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FATIGUE IN SINGLE CRYSTAL NICKEL SUPERALLOYS

Technical Progress Report

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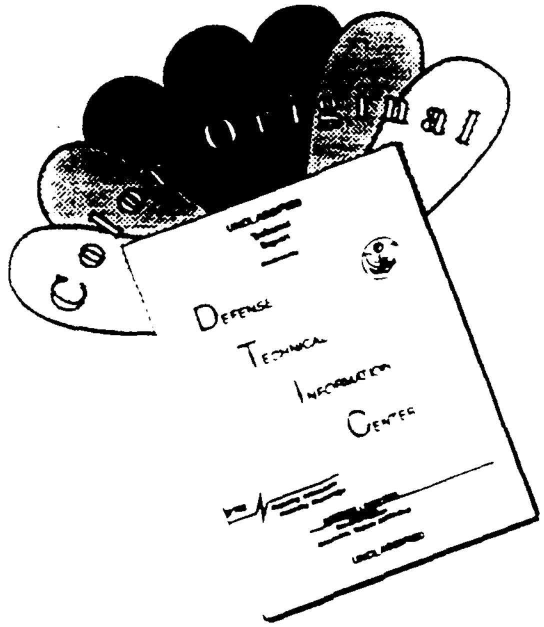

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I. Introduction and Program Objective

This program investigates the seemingly unusual behavior of single crystal airfoil materials. The fatigue initiation processes in single crystal (SC) materials are significantly more complicated and involved than fatigue initiation and subsequent behavior of a (single) macrocrack in conventional, isotropic, materials. To understand these differences it is helpful to review the evolution of high temperature airfoils.

Characteristics of Single Crystal Materials

Modern gas turbine flight propulsion systems employ single crystal materials for turbine airfoil applications because of their superior performance in resisting creep, oxidation, and thermal mechanical fatigue (TMF). These properties have been achieved by composition and alloying, of course, but also by appropriate crystal orientation and associated anisotropy.

Early aeroengine turbine blade and vane materials were conventionally cast, equiaxed alloys, such as IN100 and Rene'80. This changed in the late 1960s with the introduction of directionally-solidified (DS) MAR-M200 + Hf airfoils. The DS process produces a <001> crystallographic orientation, which in superalloys exhibits excellent strain controlled fatigue resistance due to its low elastic modulus. The absence of transverse grain boundaries, a 60% reduction in longitudinal modulus compared with equiaxed grains, and its corresponding improved resistance to thermal fatigue and creep, permitted significant increases in allowable metal temperatures and blade stresses. Still further progress was achieved in the mid-1970s with the development of single crystal airfoils[1].

The first such material, PWA 1480, has a considerably simpler composition than preceding cast nickel blade alloys because, in the absence of grain boundaries, no grain boundary strengthening elements are required. Deleting these grain boundary strengtheners, which are also melting point depressants, increased the incipient melt temperature. This, in turn, allowed nearly complete γ' solutioning during heat treatment and thus a reduction in dendritic segregation. The absence of grain boundaries, the opportunity for full solution heat treatment, and the minimal post-heat treat dendritic segregation, result in significantly improved properties as compared with conventionally cast or directionally solidified alloys. Single crystal castings also share with DS alloys the <001> crystal orientation, along with the benefits of the resulting low modulus in the longitudinal direction.

Pratt & Whitney has developed numerous single crystal materials. Like most, PWA 1480 and PWA 1484 are γ' strengthened cast mono grain nickel superalloys based on the Ni-Cr-Al system. The bulk of the microstructure consists of approximately 60% by volume of cuboidal γ' precipitates in a γ matrix. The precipitate ranges from 0.35 to 0.5 microns and is an ordered Face Centered Cubic (FCC) nickel aluminide compound. The macrostructure of these materials

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[1] Gell, M., D. N. Duhl, and A. F. Giamei, 1980, "The Development of Single Crystal Superalloy Turbine Blades," *Superalloys 1980*, proceedings of the Fourth International Symposium on Superalloys, American Society for Metals, Metals Park, Ohio, pp. 205-214.

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is characterized by parallel continuous primary dendrites spanning the casting without interruption in the direction of solidification. Secondary dendrite arms (perpendicular to solidification) define the interdendritic spacing. Solidification for both primary and secondary dendrite arms proceeds in <001> type crystallographic directions. Undissolved eutectic pools and associated microporosity reside throughout the interdendritic areas. These features act as microstuctural discontinuities, and often exert a controlling influence on the fatigue initiation behavior of the alloy. Also, since the eutectics are structurally dissimilar from the surrounding matrix their fracture characteristics will differ.

Single Crystal Fatigue

The fatigue process in single crystal airfoil materials is a remarkably complex and interesting process. In cast single crystal nickel alloys, two basic fracture modes, crystallographic and non-crystallographic, are seen in combination. They occur in varying proportions depending upon temperature and stress state. Crystallographic orientation with respect to applied load also affects the proportion of each and influences the specific crystallographic planes and slip directions involved. Mixed mode fracture is observed under monotonic as well as cyclic conditions.

Single crystal turbine blades are cast such that the radial axis of the component is essentially coincident with the <001> crystallographic direction which is the direction of solidification. Crystallographic fracture is usually seen as either octahedral along multiple (111) planes or under certain circumstances as (001) cleavage along cubic planes.

Non-crystallographic fracture is also observed. Low temperatures favor crystallographic fracture. At higher temperatures, in the 427C range, small amounts of non-crystallographic propagation have the appearance of transgranular fatigue in a related fine grain equiaxed alloy. Under some conditions, this propagation changes almost immediately to the highly crystallographic mode along (111) shear planes, frequently exhibiting prominent striations emanating from the fatigue origin and continuing to failure in overstress. Under other conditions the non-crystallographic behavior can continue until tensile failure occurs. At intermediate temperatures (around 760C) non-crystallographic propagation is more pronounced and may continue until tensile overload along (111) planes occurs, or may transition to subcritical crystallographic propagation. At 982C, propagation is almost entirely noncrystallographic, similar to transgranular propagation in a polycrystal.

Damage Catalogue

This program will identify and compile descriptions of the fracture morphologies observed in SC airfoil materials under various combinations of temperature and stress associated with advanced Navy aeropropulsion systems. We will suggest fatigue mechanisms for these morphologies and catalogue them as unique damage *states*. Most testing will be accomplished under ancillary funding, and therefore be available to this effort at not cost. The work is organized into four tasks, which are described in the following paragraphs.

II. Program Organization

The program is structured into four tasks, three technical and one reporting. The individual tasks are outlined here.

Task 100 - Micromechanical Characterization

This task will define the mechanisms of damage accumulation for the various types of fracture observed in single crystal alloys. These fracture characteristics will be used to establish a series of Damage States which represent the fatigue damage process. The basis for this investigation will be detailed fractographic assessment of failed laboratory specimens generated in concurrent programs. Emphasis will be on specifically identifying the micromechanical damage mechanisms, relating them to a damage state, and determining the conditions required to transition to an alternate state.

Task 200 - Analytical Parameter Development

This task will extend current methods of fatigue and fracture mechanics analysis to account for microstructural complexities inherent in single crystal alloys. This will be accomplished through the development of flexible correlative parameters which can be used to evaluate the crack growth characteristics of a particular damage state. The proposed analyses will consider the finite element and the hybrid Surface-Integral and Finite Element (SAFE) methods to describe the micromechanics of crack propagation.

Task 300 - Probabilistic Modeling

This task will model the accumulation of fatigue damage in single crystal alloys as a Markov process. The probabilities of damage progressing between the damage states defined in Task 100 will be evaluated for input into the Markov model. The relationship between these transition probabilities and fatigue life will then be exploited to establish a model with comprehensive life predictive capabilities.

Task 400 - Reporting

Running concurrently with the analytical portions of the program, this task will inform the Navy Program Manager and Contracting Officer of the technical and fiscal status of the program through R&D status reports.

III. Technical Progress

In our previous report we further developed the description of IMQ defects found in PWA 1480 and PWA 1484. The three principal IMQ defect species (porosity, TaC and eutectics) have been quantified for comparative purposes via metallographic image analysis. Those results are being reduced and analyzed.

The temperature dependency of the eutectic phase as a fatigue crack initiator is a point that should be further addressed. There are insufficient archival specimen fractures available to properly define the activation temperature range for eutectic decohesion; a potential method would be a constant K crack growth test with a controlled temperature gradient. Analysis of the fracture surface then yields the temperature range where decohesion occurs. The fracture surface may also provide other information.

We previously discussed the micromechanics of decohesion versus fracture and stated a desire to study the interface between the defect and the surrounding bulk microstructure. A compact tension crack growth specimen provides sufficient fracture area to obtain specimens for thin film analysis of dislocation structures associated with these two phenomena.

This test would also provide valuable fatigue crack growth mode information, producing a da/dN vs. temperature plot over the selected temperature range. If the temperature gradient range encompasses a region where a bulk fracture mode transition occurs (Fig. 1), an associated change in fatigue crack growth rate may occur. This is shown schematically in the da/dN versus temperature plot in Figure 2.

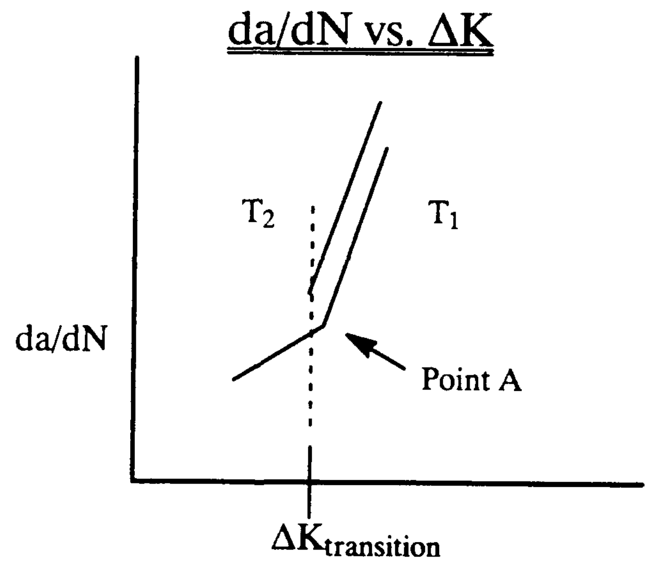

Figure 1. At T_1 a stress intensity dependent fracture mode transition is observed at Point A. At $\Delta K_{transition}$ a temperature dependent fracture mode transition exists between T_1 and T_2.

The growth rate change is expected to be proportionate to the relative amounts of the the constituent fracture modes present at any point in the transition. An example of these constituents might be microscopic octahedral fracture versus decohesion (cubic) fracture observed on either side of an isothermal K dependent transition.

Microscopic (001) fracture occurs in the threshold region of room temperature crack growth in PWA 1480. The K dependent fracture mode transition begins to occur at approximately 3-6 ksi root inches and is complete by 10 ksi root inches. The transition is to microscopic (111) fracture. Examples of these two microscopic fracture modes were described in detail in the September monthly progress report. The shaded-solid model shown in Figure 3 illustrates the fracture morphology after the transition is complete.

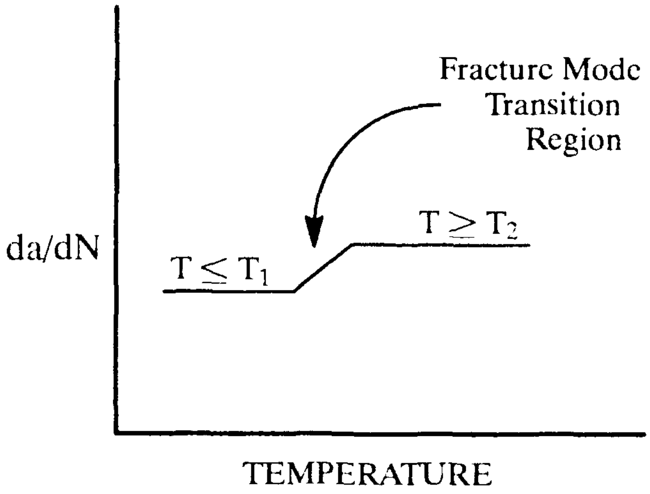

Figure 2. The temperature dependent fracture mode transition described in Fig. 1 is evaluated in a a constant K temperature gradient test at $K_{transition}$ between T_1 and T_2

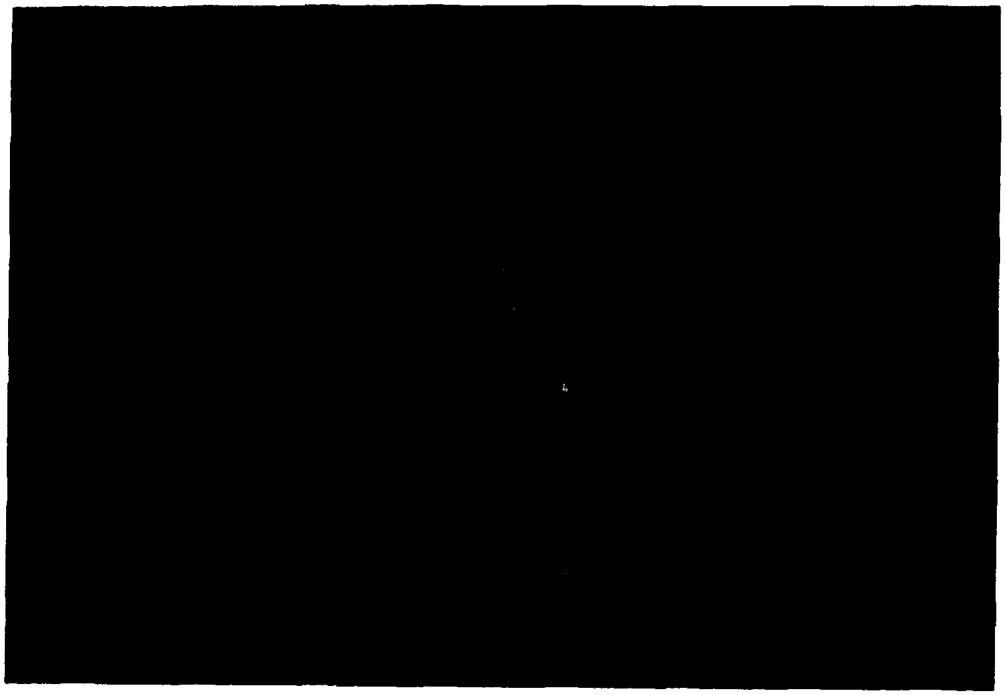

Figure 3. Shaded-solid model illustrating the end point of the K dependent transition, complete microscopic octahedral fracture (PWA 1482, 26°C, R = 0.5, 30 Hz, $\Delta K = 10 MPa\sqrt{m}$)

Our efforts to categorize and describe damage mechanisms have progressed to a point where we now theorize that the operative fatigue crack fracture mode is dependent on the rate of energy input and the dislocation mobility (degree and character) then in effect.

We have observed that in the K gradient test the sequence of a transition can operate in forward or reverse. The transition sequence is dependent on the sign of the K gradient in an isothermal test. Likewise, with K held constant, we expect that the sequence of the transition will be determined by the sign of the temperature gradient. Some transition temperature ranges may be small relative to the growth rate temperature dependance in adjacent single fracture mode regions (where no transition occurs). A temperature dependent fracture mode transition occurring over a narrow temperature range should therefore describe the effect of fracture mode alone on growth rate. Within the transition region mixed mode fracture has been observed to occur.

Hence, a paradigm appears to exist which states that the effect of K and T on a fracture mode transition are interchangeable. Either parameter can effect the relative amounts of the constituent fracture modes at any point in the mixed mode region of a transition.

The schematic in Figure 2 showed what might be expected from a T-gradient test where T spans a temperature dependent fracture mode change.

An important point is illustrated in figure 4. This figure describes the transition region in terms of the statistical variability that might be expected if tests were conducted on numerous specimens from differing heats of material. This is significant since it implies that the state transition probabilities required by the Markov paradigm are contained in the distribution indicated in the figure. The stochastic component of a fracture mode transition can be inferred because the major source of variability is expected to stem from minor differences in orientation, composition and thermal processing. Composition effects the alloys anti-phase boundary energy and therefore dislocation mobility. Orientation effects the resolved shear stresses on the octahedral planes.

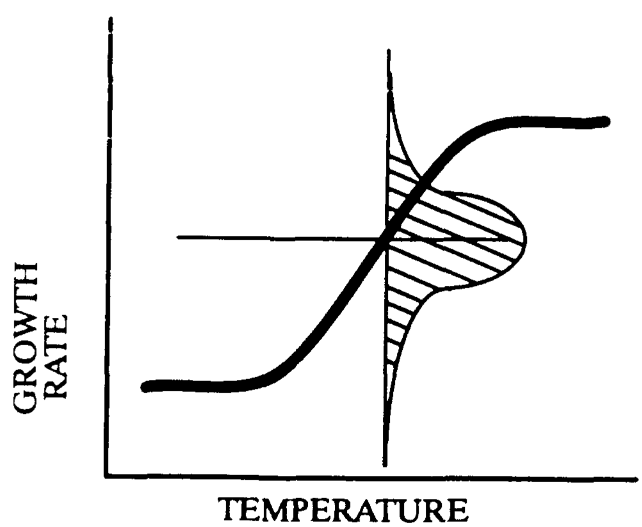

Figure 4. The variability in growth rate is representative of the variability that might be observed with multiple tests. The relationship stems from temperature dependent variation in dislocation mobility.

Thermal processing effects the propensity for cube cross slip, a function of gamma prime precipitate size.

Testing of this nature is about to commence under a parallel effort addressing threshold behavior of these alloys. Those fractures will be examined for evidence of decohesion and to assess state transition probability.

IV. Current Problems

No technical problems have been encountered during the reporting period.

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15. Supplementary Notes

16. Abstract (Limit: 200 words)

This program investigates the seemingly unusual behavior of single crystal airfoil materials. The fatigue initiation processes in single crystal (SC) materials are significantly more complicated and involved than fatigue initiation and subsequent behavior of a (single) macrocrack in conventional, isotropic, materials. To understand these differences is the major goal of this project.

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