LIFE PREDICTION AND CONSTITUTIVE MODELS FOR
ENGINE HOT SECTION ANISOTROPIC MATERIALS

GUSTAV A. SWANSON
Pratt & Whitney
United Technologies Corporation

INTRODUCTION

The development of directionally solidified and single crystal alloys is perhaps
the most important recent advancement in hot section materials technology. By reduc-
ing or eliminating grain boundaries in superalloys, the high temperature strengths
have been substantially improved. Metallurgists have developed the alloy chemistries
and casting processes so that they are now in practical use. However, the life lim-
its of gas turbine parts, under complex loading conditions, are still not well known
or understood. The objective of this program is to develop that knowledge to enable
the designer to improve anisotropic gas turbine parts to their full potential.

Program Overview

The base program, which is followed by two options (fig. 1), will concentrate on
coated turbine blade airfoil conditions. The coating, which is added to turbine air-
foils to improve their oxidation and corrosion life, plays a major role in fatigue
initiation. For this reason coated specimens are used extensively in this program.
The materials have been selected, specimen fabrication is underway, the literature
search is completed and Task III testing has begun. Table I shows the task breakdown
of the base program.

Material Selection

The two single crystal alloys selected are PWA 1480 and Alloy 185. Table II
lists the composition of these alloys. PWA 1480 was selected because it is the sin-
gle crystal alloy most widely used today in gas turbine engines. Furthermore, it is
representative of other practical single crystal alloys. Alloy 185 was selected be-
cause of differences between it and PWA 1480. These differences include a high vol-
ume fraction of $\gamma'$ due to the higher aluminum content, a large $\gamma/\gamma'$ misfit due to
the high molybdenum content, and a higher level of creep anisotropy at higher tem-
peratures. Contrast between the two alloys will provide a good test of the general-
ity of any life prediction and constitutive models developed in this program.

The coatings selected are an overlay coating, PWA 286, and an aluminide diffu-
sion coating, PWA 273. Coating chemistries are listed in Table III. These widely
used coatings represent two basic classes.

Test Specimens

The constitutive specimens are solid and cylindrical; the fatigue specimens are
hollow and cylindrical. The latter geometry is particularly applicable to thermo-
 mechanical fatigue (TMF) specimens. The thin wall facilitates thermal transient re-
sponses at reasonably fast rates. In addition, compressive stresses can be achieved
with minimum risk of buckling. The crystallographic orientation of the specimens for both the constitutive and life prediction program will include <100>, <110>, <111>, and <123>. Under tensile loading, the first two orientations produce slip along the orthogonal planes; the third along cuboidal planes, and the forth a mixture of the two.

Test specimens for the coatings' tensile, constitutive, and life properties required special preparation. The plasma-sprayed specimens were fabricated by two methods; some were machined from HIPed bulk powder. The others were sprayed with a 1.5 mm (0.060 in.) layer of coating on a metal substrate which was subsequently removed by machining. On turbine blades the plasma-sprayed coating is about 0.4 mm (0.015 in.) thick and finished with shot peen. Metallographically the two specimens bracket the actual porosity of airfoil coating (see fig. 2).

Diffusion coating properties are impossible to measure directly. The strategy in this program will be to utilize two thicknesses of substrate. Specimens of both thicknesses will be coated and then tested for tensile, creep and fatigue properties. The results will then be plotted versus substrate thickness and extrapolated to zero thickness to obtain the values for the coating alone.

Models to be Evaluated

An extensive literature search has been completed for both the constitutive and life prediction models. The bulk of the past work has been done on isotropic materials. This research will be adapted to anisotropic materials whenever possible. For example, the life prediction models may use maximum resolved shear strain ranges on the active slip planes in place of principle strain ranges. The constitutive models to be considered will include macroscopic continuum theories of Hill (ref. 1), and Lee and Zaverl (ref. 2 and 3), or a unified visco-plastic formulation such as that of Walker and Cassenti (ref. 4 and 5). The unified theory is currently being extended by Walker to recognize specific slip systems of nickel-based single crystal alloys. Stouffer, in a parallel program (ref. 6), is also developing a constitutive model for single crystal alloys. All of these models will be evaluated utilizing the test data generated in this program.

Life prediction models under consideration include a number of isotropic models: linear time-cycle fraction (ref. 7), ductility exhaustion (ref. 8 and 9), frequency modified life (ref. 10, 11 and 12), frequency separation (ref. 13 and 14), Ostergren's method (ref. 15), strain range partitioning (ref. 16), damage mechanics,(ref. 17 and 18), continuous damage (ref. 19 and 20), and cumulative damage approach (ref 21). All of these models will be evaluated utilizing resolved shear stress and/or strain on active slip planes. A model to study the interaction of the coating and substrate is being developed.

Test Results

Because the test program is in its early stages evaluation of the results would be premature. One interesting preliminary result, however, is a comparison of the fracture surfaces of tensile specimens of PWA 1480 pulled in the <001> direction shown in figure 3. Note that the faceting at 760°C (1400°F) is pronounced and that
the number of active slip planes is small. However, as the test temperature is increased to 1093°C (2000°F), the number of faceting planes becomes more numerous and the fracture surface appears more normal to the tensile load.

Plans

By October 1985, we plan to complete the Task III tests and to have a preliminary evaluation of the constitutive and life prediction models.

REFERENCES


TABLE I
BASE PROGRAM TASKS

I Material/Coating Selection and Acquisition

II Selection of Candidate Life Prediction and Constitutive Models

III Level 1 Experiments

IV Correlation of Models With Level 1 Single Crystal Experiments

V Level 2 Single Crystal Experiments

VI Final Selection of Life Prediction and Constitutive Models

VII Subcomponent Verification For Primary Single Crystal Material

VIII Alternate Single Crystal Material Characterization For Airfoil Applications

IX Model Verification On Alternate Single Crystal Material

X Delivery of Computer Code to NASA

TABLE II
SINGLE CRYSTAL ALLOY COMPOSITION
(Weight Percent)

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Ni</th>
<th>Cr</th>
<th>Co</th>
<th>Ti</th>
<th>Al</th>
<th>Ta</th>
<th>W</th>
<th>Mo</th>
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<th>C</th>
<th>B</th>
<th>Zr</th>
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<tr>
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<tr>
<td>Alloy 185</td>
<td>Bal</td>
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<td>6.8</td>
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* Balance
TABLE III

COATING MATERIALS

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<tr>
<th>Coating</th>
<th>Composition</th>
<th>Deposition Process</th>
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<tr>
<td>Overlay</td>
<td>NiCoCrAlY + Si + Hf</td>
<td>Vacuum Plasma</td>
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<td>PWA 286</td>
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<td>Spray</td>
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<tr>
<td>Diffusion</td>
<td>Aluminide/</td>
<td>Gas Phase</td>
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<td>PWA 273</td>
<td>Outward Diffusion</td>
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PROGRAM OUTLINE

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<tr>
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<td>TWO SINGLE CRYSTAL ALLOYS PWA 1480 &amp; ALLOY 185</td>
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<tr>
<td></td>
<td>TWO COATINGS OVERLAY (PWA 286) DIFFUSION (PWA 273)</td>
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| OPTION 1 |       |      |      |      |      |
|          | BLADE ROOT CONDITIONS |      |      |      |      |
|          | TWO SINGLE CRYSTAL ALLOYS SAME AS ABOVE |      |      |      |      |
|          | COATINGS NONE         |      |      |      |      |

| OPTION 2 |       |      |      |      |      |
|          | AIRFOIL & ROOT CONDITIONS |      |      |      |      |
|          | ONE DSR MATERIAL (DIRECTIONALLY SOLIDIFIED OR RECRYSTALLIZED) |      |      |      |      |
|          | ONE COATING            |      |      |      |      |

Figure 1
Figure 2
FRACTURE SURFACE OF PWA 1480 TENSILE SPECIMENS

760°C (1400°F)  

871°C (1600°F)  

962°C (1800°F)  

1093°C (2000°F)

Figure 3