M. R., Danek, Jr., G. J. and Smith, H. H., Effect on Fatigue of Gaseous Environments Under Varying Temperature and Pressure, Trans. Met. Soc. AIME, 227, No. 6, 1296-1301 (1963).

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3. Hudson, C. M. and Hardrath, H. F., Effects of Changing Stress Amplitude on the Rate of Fatigue-Crack Propagation in Two Aluminum Alloys, NASA TN-D-960 (1961).

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6. Bradshaw, F. J. and Wheeler, C., The Effect of Environment on Fatigue Crack Propagation, 1. Measurements on Al Alloy DTD 5070A, S.A.P., Pure Aluminum, and a Pure Al-Cu-Mg Alloy, RAE Tech. Report No. 65073 (1965).

7. Hoeppner, D. W. and Hyler, W. S., The Effect of Vacuum Out-Gassing Time on the Fatigue Behavior of Two Structural Aluminum Alloys, Mat. Res. Stand. 6, No. 12, 599-601 (1966).

8. Spitzig, W. A. and Wei, R. P., A Fractographic Investigation of the Effect of Environment on Fatigue-Crack Propagation in an Ultrahigh-Strength Steel, Trans. ASM 60, 279-288 (1967).

Key words: Aluminum alloys; environmental effects; fatigue (materials); fracture mechanics.

CREEP OF PRESSURE VESSELS

Penny, R. K. and Marriott, D. L. (Liverpool Univ, Liverpool, England)

ASTM, ASME, IME, Int. Conf. Creep and Fatigue in Elevated Temperature Environments, 204.1-204.9 Philadelphia, PA (23-28 September 1973) and Sheffield, England (1-5 April 1974).

A series of tests were made on model aluminum pressure vessels at 180°C. There were two objectives in this work: (1) to generate experimental data on creep of complex components; and (2) to assess the ability of some of the analytical tools at present available to designers for strain accumulation and rupture predictions. Three pressure vessels have been creep tested to rupture so far, two of slightly different configuration, under steady internal pressure, and a third under cyclic pressure conditions. A finite difference analysis has been used to predict deformations, and experimental results are also compared with the approximate reference stress techniques. Some attempt has been made to predict rupture life using both finite difference, and reference stress methods and these predictions have been compared with experiments.

Comment:

The experimental data show that a rupture life prediction based on steady state analysis is needlessly conservative. It was found necessary to include some form of damage criterion in order to obtain a reasonable estimate of creep life in this multiaxial load condition.

Important References:

1. Penny, R. K and Marriott, D. L., Design for Creep, McGraw Hill, London, England (1971).

2. Ponter, A. R. S. and Leckie, F. A., The Application of Energy Theorems to Bodies Which Creep in the Plastic Range, J. Appl. Mech. (September 1970).

3. Gill, S. S. (Ed.), The Stress Analysis of Pressure Vessels and Pressure Vessel Components, Pergamon Press, Oxford, England, (1970).

4. Kachanov, L. M., Rupture Time Under Creep Conditions, Contribution to Problems of Continuum Mechanics, in Honor of 70th Birthday of N. I. Muskhelishvili, Philadelphia, PA (1961).

Key words: Aluminum alloys; creep; creep rupture; cyclic loads; deformation; experimental data; high temperature; life predictions; low temperature; mechanical properties; strain accumulation.

FRACTURE AND FATIGUE-CRACK-PROPAGATION CHARACTERISTICS OF 1/4-INCH MILL ANNEALED Ti-6Al-4V TITANIUM ALLOY PLATE

Feddersen, C. E. and Hyler, W. S. (Battelle Columbus Labs, OH)

Battelle Report G-9706 (November 1971)

The fracture and fatigue-crack propagation behavior of central through-the-thickness cracks has been evaluated for one thickness of mill-annealed titanium alloy plate. The influence of crack aspect ratio on the fracture or residual strength of three panel widths has been determined. The fatigue-crack propagation rates for various maximum stresses, stress ratios, and panel widths have also been evaluated. It has been observed that elastic fractures in the presence of central through-cracks do not occur in panels of this material less than 18 inches wide. Uniform and regular fatigue-crack propagation behavior is noted in this material on the basis of a stress-intensity factor range, ΔK, analysis. A fatigue-crack propagation threshold is evident below 3 or 4 ksi-in.½. Power law modeling of rare data, crack life prediction, and interpretive discussions are also considered.

From the data the crack behavior of mill-annealed Ti-6Al-4V titanium alloy in 1/4-inch thickness appears to be consistent and predictable. The material is quite tough with no elastic fracture instabilities noted in panels less than 18 inches wide. However, slow stable tear (or stable crack extension) in the rising load test is noted at net section stresses above 40 ksi. The fatigue-crack propagation ratios, (2c)/n, are very consistent when evaluated on a ΔK basis. However, there is an additional distinct effect of stress ratio, R, over and above that reflected in ΔK.

A threshold stress-intensity factor range is evident and varies with stress ratio. The lowest ΔK level at which propagation was noted was about 3.5 ksi-in.½.

It is evident that the crack propagation models currently used need to be modified for threshold effect and for improved accumulation of stress ratio, R. This is a definite necessity in order to obtain a more reliable predictive tool for design purposes.

This experimental program has characterized this particular thickness of the subject titanium alloy quite well. A parallel, but more selective, program at other thicknesses is recommended.

A very critical issue, now that consistent FCP rates have been demonstrated is a study on environmental effects wherein significantly lower frequencies are applied for much longer time periods.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 73).

STRESS-CORROSION-CRACKING CHARACTERIZATION PROCEDURES AND INTERPRETATIONS TO FAILURE-SAFE USE OF TITANIUM ALLOYS

Judy, Jr., R. W. and Goode, R. J. (Naval Research Lab, Washington, DC)

J. Basic Eng. 91, 614-617 (December 1969).

Ratio analysis diagram (RAD) interpretive procedures have been evolved recently to provide generalized engineering solutions for fracture toughness assessments of structural titanium alloys. Failure-safe design also requires consideration of possible sub-critical crack propagation (slow fracture) due to stress-corrosion cracking (SCC). Procedures for incorporation of SCC characterizations into the RAD system have now been developed. These procedures serve the dual purpose of providing simplified interpretations of critical flaw size-stress instability conditions by consideration of resistance of the material size-stress instability conditions by consideration of resistance of the material to both fast fracture and SCC. The failure conditions are expressed in terms of K_I/σ_{YS}, ratios which provide an index of the general level of critical flaw sizes. The combination RAD also features limit lines that indicate: (a) the highest level of K_{ISCC}/σ_{YS} ratios for which accurate plane strain interpretation to flaw size-stress conditions for SCC can be made for 1-inch thick plate, and (b) the highest level of SCC resistance measured in extensive surveys of plate material of this thickness.

Important References:

1. Goode, R. J., Judy, Jr., R. W. and Huber, R. W., Procedures for Fracture-Safe Design for Structural Titanium Alloys, Welding Research Council Bulletin, No. 134 (October 1968).

2. Pellini, W. S., Advances in Fracture Toughness Characterization Procedures and in Quantitative Interpretations to Fracture Safe Design for Structural Steels, Weld. Res. Counc. Bull. No. 130 (May 1968).

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Key words: Critical flaw size; fracture analysis; stress corrosion cracking; stress intensity factors; titanium alloys; yield strength.

THE FATIGUE CHARACTERISTICS OF UNIDIRECTIONALLY SOLIDIFIED Al-Al_3Ni EUTECTIC ALLOY

Hoover, W. R. and Hertzberg, R. W. (Lehigh Univ, Bethlehem, PA)

Trans. Amer. Soc. Metals 61, 769-776 (1968)

Unidirectional solidification of the Al-Al_3Ni eutectic alloy produces an aligned microstructure consisting of discontinuous Al_3Ni whiskers in an Al matrix which behaves as a fiber-reinforced composite material. The fracture mechanism of this composite under cyclic loading is examined macroscopically, metallographically and fractographically. It is observed that at high stress amplitudes the fracture is controlled by the rupture of the Al_3Ni whiskers. At low stress amplitudes where the stress concentration at the crack tip is insufficient to cause whisker rupture, the fracture is controlled by the fatigue resistance of the matrix, the crystallographic orientation of the matrix and the strength of the Al_3Ni whisker-Al matrix interfacial bond. At these low stress amplitudes, the fatigue crack is found to be deflected by the Al_3Ni whiskers and is observed to propagate through the Al matrix parallel to the loading axis. Evidence is presented to show that the two phases of this composite material undergo unequal amounts of strain during cyclic loading.

Important References:

1. Lemkey, F. D., Hertzberg, R. W. and Ford, J. A., The Microstructure, Crystallography, and Mechanical Behavior of Unidirectionally Solidified Al-Al_3Ni Eucetic, Trans. AIME 233, 334 (1965).

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Key words: Cyclic loads; directional solidification eutectic alloys; fatigue (materials); fiber reinforced composites; fracture analysis; fracture mechanics; microstructures.

THE PREPARATION AND PROPERTIES OF CAST BORON-ALUMINUM COMPOSITES
Hill, R. J. and Stuhrke, W. F. (AVCO Corp. Lowell, MA; Air Force Materials Lab., Wright-Patterson AFB, OH)
Fiber Sci. Technol. 1, No. 1, 25-42 (January 1968).

A simulated pressure casting technique was used for producing high modulus and improved tensile strength reproducible boron-aluminum composite structures comprising both continuous and discontinuous fibers. The fibers used were both, uncoated and coated - some with nickel electroless plating and some with aluminum. The preheating was performed in argon as well as in air. The optimum conditions consist of vacuum infiltration with aluminum at temperatures between 720°C and 800°C for times of two to four minutes. Although voids may be present in the discontinuous case, these are entirely absent from specimens of continuous fibers prepared in the correct temperature range. It is shown that there is no significant difference in either microstructure or mechanical strength for specimens produced in either argon or air. There are large differences, however, between uncoated and nickel-coated fiber specimens. The uncoated fibers produce superior specimens in every respect. Both continuous and discontinuous aligned fiber specimens have been prepared by this method.

Comment:

This paper includes data on tests as a function of temperature. It is shown that the composite maintains its room temperature strength to within 50°C of the matrix melting point. This is a demonstration of the theoretical potential for continuous reinforced composites.

Key words: Environmental effects; fiber reinforced composites; mechanical properties; microstructures; tensile stress.

FATIGUE AND CREEP BEHAVIOR OF ALUMINUM AND TITANIUM MATRIX COMPOSITES
Shimmin, K. D. and Toth, I. J. (Air Force Materials Lab., Wright-Patterson AFB, OH)
Proc. Symp. on Failure Modes in Composites, AIME, New York, NY, 357-393 (1973).
357-393 (1973).

The fatigue and creep behavior of filamentary reinforced aluminum and titanium alloys are discussed in terms of matrix properties, filament properties residual stresses, filament content, temperature effects, specimen geometry, filament orientation, and loading mode. It is shown that the most important matrix properties that affect composite fatigue and creep strength are ductility and shear strength, respectively. The off-axis properties of both aluminum and titanium composites have significantly been improved as a result of using larger diameter filament having lesser splitting tendency.

Comment:

This experimental effort demonstrates the practical potential of metal-reinforeced ceramic composites, which are at present at a very early stage of development.

Important References:

1. Baskin, Y., Harada, Y., and Handwerk, J. H., Some Physical Properties of Thoria Reinforced by Metal Fibers, J. Amer. Ceram. Soc. 43, No. 9 (1969).

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Key Words: Fiber-reinforced composites; high temperature environments; life prediction; mechanical properties; oxidation resistance; protective coatings; thermal fatigue; thermal stresses.

Comment:

This paper demonstrates the important factors in fatigue and creep behavior of metal matrix composites. It provides the basic information necessary for the further optimization of these materials particularly for aircraft turbine engine compressor section applications.

Important References:

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2. Toth, I. J. and Shimmin, K. D., Fatigue and Fracture of Metal Matrix Composites, AFFDL-TR-70-144, 343-376 (September 1970).

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6. Chen, P. E. and Lin, J. M., Transverse Properties of Fibrous Composites, Mat. Res. Stand. 9, No. 7, 29-33 (August 1969).

Key words: Aluminum alloys; creep; fatigue (materials); fiber-reinforced composites; fracture analysis; test specimen design; titanium alloys.

METAL-REINFORCED CERAMIC COMPOSITES FOR TURBINE VANES
Bortz, S. A. (ITT Research Institute, Chicago, IL)
ASME Paper 72-GT-51 (1972)

Experiments have been performed which indicate the potential of metal-fiber reinforced-ceramic matrix composites for use as a high temperature structural matrix. The results of this work reveal that reinforced ceramics obey composite theory, and that after cracks occur in the matrix, a pseudo-ductility can be introduced into the composite. This toughness can be predicted from equations of work required to pull the fibers through the matrix. The relationship between strength, toughness, and crack depths, are dependent on the interfacial bond between the fibers and matrix as well as fiber diameter and length. Based on the results of these experiments, multicomponent materials with superior resistance to failure from oxidation, thermal shock, and high mechanical stresses in air above 2400°F can be postulated. These materials have potential for use as gas turbine engine vanes.

VII - Applications

APPLICATION OF THE RESIDUAL STRENGTH CONCEPT TO FAILURE DESIGN CRITERIA
Trent, D. J. and Bouton, I. (North American Rockwell Corp., Downey, CA)
AFFDL-TR-70-144, 117-121 (September 1970)

The residual strength concept is presented in this paper as a new approach to the fatigue design problem. The ideas and examples developed to date indicate that the approach has merit because it leads to fatigue criteria that are more closely related to the load carrying ability of the structure than are conventional criteria. Much work remains to be done before such criteria can be developed and the advantages of the residual strength concept exploited. The objective of this paper has been to stimulate thinking in this concept, which could be the key to improved fatigue criteria.

Comment:

This thought provoking paper approaches fatigue life from a slightly different angle. Emphasizing the fact, often overlooked, that failure occurs by the application of a load in excess of the materials capability at that time and not because of the accumulation of a specific number of cycles, they postulate a concept of residual strength. This is similar to the cumulative damage concepts, but recognizes the nonlinearity of the actual material. It is employed in actual practice at this time by the Air Force in the form of load and flight regime limitations on aging aircraft, which lengthen the service life of the aircraft by permitting the accumulation of additional fatigue damage before failure.

Important References:

1. Bouton, I., Trent, D. J., Fisk, M. and McHugh, A. H., Quantitative Structural Design Criteria by Statistical Methods, AFFDL-TR-67-107, Vol. I, II, III, (1968).

2. Bouton, I. and Trent, D. J., Test Factor of Safety: A New Means for Proving Compliance with Structural Reliability Requirements, Presented at the 8th AIAA Structures, Structural Dynamics, and Materials Conference, Palm Springs, CA (March 1967).

3. Bouton, I. and Trent, D. J., The Unreliability of Structural Reliability, ASM-TR-P9-12.4, Presented at the ASM Materials Engineering Congress, Philadelphia, PA (October 1969).

4. Freudenthal, A. M., Life Estimate of Fatigue Sensitive Structures, AFML-TDR-64-300 (1964).

Key words: Design criteria; failures (materials); fatigue (materials); fatigue tests; residual strength; structural reliability.

PROCEDURES FOR STRESS-CORROSION CRACKING CHARACTERIZATION AND INTERPRETATION TO FAILURE-SAFE DESIGN FOR HIGH-STRENGTH STEELS
Judy, Jr., R. W. and Goode, R. J. (Naval Research Lab, Washington, DC)
NRL Report 6988 (November 1969)

A preliminary analysis of the interpretability of fracture mechanics K_{ISCC} methods to failure-safe design for structures of high-strength steels subjected to salt water stress corrosion cracking is given. Pre-cracked cantilever bend data are used to determine K_{ISCC}. The ratio analysis diagram for steels is used. This provides a simple procedure for engineering interpretation of the fracture toughness characteristics of steel in terms of the expected critical flaw depths for fast fracture.

Important References:

1. Judy, Jr., R. W. and Goode, R. J., Stress-Corrosion Cracking Characteristics of Alloys of Titanium in Salt Water, NRL Report 6564 (21 July 1967).

2. Brown, B. F., A New Stress-Corrosion Cracking Test for High-Strength Alloys, Mater. Res. Stand. 6, No. 3, 129-133 (1966).

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4. ASTM, Proposed Method of Test for Plane-Strain Fracture Toughness of Metallic Materials, ASTM Standards, Part 31, 1099-1114 (May 1969).

5. Goode, R. J., Judy, Jr., R. W. and Huber, R. W., Procedures for Fracture Toughness Characterization and Interpretations to Failure-Safe Design for Structural Aluminum Alloys, Weld. Res. Council Bulletin 140 (April 1969).

Key Words: Analysis methods; critical flaw size; failures (materials); fracture mechanics; high strength alloys; plane strain; plane stress; stress corrosion cracking; stress intensity factor.

FATIGUE DAMAGE ACCUMULATION AND TESTING FOR PERFORMANCE EVALUATION
Freudenthal, A. M. (George Washington Univ. Washington, DC)
AD-884978, AFML-TR-71-50

The effects of mean stress and of stress amplitude on the various stages of the fatigue process is discussed in light of recent research on fatigue mechanisms with the purpose of assessing the relevance of fatigue testing processes under constant and under random loading as well as of the application of linear fracture mechanics in the prediction of the fatigue life of airframes. It is concluded that fatigue tests based on a mission-determined representative flight-by-flight loading spectrum will produce the closest approximation of service conditions and should be used both for life prediction of structures and for materials evaluation for fatigue performance.

Comment:

This paper discusses the philosophy of fatigue and fatigue testing and comes to the not unsurprising conclusion that the closer the test fatigue spectrum simulates the actual service experience the more accurate will be the fatigue life prediction.

Important References:

1. Wood, W. A., Experimental Approach to Basic Study of Fatigue, Institute Study of Fatigue and Reliability, Columbia University, Report No. 24 (1965).

2. Schijve, J., Analysis of Random Load Time Histories, in Fatigue of Aircraft Structures, W. Barris Ed., MacMillan Co., New York, NY (1963).

3. Branger, J., Life Estimation and Prediction of Fighter Aircraft, Proc. Int. Conf. on Structural Safety and Reliability, Washington 1969, Pergamon Press (1971).

Key words: Cumulative damage; fatigue (materials); fatigue life; structural reliability; testing methods.

STRESS-CORROSION-CRACKING CHARACTERIZATION PROCEDURES AND INTERPRETATIONS TO FAILURE-SAFE USE OF TITANIUM ALLOYS

Judy, Jr., R. W. and Goode, R. J. (Naval Research Lab., Washington, DC)

J. Basic Eng. 91, 614-617 (December 1969).

Ratio analysis diagram (RAD) interpretive procedures have been evolved recently to provide generalized engineering solutions for fracture toughness assessments of structural titanium alloys. Failure safe design also requires consideration of possible sub-critical crack propagation (slow fracture) due to stress-corrosion cracking (SCC). Procedures for incorporation of SCC characterizations into the RAD system have now been developed. These procedures serve the dual purpose of providing simplified interpretations of critical flaw size-stress instability conditions by consideration of resistance of the material to both fast fracture and SCC. The failure conditions are expressed in terms of K_I/σ_{YS}, ratios which provide an index of the general level of critical flaw sizes. The combination RAD also features limit lines that indicate: (a) the highest level of K_{ISCC}/σ_{YS} ratios for which accurate plane strain interpretation to flaw size-stress conditions for SCC can be made for 1-inch thick plate, and (b) the highest level of SCC resistance measured in extensive surveys of plate material of this thickness.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS, AND A DUPLICATE ABSTRACT, SEE PAGE 162).

AVOIDANCE, CONTROL, AND REPAIR OF FATIGUE DAMAGE

Manson, S. S. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

Metal Fatigue Damage - Mechanism, Detection, Avoidance, and Repair, ASTM STP 495, 254-346 (1971)

A number of approaches are outlined for improving the fatigue life of materials. The principal aspects that must be considered involve: (1) proper choice of materials or material-combinations that give the best possible fatigue resistance; (2) avoidance of strain concentrations in design, fabrication, and service; (3) provision for surface protection against inadequate design, rough handling, and pernicious environments; (4) introduction of beneficial residual compressive stresses by various means taking into account factors such as design, fabrication, and usage requirements that have a bearing on the ability of the material to retain these stresses during service; (5) property conditioning and restoration such as reheat treatment, surface husking and any other procedure which can restore fatigue resistance once damage has been incurred; and (6) fail-safe design approach together with the concept of continuous surveillance. A few potentially rewarding areas for future research are discussed. These include: further development of controlled solidification techniques; thermo-mechanical processing as a means of improving fatigue resistance; improving the compatibility of coatings and substrate and in particular metalliding. In addition, sophisticated application of fracture mechanics as an analytical tool to establish limits of permissible crack growth promises to augment the practicality of the fail-safe design philosophy. It is shown that the range of fatigue life involved in the application is important, what is good for low-cycle fatigue life range may not be good for the high-cycle-fatigue-life range, and vise versa. In all cases it is important to take into consideration the type of loading, the part geometry, the basic behavior of the material, environmental effects, reliability requirements, and a host of other factors that govern fatigue life.

Important References:

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3. Waters, W. J. and Freche, J. C., A Nickel Base Alloy, WAZ-20, with Improved Strength in the 2000°F to 2200°F Range, NASA-TN-D-5352 (1969).

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5. Manson, S. S. and Ensign, C. R., Discussion of Cumulative Damage Analysis in Structural Fatigue, ASTM STP 462, 69-72 (1970).

6. Sandor, B. I., Metal Fatigue with Elevated Temperature Rest Periods, ASTM STP 467, 254-275 (1970).

Key words: Creep; design; fatigue (materials); fatigue life; fatigue tests; heat treatment; high cycle fatigue; low cycle fatigue; materials selection; metallic materials; microstructures; residual stress; stress concentration; surface properties; thermal fatigue.

AN APPLICATION OF FRACTURE CONCEPTS TO THE PREDICTION OF CRITICAL LENGTH OF FATIGUE CRACKS

Davis, S. O. (Air Force Materials Lab., Wright-Patterson AFB, OH)
AFML-TR-70-202, Parts I, II, III, IV and V (1971).

This five part report is divided as follows:

Part 1: A Review of Pertinent Aspects of Fracture (Development of Relevant Concepts of Linear Elastic Fracture Mechanics)

Part 2: A Review of Pertinent Aspects of Fracture (Theoretical and Analytical Aspects of Fatigue of Metals)

Part 3: A Unified Theory for Fracture of Metals and Alloys

Part 4: Fracture Mechanics Analyses for Prediction of Critical Lengths and Velocities of Fatigue Cracks in 7075-T7351 Aluminum Alloy

Part 5: Experimental Determination of Fracture Toughness and Critical Crack Length of 7075-T7351 Aluminum Alloy Plates.

The purpose of this report is to synthesize technological concepts of fracture by making a historical review of the literature from 1913 up to the present time (1970). The pertinent aspects of fracture and the development of relevant concepts of linear elastic fracture mechanics derivatives were delineated and summarized for the prediction of the critical length of fatigue cracks. There is no available theory for correlating the many variables affecting fatigue failure and for successfully predicting failure. The application of linear elastic fracture mechanics and the thermodynamics of fracture to the crack propagation facet of fatigue is proposed as an approach to the prediction of critical lengths of stable fatigue cracking and unstable fracturing before failure. Thermodynamic energy approach is used to develop a unified theory of fracture relative to mechanical response of metals and alloys as a function of the atomic and metallurgical structures and the phenomenological aggregate levels collectively. The Irwin fracture criteria and Boyle mechanical compliance analysis were used to predict critical crack lengths of stable fatigue cracks in 7075-T7351 aluminum plates. The Boyd hypothesis was also used to predict the velocity of unstable cracks in these plates. The technological significance of fracture mechanics in practice was validated with a 96 percent accuracy by deducing the operational stress and calculating the critical crack length based upon a known value of K_{IC} and ω. This validated the practicability of the fracture mechanics approach in predicting the critical crack length stress for a given crack length and that failure will occur after a crack reaches a specified length and the stress reaches a critical magnitude.

Comment:

The author fails in his attempt to "synthesize technological concepts of fracture", however an extensive literature survey including a bibliography of 186 entries is valuable. The experimental data and correlation with K_{IC} information is not unexpected but is an addition to the literature.

Important References:

1. Spretank, J. W., A Summary of the Theory of Fracture in Metals, DMIC Report 157 (August 1961).

2. Manson, S. S., Fatigue, A Complex Subject - Some Simple Approximations, Exp. Mech. 5, No. 7, 193-226 (July 1965).

Key words: Aluminum alloys; bibliographies; crack propagation; critical flaw size; fatigue (materials); fracture mechanics; life prediction; theories.

INFLUENCE OF HEAT ON CRACK PROPAGATION AND RESIDUAL STRENGTH AND ITS RELATION TO THE SUPERSONIC AIRCRAFT FATIGUE PROBLEM

Maxwell, R. D. J., Kirby, W. T. and Heath-Smith, J. R. (Royal Aircraft Establishment, Farnborough, England)

ASTM, ASME, IME, Int. Conf. Creep and Fatigue in Elevated Temperature Applications, 231.1-231.9 Philadelphia, PA (23-28 September 1973) and Sheffield, England (1-5 April 1974).

The factors affecting crack propagation and residual strength of aluminum alloys as used in aircraft structures are examined and suggestions are made as to how these might be modified by heating in supersonic aircraft. Available experimental data suggests that crack propagation rates will tend to be reduced slightly as a result of exposures t- temperatures up to 150°C for times appropriate to aircraft usage. The effect of exposure to higher temperatures follows no simple pattern on the present evidence, crack rates tend to be reduced by tensile creep at temperatures up to 190°C although at this temperature there are indications that creep damage contributes to the crack propagation. There is no evidence within the range of conditions covered of appreciable changes in residual static strength of structures subjected to cold tests after heat or creep, but residual strengths do seem to improve if the static tests are at elevated temperatures up to 150°C.

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4. Kiddle, F. E., The Influence of a Single Application of Heat on Fatigue Crack Propagation on DTD 5070A (RR58) Alumunum Alloy Sheet, RAE-TR-72108 (1972).

5. Raju, K. N., Effects of Overaging on Fatigue Crack Growth in Commercial Al-Sn-Mg and Al-Cu-Mg Alloys at Room Temperature, Int. J. Fract. Mech. 7, 491-495 (1971).

Key words: Aircraft structures; crack growth rate; crack initiation; crack propagation; cracks; critical flaw size; failures (materials); fatigue (materials); fatigue life; load cycles; residual strength; structural failure; temperature effects; thermal stresses.

ENGINEERING SIGNIFICANCE OF STATISTICAL AND TEMPERATURE-INDUCED FRACTURE MECHANICS TOUGHNESS VARIATIONS ON FRACTURE-SAFE ASSURANCE

Loss, F. J. (Naval Research Lab, Washington, DC)

J. Eng. Ind., 137-144 (February 1973)

An appraisal is made of linear elastic fracture mechanics (LEFM) as a method of fracture-safe assurance for carbon and low-alloy steels. The theoretical advantage of an exact flaw size-stress level relationship offered by LEFM is contrasted with the limitations posed in actual application. These limitations relate to statistical variations in K_{IC} and K_{ID} data. The variations considered here are (a) data scatter at a given temperature, and (b) toughness variations between different heats of a given alloy. In an engineering context, LEFM is considered applicable only in the temperature region representing the initial development of the brittle-ductile transition that characterizes low-alloy steels. In this region statistical variations in the data suggest that critical flaw sizes could be significantly smaller than the values calculated on the basis of limited experimental data.

The prime objective in determining fracture toughness is for use in evolving a fracture control plan that assures structural integrity under a variety of environmental and loading conditions. Often the exact flaw size is unknown, particularly if the structure has not yet been built. Since the toughness increases sharply in the transition region, a practical solution is to take advantage of this behavior and choose a minimum operation temperature that assures a high fracture toughness such that postulated flaws cannot propagate in an unstable manner.

The objective of being able to define the temperature range and statistical distribution of K_{ID} curves is met equally by the use of Dynamic Tear (DT) and K_{ID} tests. The DT test, as contrasted with LEFM methods, is shown to be an effective engineering tool with which to determine the Fracture Transition Elastic (FTE) temperature; above this temperature, plane strain constraint is lost for the given thickness, and flaws cannot propagate at stress levels less than yield. The determination of a minimum structural operating temperature based on dynamic LEFM values, when modified by conservatisms necessitated by statistical variations in the data and inaccuracies in temperature measurement, is shown to be essentially equivalent to the FTE temperature.

Comment:

This paper presents a detailed analysis of the application of linear elastic fracture mechanics to structural steels, based on experimental data. The limitations of this approach due to the inherent ductility and ductile brittle transition are well characterized. In addition the more discriminatory nature of the dynamic toughness test for these alloys is shown.

Important References:

1. Loss, F. J. and Pellini, W. S., Coupling of Fracture Mechanics and Transition Temperature Approaches to Fracture-Safe Design, Practical Fracture Mechanics for Structural Steels, Chapman and Hall, London, England (1969); also NRL Report 6913 (April 14, 1969).

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4. Loss, F. J., Effect of Mechanical Constraint on the Fracture Characteristics of Thick-Section Steel, Nucl. Eng. and Design, 7, No. 1, 16-31 (August 1971).

Key words: Fracture mechanics; plane strain; steels; stress intensity factor; structural safety.

STRUCTURAL INTEGRITY IN AIRCRAFT

Hardrath, H. F. (National Aeronautics and Space Administration, Langley Research Center, Langley Station, VA)

J. Test. Eval. 1, No. 1, 3-12 (January 1973)

The current design philosophies for achieving long, efficient, and reliable service in aircraft structures are reviewed. The strengths and weaknesses of these design philosophies and their demonstrated records of success are discussed. The state of the art has not been developed to the point where designing can be done without major test inspection and maintenance programs.

A broad program of research is proposed through which a viable computerized design scheme will be provided during the next decade. The program will correlate existing knowledge on fatigue and fracture behavior, identify gaps in this knowledge, and guide specific research to upgrade design capabilities. An early application of the scheme leads to an objective choice of materials to provide maximum reliability between inspections. An analytical tool has been developed that assesses the resistance of a structural configuration to fatigue and static crack propagation.

Comment:

The author in this Gillett Memorial Lecture has reviewed the state of the art of fatigue processes in terms of design and design philosophies. Safe life design and damge tolerant design are discussed in terms of both current programs and a proposed integrated program of research. He shows how the technology has been integrated and employed in several preliminary applications. The effort places into applications perspective much of the present fatigue and crack growth technology and illuminates the planned directions of future work.

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2. Snider, H. L., Reeder, F. L. and Dirkin, W., Residual Strength and Crack Propagation Tests on C-130 Airplane Center Wings with Service-Imposed Fatigue Damage, NASA-CR-2075 (July 1972).

3. Poe, Jr., C. C. and Leybold, H. A., Some Factors that Affect the Inspection of Aircraft for Fatigue Damage, NASA SP 270 1, 391-401 (1971).

Key words: Aircraft structures; cumulative damage; design; fatigue (materials); fractures (materials); mechanical properties; metallic materials; NDE; structural reliability.

CONSIDERATIONS OF CREEP-FATIGUE INTERACTION IN DESIGN ANALYSIS
Ellis, J. R. and Esztergar, E. P. (Gulf General Atomic, San Diego, CA)
Design for Elevated Temperature Environments, ASME, New York, NY, 29-43 (1971)

Recent investigations into the effects of strain rate and hold-periods on the high-temperature fatigue properties of engineering materials are reviewed. A new method for analyzing data generated in these investigations is presented based on diagrams in which time-to-failure (T) is plotted against cycles-to-failure (N). These T-N diagrams are used to isolate the effects of time on fatigue behavior. It is demonstrated that T-N diagrams can also be used to predict rate and hold-period effects outside the range practicable for testing. A method of high temperature design analysis is described based on T-N diagrams and on a form of Miners law modified to account for creep-fatigue interaction. An analysis performed for sample load histories illustrates that this method involves simple procedures similar to those currently used in low-temperature design analysis.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 40).

DESIGN CONSIDERATIONS FOR LIFE AT ELEVATED TEMPERATURES
Manson, S. S. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)
Proc. Int. Conf. Creep, 1963-64 178, Part 3A, London, England, (October 1963)

This paper examines the analysis methods for gas turbine engine structures subjected to (a) complex loadings and stress distribution, (b) suitable methods for estimating long-time properties from data obtained at shorter times, and (c) the relation between analysis and laboratory or service performance. Both rupture and creep are examined for steel and niobium alloys at temperatures upwards of 1350°F. Reasonably good correlation results have been obtained where experimental studies have been undertaken to verify existing creep and plasticity theory.

Important References:

1. Orr, R. L., Sherby, O. D. and Dorn, J. E., Correlations of Rupture Data for Metals at Elevated Temperatures, Trans. Amer. Soc. Metals 46, 113 (1954).

2. Clauss, F. J., An Examination of High-Temperature Stress-Rupture Correlating Parameters, Proc. ASTM 60, 905 (1960).

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Key words: Creep; fatigue (materials); fatigue tests; heat resistant alloys; heat treatment; high temperature; life prediction; mechanical properties; plastic properties; plastic strain; strain; stress; stress analysis; stress corrosion; thermal fatigue; turbine blades.

HOT CORROSION OF GAS TURBINE ALLOYS
Bergman, P. A. (General Electric Co., Lynn, MS)
Corrosion 23, No. 3, 72-81 (March 1967)

Types of hot corrosion encountered in aircraft gas turbines operating in marine environments were reproduced in laboratory tests. Nickel and cobalt-base alloys were tested in the products of combustion of JP-5 and 0, 2 and 200 PPM sea salt between 1600°F and 2000°F. Higher chromium alloys were generally (but not always) more resistant to hot corrosion. Attack was caused by sodium sulfate, corrosion occurring only in the temperature range in which sodium sulfate was deposited in a molten sate. Microstructural changes were studied by metallographic techniques and chemical compositional changes and sulfide were identified by electron microprobe analyses. The nature of attack is discussed and some concepts of the hot corrosion mechanism postulated. Apparently, depletion of chromium in surface zones through the formation of oxides and sulfides reduce the corrosion resistance of depleted zones, thereby promoting severe hot corrosion.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 118).

METAL REINFORCED CERAMIC COMPOSITES FOR TURBINE VANES
Bortz, S. A. (ITT Research Institute, Chicago, IL)
ASME Paper 72-GT-51 (March 1972)

Experiments have been performed which indicate the potential of metal-fiber reinforced-ceramic matrix composites for use as a high temperature structural matrix. The results of this work reveal that reinforced ceramics obey composite theory, and that after cracks occur in the matrix, a pseudo-ductility can be introduced into the composite. This toughness can be predicted from equations of work required to pull the fibers through the matrix. The relationship between strength, toughness, and crack depths, are dependent on the interfacial bond between the fibers and matrix as well as fiber diameter and length. Based on the results of these experiments, multicomponent materials with superior resistance to failure from oxidation, thermal shock, and high mechanical stresses in air above 2400°F can be postulated. These materials have potential for use as gas turbine engine vanes.

Comment:

This experimental effort demonstrates the practical potential of metal-reinforced ceramic composites, which are at present at a very early stage of development.

Important References:

1. Baskin, Y., Harada, Y. and Handwerk, J. H., Some Physical Properties of Thoria Reinforced by Metal Fibers, J. Amer. Ceramic Soc. 43, No. 9 (1969).

2. Lockhart, R. J., Composite Turbine Engine Components, Final Report, IITRI Project G8027, Ford Motor Co. (April 1968).

3. Holliday, L., Composite Materials, Elsevier Publ. Co., New York, NY, 91-126 (1966).

Key words: Fiber-reinforced composites; high temperature environments; life prediction; mechanical properties; oxidation resistance; oxidation resistant coatings; refractory materials; thermal fatigue; thermal stresses.

DEVELOPMENT OF ALLOY FOR CAST AIR-COOLED TURBINE BLADES
Collins, H. E. and Graham, L. D. (TRW, Inc., Cleveland, OH)
AFML-TR-72-128 (January 1972)

The objective of this program was to develop an alloy for cast air cooled turbine blades, specifically the target goals for the alloy were, intermediate temperature tensile ductility in cast thin sections equivalent to that of high strength superalloys in thick sections, creep-rupture life of 100 hours at 982°C/1400 KG/SQ CM, oxidation and corrosion resistance at 982°C equivalent to that of U-700 at 890°C. Alloy TRW-NASA VIA was selected as the basic composition. Alloys IIIH and IIIK satisfied the stress-rupture life and corrosion resistance target goals, but they fell short of the tensile ductility of the thick section value of TRW-NASA VIA. Corrosion resistance was good for both alloys. Further alloy development work is suggested.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 140).

NASA PROGRAMS FOR DEVELOPMENT OF HIGH-TEMPERATURE ALLOYS FOR ADVANCED ENGINES
Freche, J. C. and Hall, R. W. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)
J. Aircraft 6, No. 5, 424-431 (September-October 1969)

An intensive research effort is underway at the NASA Lewis Research Center to provide improved materials for the hot components of advanced aircraft gas turbine engines. Research is being conducted both in-house and under NASA sponsorship to develop advanced materials for such applications as stator vanes, turbine buckets and disks, combustion chamber liners, and the latter compressor stages. Major areas of work deal with the development of nickel and cobalt base alloys, chromium base alloys dispersion strengthened materials, composite materials, and protective coatings. Progress in NASA programs dealing with all these areas is described. Of most immediate importance is the development of an advanced cast nickel base alloy, NASA-TRW-VI-A. This alloy shows approximately a 50°F (28°C) improvement in use temperature over the strongest superalloys currently in use. Even larger improvements over the strengths of currently used superalloys have been achieved in chromium alloys and metal matrix composite materials. However, many problems remain to be solved before the opportunities indicated by these later developments can be utilized in aircraft engines. Foremost among the needs at this time is that for improved oxidation, nitridation, and erosion resistant coatings to permit use of these stronger materials at temperatures consistent with their strength potential.

Important References:

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2. Freche, J. C., Progress in Superalloys, NASA-TN-D-2495 (1964).

3. Waters, W. J. and Freche, J. C., Investigation of Columbium-Modified NASA TAZ-8 Superalloy, NASA-TN-D-3597 (1966).

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5. Collins, H. E., Development of High Temperature Nickel-Base Alloys for Jet Engine Turbine Bucket Applications, NASA-CR-54517 (1967).

6. Sandrock, G. D., Ashbrook, R. L. and Freche, J. C., Effect of Variations in Silicon and Iron Content on Embrittlement of a Cobalt-Base Alloy (L-605), NASA-TN-D-2989.

7. Sandrock, G. D. and Leonard, L., Cold Reduction as a Means of Reducing Embrittlement of a Cobalt-Base Alloy (L-605), NASA-TN-D-3528 (1966).

Key words: Cobalt alloys; creep; creep tests; directional solidification; environmental effects; gas turbine engines; heat resistant alloys; high temperature environments; nickel alloys; protective coatings; stress rupture.

"BLACK PLAGUE" CORROSION OF AIRCRAFT TURBINE BLADES
Belcher, P. R., Bird, R. J. and Wilson, R. W. (Shell Research Ltd., Chester, England) Hot Corrosion Problems Associated with Gas Turbines, ASTM STP 421, 123-145 (1967).

"Black Plague" is the name given to a particular type of high temperature corrosion encountered on certain nickel-rich alloys used for turbine blades. Meta-lurgical examination of corroded blades shows that black plague corrosion has certain distinctive characteristics and that it is not a special form of internal oxidation ("green rot") or sulfide attack. Rig tests were carried out in which the combustion products from artifically contaminated fuels were passed over new and used blades at 850°C to 950°C. The results showed that contamination with tetraethyl-lead, chlorine, sulfur, or residual fuel does not cause accelerated corrosion. However, when very dilute salt solution was introduced in minute quantities, black plague was reproduced. In all tests, used blades corroded more than new blades, and it was shown that the prolonged preheating of new blades in air at elevated temperatures renders them more susceptible to corrosion. Corroded blades from test rigs and from service have been examined by metallographic, x-ray, and electron probe techniques. From these investigations it appears that black plague should be regarded as an oxidation phenomenon.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 117).

LIFE PREDICTION OF TURBINE COMPONENTS: ON-GOING STUDIES AT THE NASA LEWIS RESEARCH CENTER

Spera, D. A. and Grisaffe, S. J. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

NASA TM-X-2664 (1973)

This report presents an overview of the many studies of the NASA Lewis Research Center which together form the turbine component life-prediction program. This program has three phases: (1) development of life prediction methods for each of the major potential failure modes through a wide range of materials studies, (2) evaluation and improvement of these methods through a variety of burner rig studies on simulated components, and (3) application of a unified life-prediction method to prototype turbine components in research engines and advanced rigs.

In different temperature ranges, different properties become dominant in determining engine component life. The resistance of materials to fatigue, creep, and oxidation are being determined through closely controlled laboratory tests. In addition to conventional testing machines, specialized equipment has been developed to obtain material properties under simulated engine environments. For example, automatic cycling furnaces are used to determine changes in weight, surface chemistry, microstructure, and oxide scale. Fluidized beds are used to study thermal-fatigue cracking in various alloys and coatings and to evaluate fatigue-life theories.

Because the engine environment is much more aggressive than that in furnaces or fluidized beds, it can cause important changes in material behavior. Tests in high-velocity burner rigs have shown drastic increases in weight loss, consumption of coatings, and creep rates. Large decreases have been found in rupture and fatigue lives. Thus, rig and furnace test data must be integrated before the lives of engine components can be predicted.

Computer codes are now being developed that consider fatigue, creep, and oxidation life prediction in a unified manner. The first tow of these failure modes are now included in a computer code called THERMF 1. With this code, thermal-fatigue life can be calculated for known temperature and deformation cycles using conventional mechanical properties. THERMF 1 has been verified with a variety of laboratory and rig tests. Studies are in progress to extend this code to include failure by coating consumption during long hold times at elevated temperature.

A bibliography of Lewis publications in the fields of fatigue, oxidation and coatings, and turbine engine alloys is included in this report.

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1. Livingood, J. N. B., Ellerbrock, H. H., and Kaufman, A., 1971 NASA Turbine Cooling Research Status Report, NASA-TM-X-2384 (1971).

2. Freche, J. C., and Hall, R. W., NASA Programs for Development of High-Temperature Alloys for Advanced Engines, J. Aircraft 6, No. 5, 424-431 (October 1969).

3. Manson, S. S., and Ensign, C. R., A Specialized Model for Analysis of Creep Rupture Data by the Minimum Commitment, Station-Function Approach, NASA-TM-X-52999 (1971).

4. Manson, S. S., Fatigue: A Complex Subject - Some Simple Approximations, Exp. Mech. 5, No. 7, 193-226 (July 1965).

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6. Spera, D. A., Howes, M. A. H., and Bizon, P. T., Thermal Fatigue Resistance of 15 High-Temperature Alloys Determined by the Fluidized-Bed Technique, NASA-TM-X-52975 (1971).

7. Johnston, J. R., and Ashbrook, R. L., Oxidation and Thermal Fatigue Cracking of Nickel and Cobalt-Base Alloys in a High Velocity Gas Stream, NASA-TN-D-5376 (1969).

8. Spera, D. A., Calfo, F. D., and Bizon, P. T., Thermal Fatigue Testing of Simulated Turbine Blades, NASA-TM-X-67820 (1971).

Key words: Analysis methods; bibliographies; creep; creep analysis; environmental effects; fatigue (materials); gas turbine engines; heat resistant alloys; high temperature environments; laboratory simulations; life prediction; oxidation; oxidation resistant coatings; thermal fatigue; turbine blades.

ROLLING-ELEMENT BEARINGS: A REVIEW OF THE STATE OF THE ART
Anderson, W. J. and Zaretsky, E. V. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)
NASA TM-X-71441 (1973)

Some of the research conducted which has brought rolling-element technology to its present state is discussed. Areas touched upon are material defects processing variables, operating variables, design optimization, lubricant effects and lubrication methods. Finally, problem areas are discussed in relation to the present state-of-the-art and anticipated requirements. Classical rolling-element fatigue has always been considered the prime life limiting factor for rolling-element bearings although in actuality less than 10 percent of them fail by fatigue. With proper handling, installation lubrication and maintenance of lubrication, system cleanliness, and rolling-element bearing will fail by fatigue. Because fatigue results from material weaknesses, reserach to improve material quality has been a continuing activity. The results of this research are discussed. Based upon the problems and criteria set forth, it is the objective of the paper to review the state of the art advancements in the field of rolling-element technology. Because of the extensive amount of work which has been performed over the past decade it is difficult to incorporate the entire spectrum of research performed. However, the authors attempt to refer the reader to those pertinent references which will provide an indepth study into particular aspects of rolling-element bearing technology. With proper definition of the technology and problems related thereto, the reader can define pertinent research which should be performed.

Comments:

This review is one of the most complete in this area and an excellent basic background to the problem. In addition the directions of future research are well documented.

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1. Parker, R. J., Zaretsky, E. V. and Dietrich, M. W., Rolling-Element Fatigue Lives of Four M-Series Steels and AISI 52100 at 150°F, NASA TN-D-7033 (1973).

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Key words: Bearing alloys; bearing life; bearing loads; carbides; cyclic loads; cyclic testing; design criteria; dynamic tests; fatigue (materials); frequency effects; gas turbine engines; hardness; high-cycle fatigue; life prediction; lubricants; metallography; residual stress; temperature effects.

A NEW CRITERION FOR PREDICTING ROLLING ELEMENT FATIGUE LIVES OF THROUGH-HARDENED STEELS

Chevalier, J. L., Zaretsky, E. V. and Parker, R. J. (Army Air Mobility Research and Development Lab., Fort Eustis, VA; National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

ASME Paper 72-LUB-32 (October 1972)

Research was conducted to determine the effect of carbide size area, and number of bearing fatigue life with eight consumable-electrode vacuum-melted steels, whcih were fatigue tested in the five-ball fatigue tester at 150°F. Hardness measurements were conducted on five of the eight materials to temperatures of 1000°F. The following results were obtained:

A carbide factor was derived based upon a statistical analysis which related rolling element fatigue life to the total number of residual carbide particles per unit area, median residual carbide size, and percent residual carbide area. An equation was empirally determined which predicts material hardness as a function of temperature. The limiting temperatures of all the materials studied were dependent on initial room temperature hardness and tempering temperature. An equation was derived combining the effects of material hardness, carbide factor, and bearing temperature to predict rolling-element bearing life.

Comment:

The equation derived in this paper is a useful addition to the science of bearing life prediction and opens up the area of detailed microstructure effects on life.

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Key words: Bearings; carbides; fatigue (materials); fatigue life; grain boundaries; high-cycle fatigue; life prediction; microstructures.

EFFECT OF RESIDUAL STRESSES INTRODUCED BY PRESTRESSING ON ROLLING-ELEMENT FATIGUE LIFE

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NASA TN-D-6995 (1972)

A mechanical prestress cycle suitable to induce compressive stress beneath the surface of the inner race of radially loaded 207-size bearings was determined. Compressive residual stresses in excess of 68950 N/cm^2, as measured by x-ray diffraction, were induced at the depth of maximum shearing stress. The prestress cycle consisted of running the bearings for 25 hours at 2750 rpm at a radial load which produced a maximum Hertz stress of 330.960 N/cm^2 at the contact of the inner race and the heaviest loaded ball. Bearings subjected to this prestress cycle and subsequently fatigue tested gave a 10 percent fatigue life greater than twice that of a group of baseline bearings.

Important References:

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Key words: Bearing life; bearings; compressive loads; fatigue (materials); fatigue life; fatigue tests; residual stress; rolling steels; x-ray diffraction.

INDEXES

AUTHOR INDEX

This Index lists the name of each author, or co-author of a document that is abstracted in this report and also the names of the authors or co-authors of all important references cited with the abstracts. Authors of documents that are abstracted are identified by an asterisk (*).

KEYWORD INDEX