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FATIGUE IN SINGLE CRYSTAL NICKEL SUPERALLOYS
Technical Progress Report

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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 is characterized by parallel continuous primary dendrites spanning the casting without interruption in the direction of solidification. Secondary dendrite arms (perpendicular to solidification) define

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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, Metal Park, Ohio, pp. 205-214

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 non-crystallographic, 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 no 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

During this reporting period our activities have centered around elevated temperature fatigue crack growth (FCG) threshold behavior. We have shown that underlying dislocation dynamics determine (and are mirrored in) observed fracture morphologies. The particular fracture mode in effect is a function of dislocation mobility (and character) and rate of strain energy input. In turn the operative fracture mode effects FCG behavior. As a result of the two phase micro structure present in the single crystal alloys a complex set of fracture modes exist. To a large extent this complexity derives from constituent dislocation motion in the γ and γ' phases and interactions at the matrix precipitate interface.

The driving force behind dislocation motion is input energy (stress / strain in fatigue or stress intensity in fracture). The resistive force , dislocation mobility / character, is a function largely of temperature. Since dislocation dynamics represent temperature dependent diffusion processes they may be modeled by Arrhenius rate kinetics. Discrete events such as fracture mode transitions or threshold stress intensity limits can be characterized by apparent activation energies and could form the basis for an energy based micromechanical life prediction system. Since fatigue crack initiation is controlled by the same dislocation dynamics as fracture the system could be a unified life prediction model treating initiation and propagation as a continuum. A number of opportunities present themselves when contemplating such a system. In an earlier progress report we described a temperature gradient FCG test that could be used to provide information about fracture mode transitions. This test would provide the means to obtain the activation energies for various condition dependent discrete events such as ΔK_{lim} (threshold stress intensity).

Factors other than bulk dislocation dynamics that exert a controlling influence on life are environmental (i.e.., oxidation, hydrogen, hot salt stress corrosion). These factors can also be expressed as an activation energy. An example can be seen in the influence of oxidation kinetics on the near threshold fatigue crack growth behavior of PWA 1484. There exists a minimum energy that must be supplied to an advancing crack tip to produce a free surface (ΔK_{lim}). This minimum energy stems from the need to attain a critical dislocation density in the cyclic plastic zone ahead of the crack tip. Thermally activated recovery processes result in instability in maintaining these dislocation concentrations. To achieve fracture one must supply sufficient energy to exceed the rate of dislocation recovery from the cyclic plastic zone. Oxidation complicates this processes by effectively reducing ΔK through the closure mechanism. The buildup of oxidation products on the fracture surfaces near the crack tip causes the crack surfaces to come into contact prior to minimum load in the cycle. The apparent environmental interaction (oxidation) energy can be obtained from the crack arrest point by assuming the rate of oxidation processes approaches the crack growth velocity when crack growth arrests.[2]

Thus, $\frac{da}{dt})_a = \frac{da}{dn})_a \times frequency = B\, e^{(\frac{-Q}{RT})}$ where Q is the apparent activation energy, T is temperature in K, R is the universal gas constant, and B is a constant. Table I below shows "arrest" points observed from PWA 1484 crack growth tests.

Table I: Crack Growth Arrest Points for PWA 1484

T, K	1/T (10^3K)	*da/dN* (10^{-6} in/cycle)	*da/dt* (mm/sec)
866	1.154	0.1571	7.98×10^{-05}
1,033	0.968	0.9763	4.96×10^{-04}
1,144	0.874	9.813	4.98×10^{-03}

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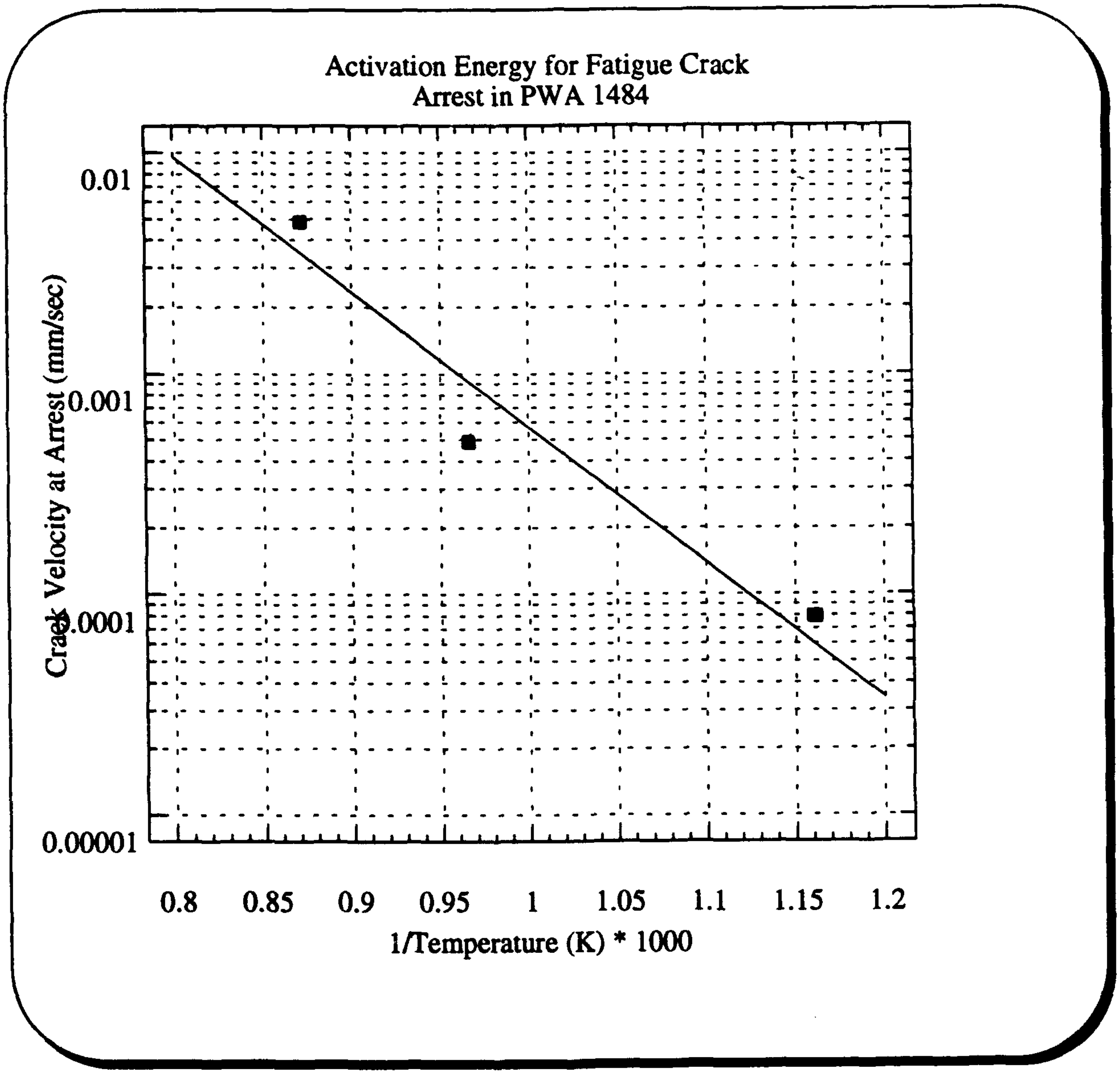
[2] Yuen, J. L., P. Roy, and W. D. Nix, Met. Transl. 15a, Sept., 1984 (1769-1775)

The data from Table I are shown in figure 1 below:

Figure 1:



Least squares regression gives $-Q/RT = -14.072$ K if $R = 3.779$ KJ/mol K which implies that $Q = 53.178$ KJ/mol.

IV. Current Problems

No technical problems have been encountered during the reporting period.

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16. Abstract (Limit: 200 words)

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