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Office of Navy Research  
Scientific Officer  
Attn: Dr. A. K. Vasudevan, Code 1222  
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Arlington, Va 22217-5000

Subject: Submittal of the Progress Report, FR21998-8

Gentlemen:

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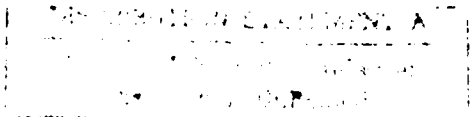
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# FATIGUE IN SINGLE CRYSTAL NICKEL SUPERALLOYS

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  $\langle 001 \rangle$  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<sup>1</sup>.

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  $\gamma'$  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  $\langle 001 \rangle$  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  $\gamma'$  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  $\gamma'$  precipitates in a  $\gamma$  matrix. The precipitate ranges from 0.35 to 0.5 microns and is an ordered Face Centered Cubic (FCC) nickel aluminate compound. The macrostructure of these materials

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<sup>1</sup> Gell, M., D. N. Duhi, 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.

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  $\langle 001 \rangle$  type crystallographic directions. Undissolved eutectic pools and associated microporosity reside throughout the interdendritic areas. These features act as microstructural 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  $\langle 001 \rangle$  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**

Our continuing efforts at categorizing damage states have given us the opportunity to contemplate some of the finer points of microstructural and behavioral relationships. Although aimed at enhanced airfoil durability through more intelligent methods of life prediction, our research has value in other areas worth mention here.

In our proposal we stated our intent to investigate the effects of pernicious environments such as hydrogen. Our interest in this area stems from experience with single crystals in liquid hydrogen fueled rocket engines. Fatigue and fracture of single crystals in high pressure hydrogen, however, parallels air behavior in

certain aspects. This has given us a view of IMQ defect activation and anti-phase boundary energy effects from a unique perspective.

The presence of atomic hydrogen has been found to have pronounced effects on dislocation dynamics in the cuboidal gamma prime precipitate strengthened superalloys. The chief manifestations are the activation of a normally benign IMQ defect species and an environmentally induced fracture mode transition. The May report discussed the fatigue crack initiation element of this micromechanical phenomenon. Through the modification of the eutectic distribution we have demonstrated an order of magnitude increase in LCF life in hydrogen.

In our December report we described a K dependant fatigue crack growth (FCG) mode transition. The near threshold FCG fracture mode is environmentally activated in the Paris region by high pressure hydrogen. The result of invoking a "low energy" fracture mode under high energy conditions is to experience a 100X increase in FCG propagation rate. Since the effect occurs on the strengthening precipitate level, a modification of the alloy on that level was effected. The result was to half the FCG rate under the most severe operating condition.

These practical applications resulting from our understanding of such points illustrate the value of an intimate knowledge of micromechanical damage processes. The alloy modifications were developed solely from micromechanical damage insight.

#### **IV. Current Problems**

No technical problems have been encountered during the reporting period.

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