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Gentlemen:

In accordance with the applicable requirements of the contract, we herewith submit one (1) copy of the subject report.

Very truly yours,

UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney

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Contract Data Coordinator

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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

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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.

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 427°C 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 982°C, 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

During this reporting period we have focussed on elevated temperature microscopic fracture modes observed in fatigue crack growth (FCG). Approximately 25 single edge notch, surface flaw and compact tension specimens run in *K*gradient or constant load were the subjects of the investigation.

Fracture details have been correlated with experimental FCG data for a variety of temperatures, stress ratios, and orientations. This effort has evolved into a study of the nature of energy-dependent fracture processes and has led us to view the material as a complex energy conversion system. The complexity derives from dislocation dynamics in the constituent phases and interactions with the ordered/disordered interface.

The micromechanisms by which the system dissipates imparted mechanical energy, through the development of a free surface, is dependent on the rate of energy input (ΔK or K_{max}) and the system energy. System energy refers to a number of temperature dependent phenomena:

- Increased amplitude of lattice fluctuations
- $\gamma - \gamma'$ mismatch
- Antiphase boundary energy (APBE)
- Superlattice intrinsic stacking fault energy (S-ISFE)

These affect dislocation mobility and character (octahedral slip, cube cross slip, climb, and bypass.). System energy also encompasses alloy composition and environmental modifiers since they also dictate dislocation mobility. These phenomena determine the micromechanical modes of fracture. Microscopic fracture modes are important because they can effect fatigue crack growth rate, ΔK_{limit} and closure mechanisms, for example

Our assessments of the fracture process have led us to hypothesize that the operative microscopic fatigue crack fracture mode is under some circumstances dictated by an activation energy, set by input and system or "state" energies. They in turn determine the available modes of energy dissipation and the particular mode that will be operative for a given set of service conditions. An example of one such activation energy was shown in the previous monthly report.

To date five of these microscopic fracture modes have been identified. They are (in order of ascending energy):

Low Energy Regime - Room Temperature (ΔK_{limit})

- $\gamma - \gamma'$ decohesion (sub microscopic octahedral fracture predominately confined to the γ matrix phase) - Restricted to PWA 1480
- Submicroscopic octahedral transprecipitate fracture - Restricted to PWA 1484
- Microscopic octahedral fracture (transprecipitate-crystallographic) - Room temperature Paris

Intermediate Energy Regime - 427°C

- Ancillary decohesion ($R = 0.1\ \Delta K_{limit}$) (under study)
- Transprecipitate non crystallographic fracture (monoplanar) ($R = 0.5\ \Delta K_{limit}$)

High Energy Regime - 427°C, $R = 0.5$ to 580°C $R = 0.1$ K dependent

- Transprecipitate non crystallographic fracture (ancillary)

Other states may exist. Those listed are under study and may be redefined as our understanding of them progresses.

Transitional regions between microscopic fracture modes have also been studied. As stated earlier, transitions have been correlated with ΔK for various stress ratios and temperatures. The following observations have been documented:

1. Microscopic fracture mode transitions from one mode to another have been observed at nearly all temperatures and stress ratios.
2. The available microscopic fracture modes are system energy dependent.
3. The operative microscopic fracture mode is input energy dependent.
4. The order in which sequential transitions occur is dependent upon the sign of the K gradient.
5. The point (ΔK) at which a transition occurs is independent of K gradient sign.
6. Transition behavior (at constant temperature) is R and K dependent. Restated, with system energy constant a transition will be input energy dependent.
7. The effects of system energy and input energy are likely to be interchangeable ie. with input energy constant transitions will be system energy dependent. This is significant in terms of TMF crack growth.

The probability of a fracture mechanism transition is important to alternative (statistically based) life modeling approaches (Annis and DeLuca[2]). Between initially decohesion and then microscopic octahedral fracture there exists a transition region where mixed mode fracture occurs. What takes place there is a unique process where increasing input energy results in little or no increase in growth rate. Telesman[3] referred to this region as one "where crack growth rate is independent of stress intensity." The source of the stochasm can be hypothesized. While it is true that the cuboidal γ' precipitate structure is uniform and geometrically ordered within the γ matrix, individual precipitates do exhibit significant deviation from perfect cubes of equal size. This is important since FCG behavior is a function of the operative fracture mode occurring on the precipitate level. The transition in the cuboidal γ' is not a discrete event but rather a K dependent trend due to the variability of a γ' precipitates ability to resist dislocation penetration. The transition occurs over a range of 3-5 $\text{ksi}\sqrt{in.}$ at room temperature. With increasing intensity the size of the microscopic octahedral facets increases up to overstress[4]

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[2] Annis, C. and D. P. DeLuca, "Markov Fatigue in *Single Crystal Airfoils*," ASME 92-GT-95, presented at the International Gas Turbine and Aeroengine Congress and Exposition, Cologne, Germany, June 1-4, 1992.

[3] Telesman, J. and P. Kantzos, "Fatigue Crack Growth Behavior of a Singel Crystal Alloy as Observed Through an In Situ Fatigue Loading Stage," NASA TM 100863, presented at the SAMPE Metals Processing Conference, Dayton, Ohio, Aug. 2-4, 1988.

[4] Telesman, op. cit.

IV. Current Problems

No technical problems have been encountered during the reporting period.

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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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