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CREEP AND FATIGUE RESEARCH EFFORTS ON ADVANCED MATERIALS

John Gayda

ABSTRACT

Two of the more important materials problems encountered in turbine blades of aircraft engines are creep and fatigue. To withstand these high-temperature phenomena modern engines utilize single-crystal, nickel-base superalloys as the material of choice in critical applications. In this presentation we will discuss recent research activities at Lewis on single-crystal blading material as well as future research initiatives on metal matrix composites related to creep and fatigue. The goal of these research efforts is improving the understanding of microstructure-property relationships and thereby guide material development.

Although single crystals exhibit superior creep properties compared to conventionally cast, polycrystalline blading material, recent work at Lewis and other aerospace laboratories has shown that greater improvements can be attained by developing single-crystal alloys with a "rafted" microstructure. In this microstructure, the small, cuboidal γ' precipitates that strengthen these alloys are converted into nearly continuous layers or "rafts" of γ'. The factors, both internal and external, which affect raft formation have been studied from an experimental and analytical standpoint. These include the effect of stress, temperature, lattice misfit, and elastic constants of the precipitate and matrix.

In addition to creep damage, thermomechanical fatigue (TMF) of single-crystal blading material has received much attention in recent years because it is often found to be life limiting. TMF damage results from simultaneous fluctuations of temperature and mechanical loads. Recent work at Lewis on coated single crystals has identified an environmentally driven damage mechanism for the deleterious out-of-phase TMF cycle. Experimental evidence for this mechanism is presented, together with a qualitative model describing the damage mechanism.

As advanced superalloys, such as single-crystal, nickel-base alloys described here, approach their theoretical temperature limitation, research on creep and fatigue is being redirected toward lightweight, high-temperature, metal matrix composites. Future plans for modeling creep and fatigue phenomena of metal matrix composites are described for three very different systems.

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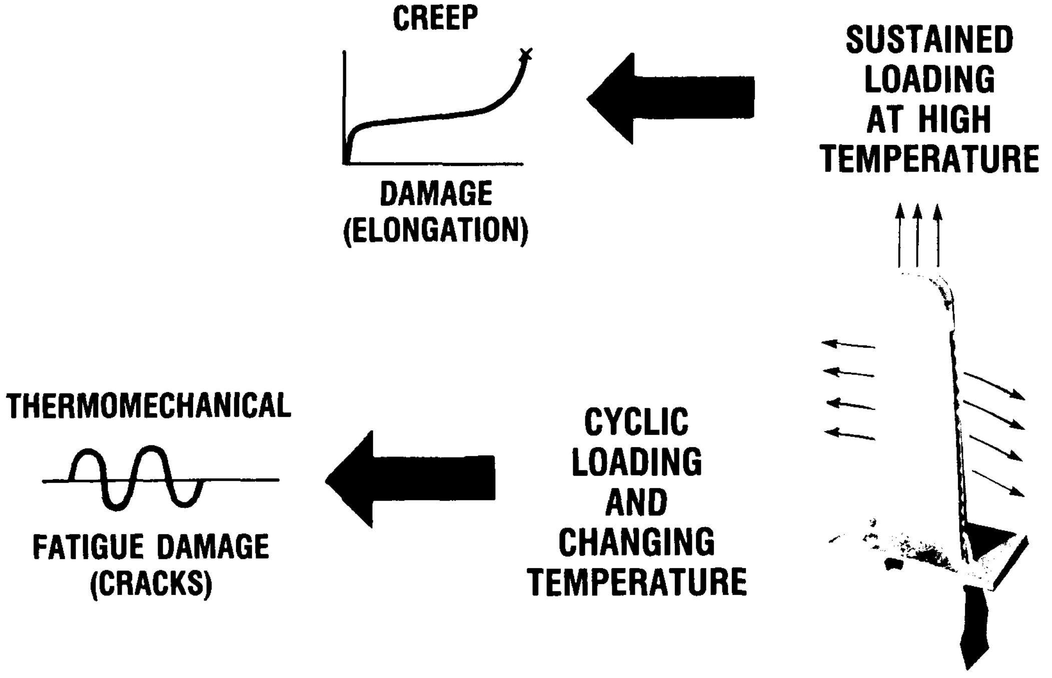
PHYSICAL ORIGIN OF CREEP AND FATIGUE DAMAGE IN TURBINE BLADES

The harsh operating environment encountered in the turbine section of an aircraft engine gives rise to numerous materials problems. Two of the more important problems are associated with creep and fatigue damage of turbine blades. Sustained, centrifugal loads on the blades at elevated temperature give rise to creep damage, a time-dependent, permanent elongation. Cyclic loads, associated with starting and stopping of the engine, coupled with the simultaneous changes in material temperature produce thermomechanical fatigue (TMF) damage. Unlike creep damage, TMF damage and subsequent growth of TMF cracks are directly dependent on the number of stress cycles the blades encounter, not the total exposure time at elevated temperatures.

PHYSICAL ORIGIN OF CREEP AND FATIGUE DAMAGE IN TURBINE BLADES



CREEP

DAMAGE (ELONGATION)

SUSTAINED LOADING AT HIGH TEMPERATURE

THERMOMECHANICAL

FATIGUE DAMAGE (CRACKS)

CYCLIC LOADING AND CHANGING TEMPERATURE

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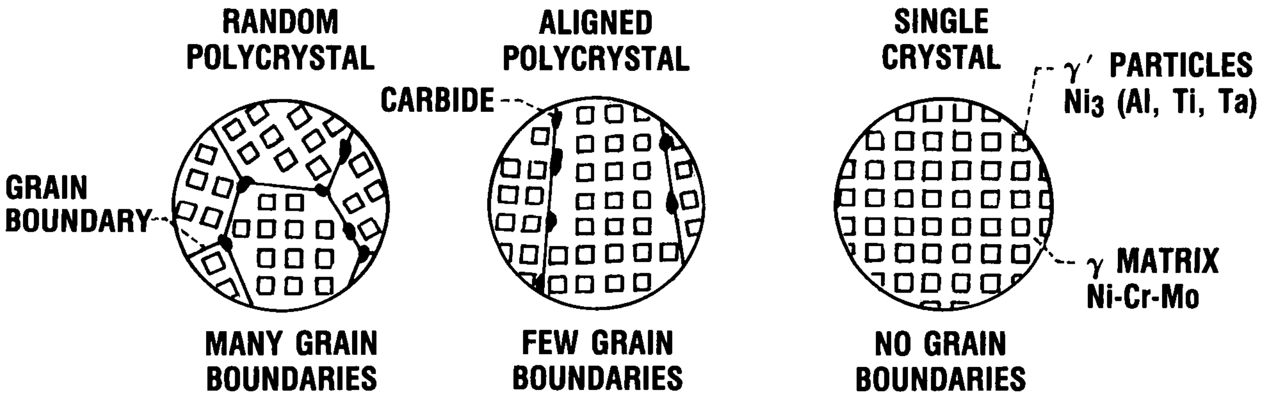
NICKEL-BASE SUPERALLOY TURBINE-BLADE MATERIALS MICROSTRUCTURES

To withstand the high-temperature loads developed in turbine blades, nickel-base superalloys are used in modern day engines. These blade alloys can be made as conventional castings or as directionally solidified castings. In the former instance, a random polycrystalline microstructure is produced, whereas, in the latter instance, an aligned polycrystalline microstructure is produced. The directionally solidified casting can also be produced such that the entire blade is a single grain or crystal. In all three forms, the superalloy derives much of its high-temperature strength from the γ' particles. Carbides are also present in the polycrystalline forms to enhance the creep strength of the grain boundaries.

NICKEL-BASE SUPERALLOY TURBINE-BLADE MATERIAL MICROSTRUCTURES



ALL THREE FORMS DERIVE HIGH-TEMPERATURE STRENGTH FROM THE γ' PRECIPITATE PARTICLES

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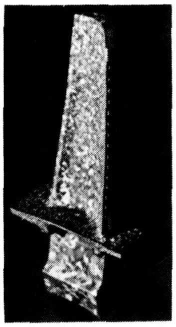
DEVELOPMENT OF NICKEL-BASE SUPERALLOY BLADING MATERIAL AND ASSOCIATED DAMAGE MECHANISMS

Of the three forms of nickel-base superalloy blading materials mentioned on the preceding page, the single-crystal form has the highest temperature, longest life capability because the detrimental effect of grain boundaries is eliminated. Further enhancement of single-crystal fatigue properties is attained by removal of carbides, which improve creep properties of grain boundaries, but also serve as initiation sites for fatigue cracks.

Materials research on single crystals at Lewis is aimed at improving the understanding of microstructure-property relationships and thus identifying ways to improve performance and to extend life by developing better materials. Examples of recent research activities in the area of creep and fatigue will be presented.

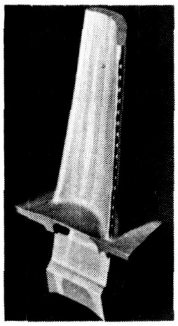
DEVELOPMENT OF NICKEL-BASE SUPERALLOY BLADING MATERIAL AND ASSOCIATED DAMAGE MECHANISMS

RANDOM POLYCRYSTAL



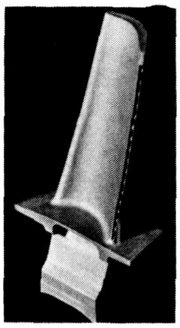
- CREEP DAMAGE
  - GRAIN BOUNDARY
  - BULK
- FATIGUE DAMAGE
  - GRAIN BOUNDARY
  - CARBIDES
  - MACROPOROSITY

ALIGNED POLYCRYSTAL



- CREEP DAMAGE
  - BULK
- FATIGUE DAMAGE
  - CARBIDES
  - MICROPOROSITY

SINGLE CRYSTAL



- CREEP DAMAGE
  - BULK
- FATIGUE DAMAGE
  - MICROPOROSITY

HIGHER TEMPERATURE CAPABILITY
LONGER LIFE ➡

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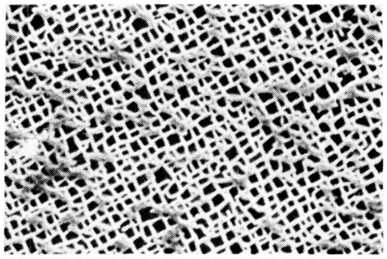
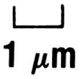
TAILORED MICROSTRUCTURE IMPROVES USEFUL LIFE

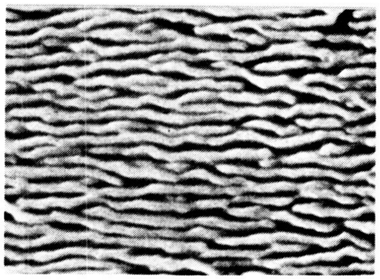
The typical heat-treated microstructure of modern single-crystal superalloys contains about 60 percent of the γ' precipitates dispersed in a continuous matrix of γ. The γ' particles are usually present as spheres or cubes after heat treatment, and an example of this microstructure is shown on the left. However, under an applied stress at elevated temperatures, these discrete γ' particles link up in certain alloys to form plates, which are commonly called γ' rafts. These γ' rafts have been shown to improve the creep life of single crystals at elevated temperatures.

TAILORED MICROSTRUCTURE IMPROVES USEFUL LIFE*

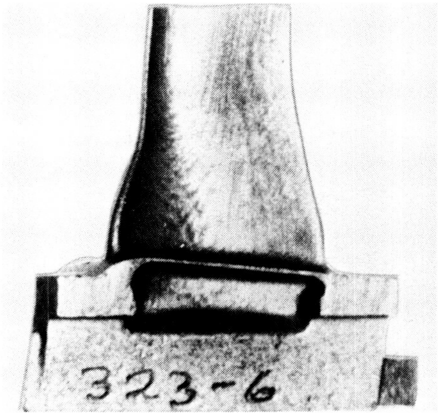


60 v/o FINE γ' STRENGTHENING PHASE

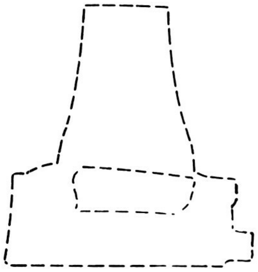




RAFTED γ'



SINGLE-CRYSTAL BLADE



IMPROVED SINGLE-CRYSTAL BLADE, LONGER LIFE

*MACKAY AND EBERT, SCRIPTA MET, 1983

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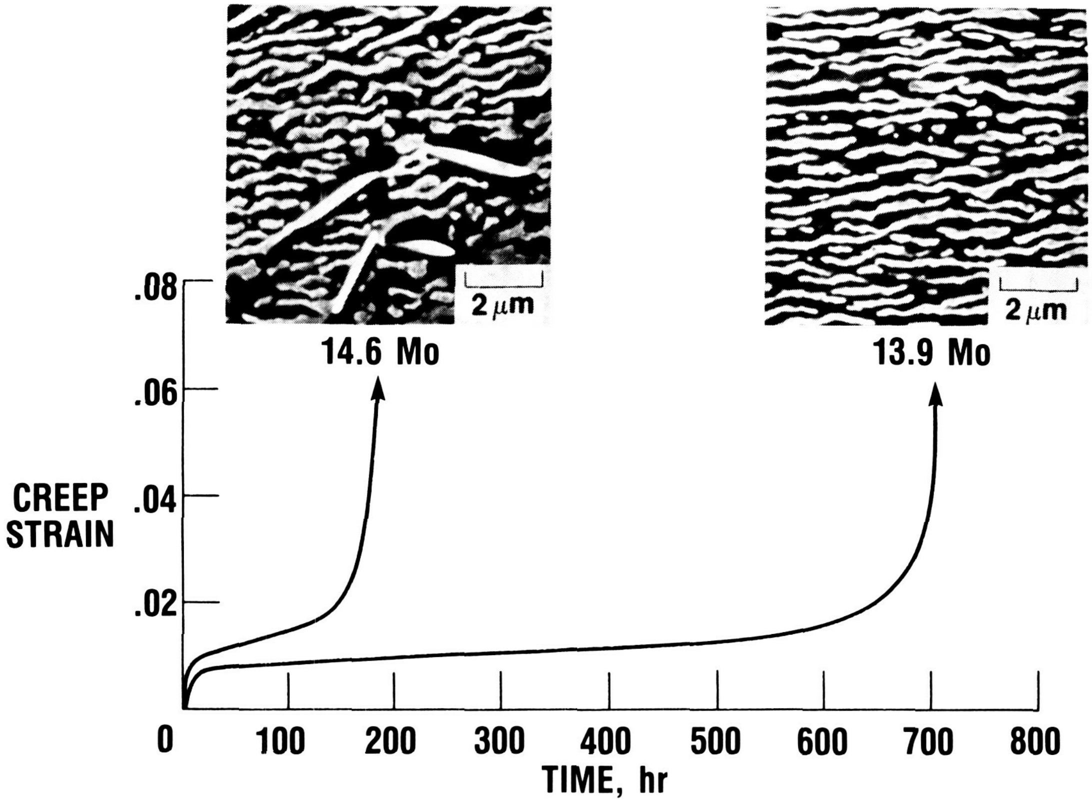
SUPERSATURATED ALLOY DEGRADES CREEP PROPERTIES

The γ' rafts have a beneficial effect on creep life if they form rapidly and are relatively perfect. An example of a "perfect" rafted microstructure is shown on the right for a single-crystal alloy containing 13.9 percent molybdenum. However, when the molybdenum content of the alloy was increased slightly to 14.6 percent, an additional phase forms which causes imperfections or gaps in the rafts. An example of this discontinuous rafted structure is shown on the left. The degradation in raft perfection causes a dramatic decrease in the creep life. Thus, our research is aimed at understanding the mechanisms of this phenomenon to exploit the maximum benefit from rafted microstructures.

SUPERSATURATED ALLOY DEGRADES CREEP PROPERTIES*



*MACKAY AND EBERT, 5TH INTERNATIONAL SYMPOSIUM ON SUPERALLOYS, 1984

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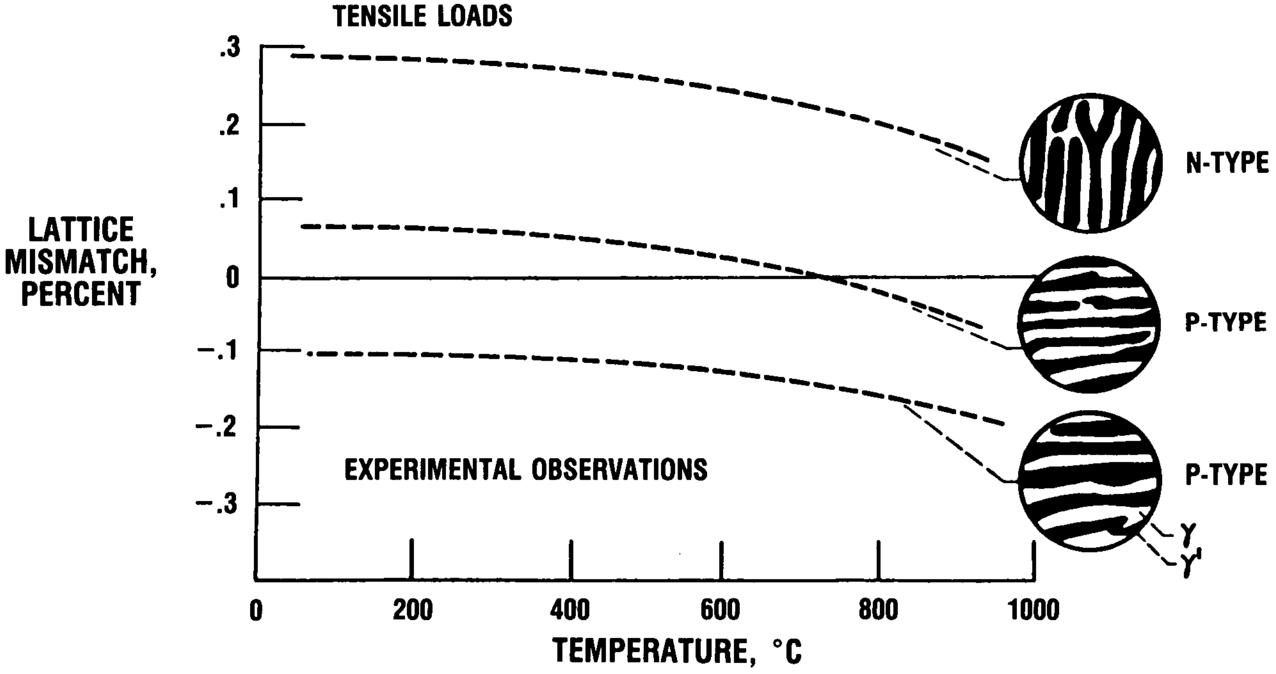
INFLUENCE OF ELEVATED-TEMPERATURE LATTICE MISMATCH ON γ' PLATE ORIENTATION

A major factor which influences γ' rafting behavior is the lattice mismatch. The magnitude of the lattice mismatch indicates the difference in lattice parameters (the dimensions of the atomic structure) between the γ and γ' phases. The sign of the mismatch is one factor which determines the orientation of the rafted structure. Superalloys with large, negative values of lattice mismatch form rafts perpendicular (P-type) to the applied tensile axis, whereas alloys with large, positive values of mismatch form rafts parallel (N-type) to the applied tensile axis. However, the sign of the mismatch can actually change from positive to negative as temperature increases. Thus P-type rafts can form at elevated temperatures in some alloys which have a small positive mismatch at room temperature. It is therefore important to obtain lattice mismatch measurements at elevated temperatures in order to make accurate predictions of raft orientation.

INFLUENCE OF ELEVATED-TEMPERATURE LATTICE MISMATCH ON γ' PLATE ORIENTATION*



*MACKAY AND NATHAL, MICON SYMPOSIUM, 1986

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MODELING STRESS-ASSISTED PRECIPITATE GROWTH

To gain more insight, we developed (with D. Srolovitz now at the University of Michigan) a field-oriented, microstructural lattice model to simulate the rafting phenomenon. In this approach the microstucture is discretized onto a fine lattice. Each element in the lattice is labeled accordingly as γ or γ'. Diffusion, that is, physical transport of material at elevated temperatures, is simulated by allowing exchanges of neighboring elements if the exchange lowers the total energy of the system. A Monte Carlo approach is used to select the exchange site, whereas the change in energy associated with the stress fields, that is, precipitate misfit and external creep load, is computed by using a finite-element technique.

MODELING STRESS-ASSISTED PRECIPITATE GROWTH

MONTE CARLO TECHNIQUE FOR DIFFUSION SIMULATION

FINITE-ELEMENT TECHNIQUE FOR STRESS FIELD SIMULATION

MERGE THESE EXISTING "TOOLS" INTO A TIME EFFICIENT COMPUTER CODE

ANALYTICALLY EVALUATE KEY MICROSTRUCTURAL PARAMETERS TO MODEL γ' RAFTING IN SINGLE CRYSTALS

REAL MICROSTRUCTURE

SIMULATION LATTICE

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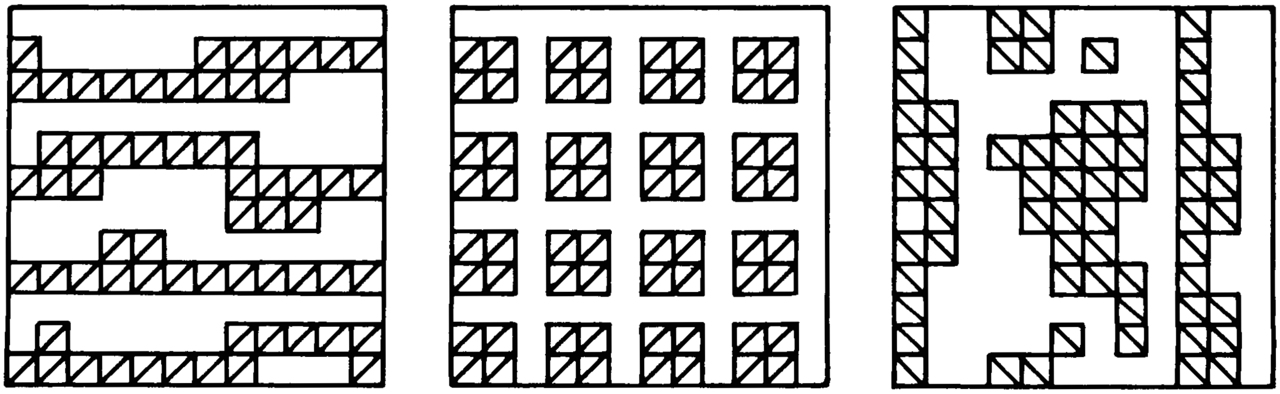
PREDICTED RAFTING BEHAVIOR OF POSITIVE AND NEGATIVE MISFIT ALLOYS AGREES WITH EXPERIMENT

To date, simulations of the rafting phenomenon in single crystals agree with real world behavior. The orientation of the rafted structure under tensile loads and its dependence on precipitate misfit is illustrated here. The two alloys shown have identical properties and starting microstructures, except that one has a negative misfit and the other has a positive misfit. Rafting simulations run on both alloys show that rafts develop which are perpendicular to the stress axis for negative misfit but parallel to the stress axis for positive misfit. This is consistent with the experimental results.

PREDICTED RAFTING BEHAVIOR OF POSITIVE AND NEGATIVE MISFIT ALLOYS AGREES WITH EXPERIMENT*



NEGATIVE
MISFIT ALLOY

INITIAL
⬅ MICROSTRUCTURE ➡
BEFORE
CREEP LOADING

POSITIVE
MISFIT ALLOY

*SROLOVITZ, HASSOLD, AND GAYDA, INTERNATIONAL SYMPOSIUM OF ORDERING PROCESSES IN CONDENSED MATTER, 1987

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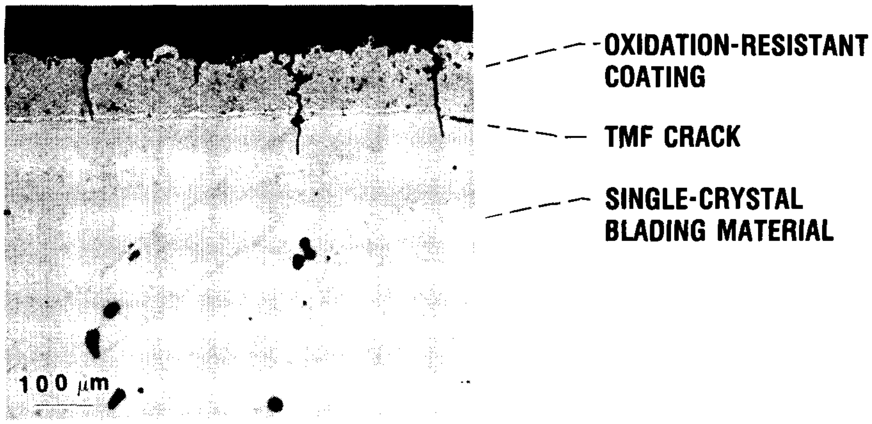
ALTHOUGH CREEP IS IMPORTANT, THERMOMECHANICAL FATIGUE (TMF) CRACKING OF COATED SINGLE CRYSTALS IS OFTEN LIFE LIMITING

Although the creep damage produced at high temperatures by sustained loads affects the life of single-crystal turbine blades, failure is often attributed to thermomechanical fatigue damage. This damage is produced by the application of cyclic loads during heating and cooling of the blade. The damage often starts as cracks in the oxidation-resistant coating applied to single-crystal turbine blades. These cracks grow into the single crystal and eventually cause failure of the blade.

ALTHOUGH CREEP IS IMPORTANT, THERMOMECHANICAL FATIGUE (TMF) CRACKING OF COATED SINGLE CRYSTALS IS OFTEN LIFE LIMITING

- **CYCLIC LOADS**
- **HEATING AND COOLING**



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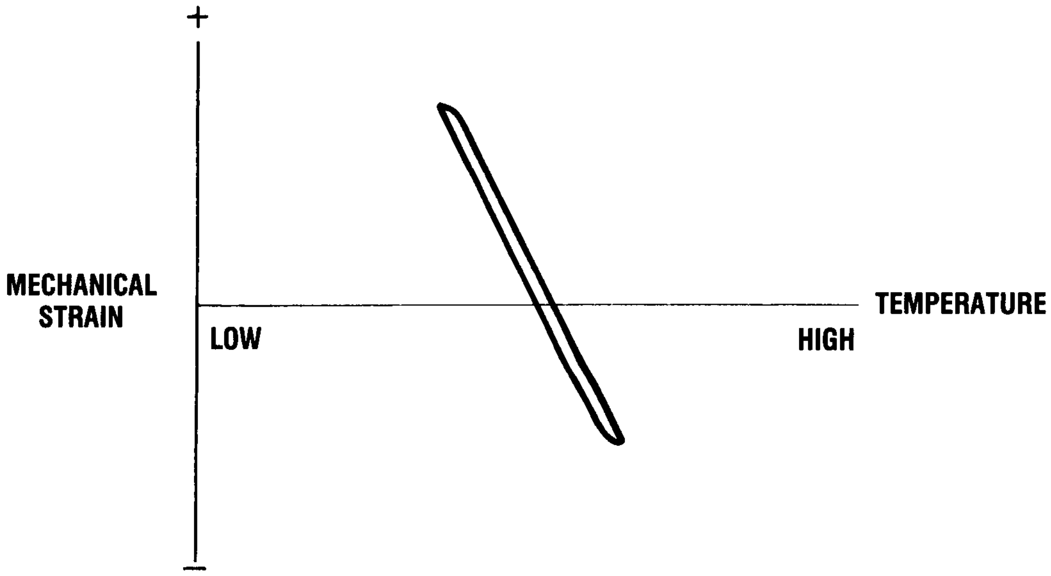
OF POOR QUALITY

IT IS KNOWN THAT TMF LIFE IS LOW FOR CYCLES IMPOSING TENSION AT TEMPERATURES $\lesssim$ 800 °C

Thermomechanical fatigue (TMF) is particularly harmful in cycles where tensile loads are applied at temperatures below 800 °C, where ductility of superalloys is lowest. A TMF cycle of this type is termed out-of-phase (OP) and is often encountered in real engine cycles. Here the load and temperature change in opposite directions at the same time. This cycle produces tensile mechanical strains at the minimum temperature and compressive mechanical strains at the maximum temperature. Analysis is complicated, since the mechanical strain due to the changing load is mixed with thermal strains due to the changing temperature.

IT IS KNOWN THAT TMF LIFE IS LOW FOR CYCLES IMPOSING TENSION AT TEMPERATURES $\lesssim$800 °C



THIS CYCLE TYPE IS TERMED OUT-OF-PHASE (OP), SINCE MAXIMUM TEMPERATURE COINCIDES WITH MINIMUM (-) STRAIN; SIMILAR SITUATIONS ARE ENCOUNTERED IN REAL ENGINE CYCLES

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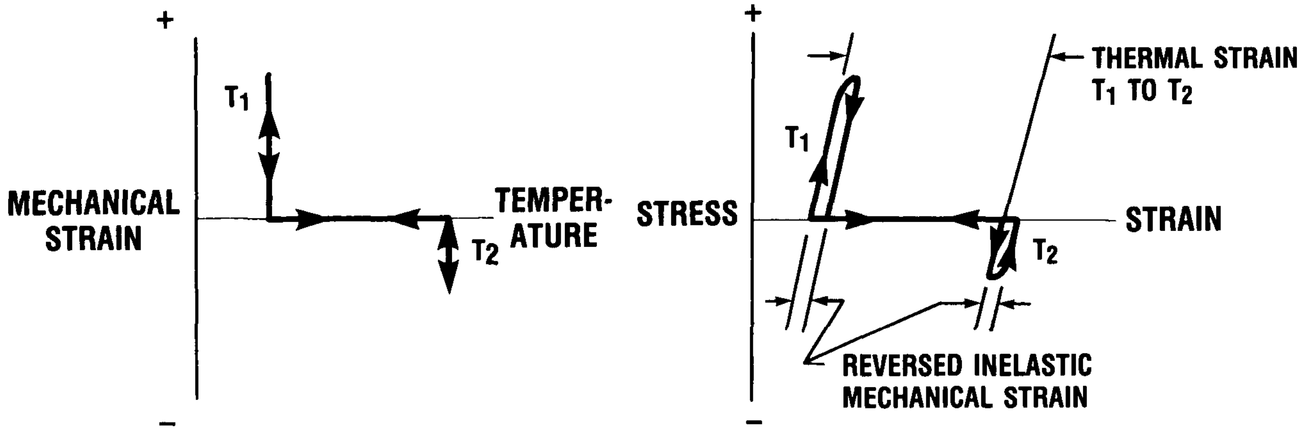
A SIMPLIFIED BITHERMAL TMF TEST ALLOWS STRAINS TO BE SEPARATED

A large body of knowledge exists on fatigue damage produced by cyclic loads at constant temperature. This understanding cannot be easily applied to the TMF problem, where cyclic loads produce damage at continuously changing temperatures. But the "bithermal" TMF cycle provides the means to apply this knowledge. In this simplified TMF cycle, equal amounts of inelastic mechanical strain, of opposite sign, are applied at the temperature extremes in the cycle. The inelastic strain is a permanent, or nonrecoverable, strain which produces damage within the material.

A SIMPLIFIED BITHERMAL TMF TEST ALLOWS STRAINS TO BE SEPARATED

OUT-OF-PHASE (OP) BITHERMAL TEST



FIXED TEMPERATURES AND REVERSED INELASTIC STRAIN LINK TMF BEHAVIOR TO UNDERSTANDING OF ISOTHERMAL FATIGUE MECHANISMS AT T_1 AND T_2

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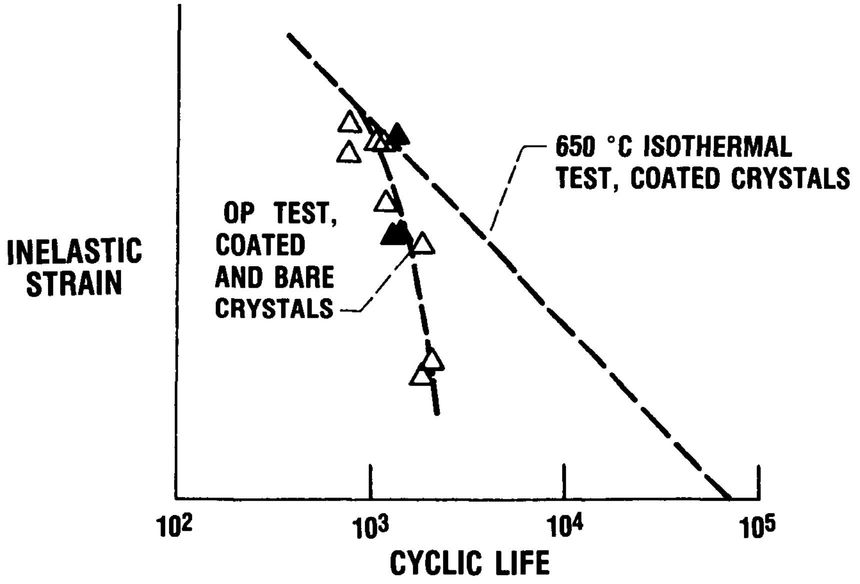
IN 650 TO 1050 °C OUT-OF-PHASE (OP) BITHERMAL TEST, SURFACE CRACKS INITIATE EARLY IN COATED AND BARE CRYSTALS AS IN 650 °C ISOTHERMAL TEST OF COATED CRYSTALS

The bithermal TMF cycle produces the same type of damage as the more realistic TMF cycle. In out-of-phase (OP) tests where the temperature is changed between 650 and 1050 °C, both cycles produce premature surface cracks. Surface cracking also occurs in constant-temperature fatigue tests at 650 °C, and, at high cyclic strains, all cycles have comparable life. But in tests at low cyclic strains, the OP TMF life is up to 10 times shorter than in tests at 650 °C.

IN 650 TO 1050 °C OUT-OF-PHASE (OP) BITHERMAL TEST, SURFACE CRACKS INITIATE EARLY IN COATED AND BARE CRYSTALS AS IN 650 °C ISOTHERMAL TEST OF COATED CRYSTALS*



HOWEVER, IN THE LOW-STRAIN REGIME, OP TEST LIFE IS EVEN SHORTER THAN AT 650 °C

*GAYDA, GABB, AND MINER, NASA TM 89831, 1987

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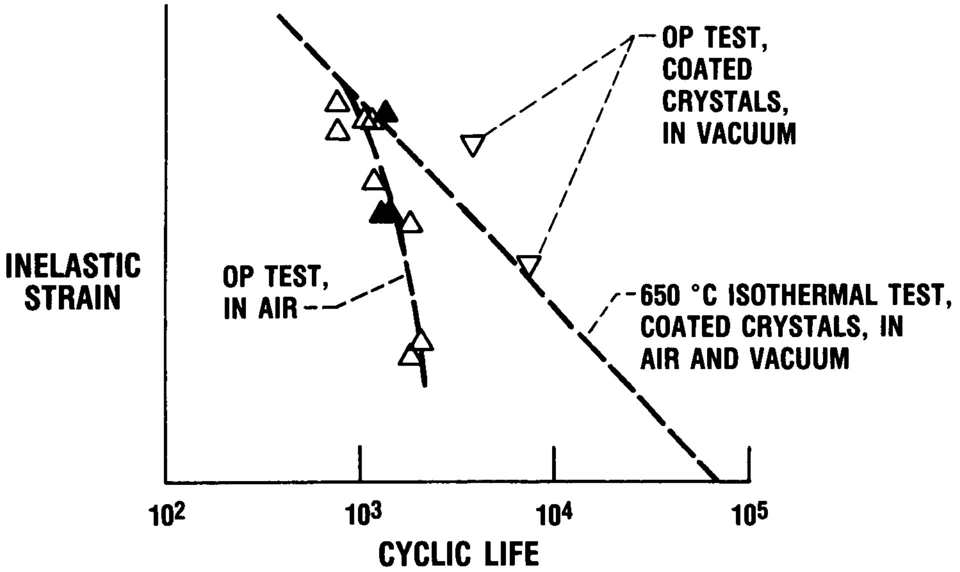
LOW 650 TO 1050 °C OUT-OF-PHASE (OP) BITHERMAL TEST LIFE IN LOW-STRAIN REGIME IS LARGELY AN EFFECT OF OXIDATION AT 1050 °C

At low strains, foreshortening of cyclic life in the OP bithermal TMF test results in part from oxidation damage at 1050 °C. When these tests are performed in vacuum, the OP bithermal TMF test lives increase and are approximately equivalent to the constant-temperature tests at 650 °C. Early surface cracking occurs in all of these tests, the OP bithermal TMF tests and the constant-temperature tests at 650 °C in both air and vacuum. Therefore oxidation at 1050 °C apparently accelerates growth of surface cracks in the OP bithermal TMF test.

LOW 650 TO 1050 °C OUT-OF-PHASE (OP) BITHERMAL TEST LIFE IN LOW-STRAIN REGIME IS LARGELY AN EFFECT OF OXIDATION AT 1050 °C*



EARLY CRACK INITIATION IS OBSERVED IN ALL THESE TESTS. THE OP TEST REDUCES CRACK PROPAGATION PORTION OF LIFE.

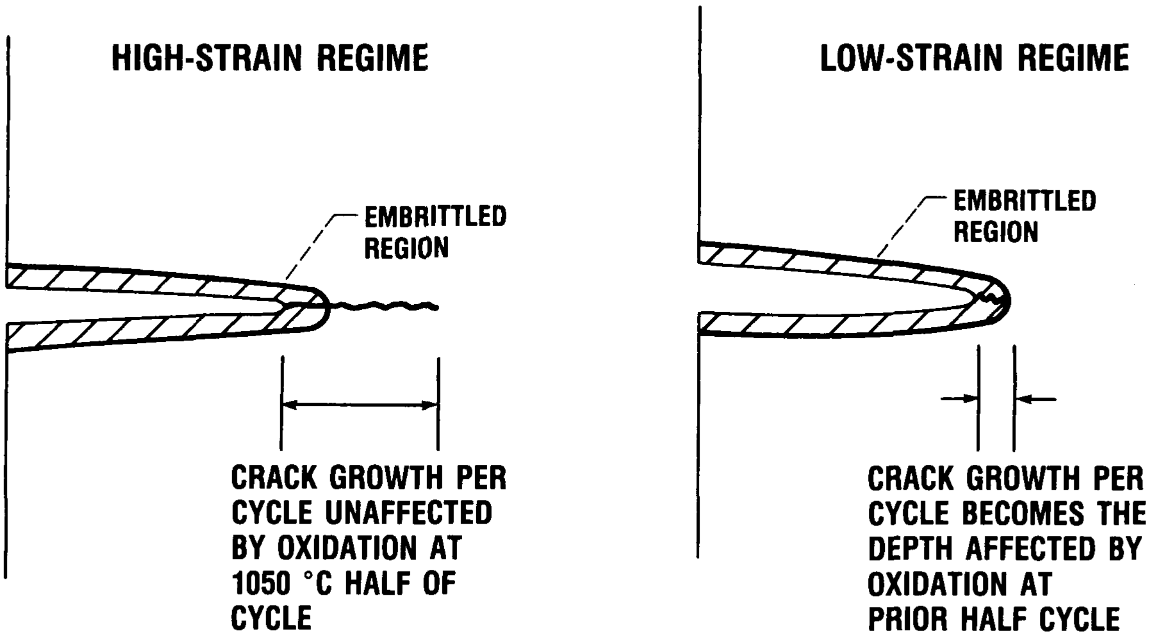
*GAYDA, GABB, AND MINER, NASA TM 89831, 1987

CD-87-28784

A MODEL FOR OUT-OF-PHASE BITHERMAL CRACK GROWTH

Presented here is a schematic illustration of the damage mechanism for the OP bithermal cycle, which explains life degradation at low strains. Surface cracks appear early in all tests. The crack tips are oxidized and thereby embrittled at 1050 °C. In tests employing large cyclic strains, the crack grows far beyond the embrittled region during a single cycle. Therefore the crack growth resistance of the unoxidized superalloy controls life, and oxidation at 1050 °C has little effect. But in tests at small cyclic strains, crack growth in the superalloy is slow compared to the advance of the oxidized region. Fracture of this environmentally damaged zone requires little load at low temperatures, such as 650 °C, and therefore provides a faster crack growth rate and shorter life at lower cyclic strains.

A MODEL FOR OUT-OF-PHASE BITHERMAL CRACK GROWTH



HIGH-STRAIN REGIME

CRACK GROWTH PER CYCLE UNAFFECTED BY OXIDATION AT 1050 °C HALF OF CYCLE

LOW-STRAIN REGIME

CRACK GROWTH PER CYCLE BECOMES THE DEPTH AFFECTED BY OXIDATION AT PRIOR HALF CYCLE

IN THE LOW-STRAIN REGIME, CRACK GROWTH RATE BECOMES NEARLY INDEPENDENT OF STRAIN RANGE

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METALS SCIENCE BRANCH QUANTITATIVE PHYSICAL METALLURGY OF METAL MATRIX COMPOSITES

As superalloys approach their theoretical temperature limitation, a new generation of lightweight, high-temperature, metal matrix composites are being considered as alternate materials for advanced aircraft engines. One of the most serious problems encountered in the development of these new-generation composite materials is durability. An area of critical concern here is thermomechanical fatigue, because differences in the thermal expansion coefficients between fiber and matrix create additional problems not found in more conventional materials, such as the single-crystal superalloys.

METALS SCIENCE BRANCH

QUANTITATIVE PHYSICAL METALLURGY OF METAL MATRIX COMPOSITES

NASA NEEDS: DEVELOP COMPOSITE MATERIALS WHICH HAVE HIGHER TEMPERATURE CAPABILITY, WHICH ARE LIGHTER, AND WHICH SHOW DURABILITY AS GOOD AS OR BETTER THAN CONVENTIONAL SUPERALLOYS

OBJECTIVE: PROVIDE THE ANALYTICAL TOOLS FOR COMPOSITE DEVELOPMENT. SPECIFICALLY, DEVELOP A PHYSICALLY BASED MODEL FOR FATIGUE AND CREEP OF METAL MATRIX COMPOSITES BY 1992.

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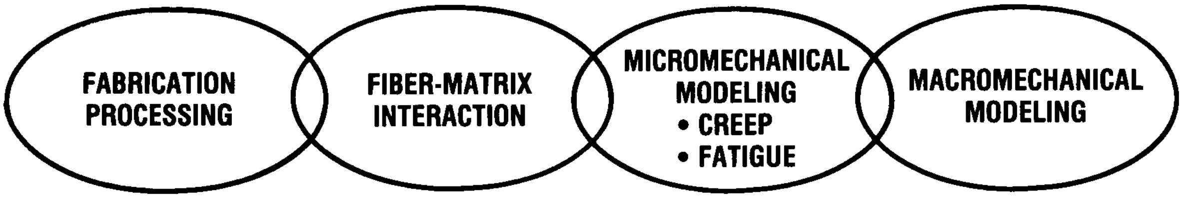
METAL MATRIX COMPOSITE PROGRAM REQUIRES NUMEROUS SKILLS

The work in high-temperature, metal matrix composites requires many diverse skills. To address this need, activities at Lewis involve personnel from four branches and two divisions. Micromechanical modeling of fatigue on these materials will be the primary responsibility of the Metals Science Branch and the Fatigue and Fracture Branch.

METAL MATRIX COMPOSITE PROGRAM REQUIRES NUMEROUS SKILLS



ADVANCED METALLICS BRANCH
(MATERIALS DIVISION)

METALS SCIENCE BRANCH
(MATERIALS DIVISION)

FATIGUE AND FRACTURE BRANCH
(STRUCTURES DIVISION)

STRUCTURAL MECHANICS BRANCH
(STRUCTURES DIVISION)

CD-87-30044

CURRENT PROGRAM FOR QUANTITATIVE PHYSICAL METALLURGY OF METAL MATRIX COMPOSITES

Models for fatigue behavior of metal matrix composites will be developed and validated on three diverse systems: W/Cu, SiC/Ti alloy, and SiC/FeAl. These systems are representative of ductile fiber/ductile matrix, brittle fiber/ductile matrix, and brittle fiber/brittle matrix composites, respectively. Characterization and actual testing of fiber, matrix, and composite will be a key part of the program early on, as will the use of a simple, one-dimensional, two-bar model to analyze this data. Eventually a three-dimensional model which incorporates viscoplastic theory for time-dependent effects will be developed and validated under a nonisothermal, multiaxial stress state.

CURRENT PROGRAM FOR QUANTITATIVE PHYSICAL METALLURGY OF METAL MATRIX COMPOSITES

MODEL MATERIAL SYSTEMS

- DUCTILE FIBER/DUCTILE MATRIX = W/Cu
- BRITTLE FIBER/DUCTILE MATRIX = SiC/Ti ALLOY
- BRITTLE FIBER/BRITTLE MATRIX = SiC/FeAl

CHARACTERIZATION AND TESTING

- FIBER, MATRIX, AND COMPOSITE CHARACTERIZATION
- ISOTHERMAL AND THERMOMECHANICAL FATIGUE
- UNIAXIAL AND MULTIAXIAL STRESSES

MODELING THERMOMECHANICAL FATIGUE

- ONE-DIMENSIONAL MODEL WITH TIME-DEPENDENT EFFECTS
- THREE-DIMENSIONAL MODEL USING ADVANCED VISCOPLASTICITY APPROACH FOR TIME-DEPENDENT EFFECTS

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