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CONSTITUTIVE AND LIFE MODELING OF SINGLE CRYSTAL BLADE ALLOYS FOR ROOT ATTACHMENT ANALYSIS

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ABSTRACT

This paper describes work in progress under a NASA contract (NAS3-23939) to develop fatigue life prediction and constitutive models for uncoated attachment regions of single crystal gas turbine blades. At temperatures relevant to attachment regions, deformation is dominated by slip on crystallograhic planes. However, fatigue crack initiation and early crack growth are not always observed to be crystallographic. The influence of natural occurring microporosity will be investigated by testing both hot isostatically pressed and conventionally cast PWA 1480 single crystal specimens. Several different specimen configurations and orientations relative to the natural crystal axes are being tested to investigate the influence of notch acuity and the material's anisotropy. Global and slip system stresses in the notched regions have been determined from three dimensional stress analyses and will be used to develop fatigue life prediction models consistent with the observed lives and crack characteristics.

INTRODUCTION

The attachment regions of turbine airfoils are geometrically complex with a variety of notched features at the interface with the turbine disk and in the transition to the blade platform. These features lead to stress concentrations which are potential fatigue crack initiation sites. In single crystal components, the critical regions can have a variety of local material orientations depending upon the location of the notch and the crystallographic orientation in which the component is cast.

This paper describes a three year combined analytical and experimental program intended to develop constitutive and fatigue life prediction models for single crystal attachment regions. The work is a part of NASA contract NAS3-23939, "Life Prediction and Constitutive Models for Engine Hot Section Anisotropic Materials ". The contract is divided into two parts with the Base Program focussed on developing models for the coated airfoil regions of turbine blade and the Option 1 Program addressing the lower temperature uncoated attachment regions. This paper is confined to the second part of the contract and presents results from the first year of the effort.

DISCUSSION

Over 150 constitutive and fatigue tests will be conducted on single crystal PWA 1480 specimens in three notched configurations and in several crysatllographic orientations. All tests are being conducted isothermally and will be limited to temperatures below 1600F. Conventionally cast and heat treated PWA 1480 is used in the bulk of these tests, but some tests will be conducted on hot isostatically pressed (HIP'd) PWA 1480 to investigate the influence of microporosity on fatigue life, since fatigue initiation sites are commonly associated with pores in conventionally cast material.

Double edge notched plates with two different sized notches as shown in Figure 1 are being used in the program. The gage section thickness of the sharp notched specimen is 0.050 inches while the mild notched geometry will be tested two thicknesses; 0.050 and 0.200 inches. To completely describe the orientation of a notched specimen, both primary orientation (i.e. the loading direction) and secondary orientation (i.e. the direction normal to the notch) must be specified as illustrated in Figure 2. The orientations are designated by a pair of Miller indices, <HKL><PQR>, which define the primary and secondary orientations respectively. Six different crystallographic orientations have been selected for the notched specimens; <001><100>, <001><210>, <101><10$\bar{1}$>, <101><1$\sqrt{2}\bar{1}$>, <111><011> and <213><4$\bar{5}\bar{1}$>. These orientations were selected to span the full range of possible crystal orientations in the attachment region while minimizing the out-of-plane distortions that can occur in nonsymmetrically aligned anisotropic bodies.

The prediction models must properly account for crystallographic orientation in the notch. Life parameters based on slip system quantitites will be among those investigated since deformation (and presumably damage) is known to occur by slip in specific crystal directions at temperatures in the regime of interest. Such models can be expected to account for orientation effects in an implicit manner. More conventional life parameters such as maximum principal stress or

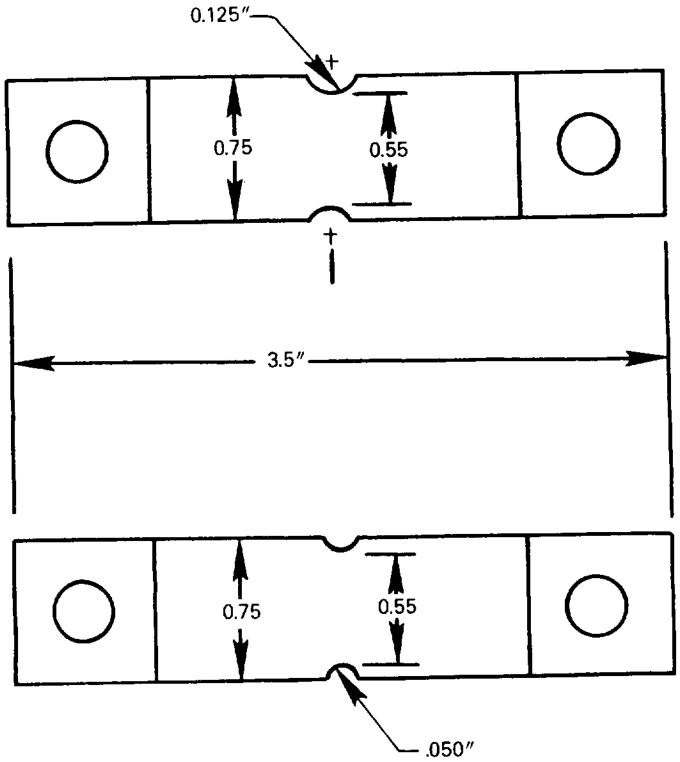

FIGURE 1 MILD AND SHARP NOTCH SPECIMEN GEOMETRIES

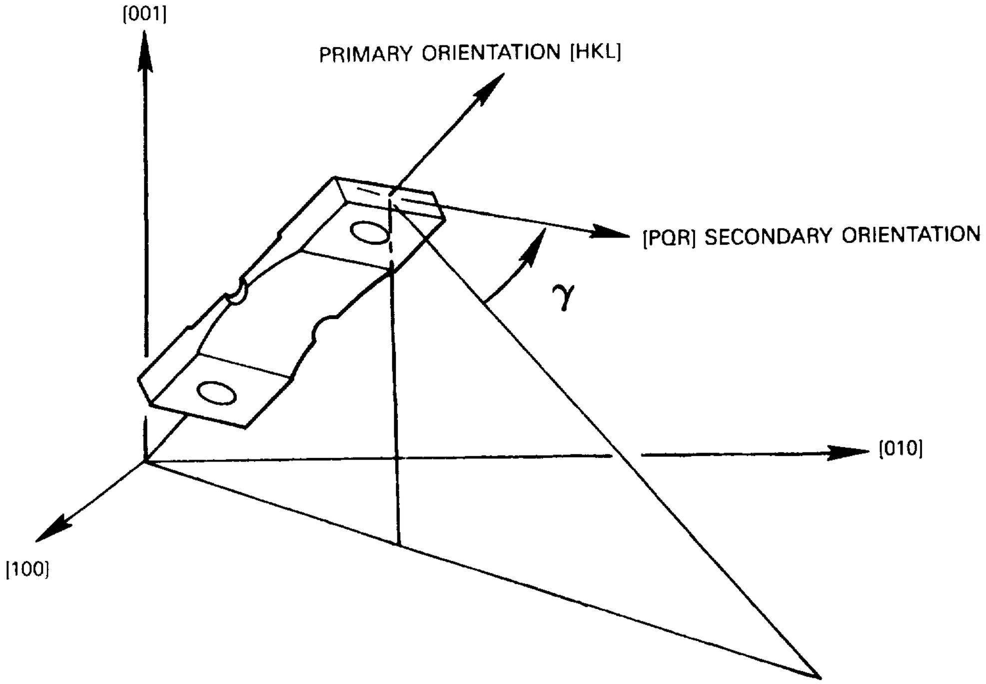

FIGURE 2 PRIMARY AND SECONDARY ORIENTATIONS OF SPECIMENS

strain also account for orientation through proper anisotropic stress analysis. Three dimensional stress analyses are being used to determine the local stresses and strains in each configuration and orientation. In some orientations the location of maximum stress does not occur at the minimum section as would be expected in isotropic specimens of the same shape. Global and slip system stresses and strains have been determined as a function of location in the notch. See Figure 3. Finite element results for the thin, mild notched specimen in the <001>, <101> and <111> primary orientations are shown in Table 1. The values presented are at the element integration points closest to the notched surface. Figure 4 shows the finite element mesh used in the analysis. Additional analyses using a more refined finite element mesh as well as boundary element analyses are being conducted to provide more accurate stresses and strains on the notch surface. The boundary element code being used is the BEST3D (Boundary Element Stress Analysis Technology - Three Dimensional) which was developed by Pratt & Whitney and SUNY-Buffalo as part of NASA contract NAS3-23697. For convenience, the stresses and strains in Table 1 have been normalized by the net section stress or strain to give a stress or strain concentration factor.

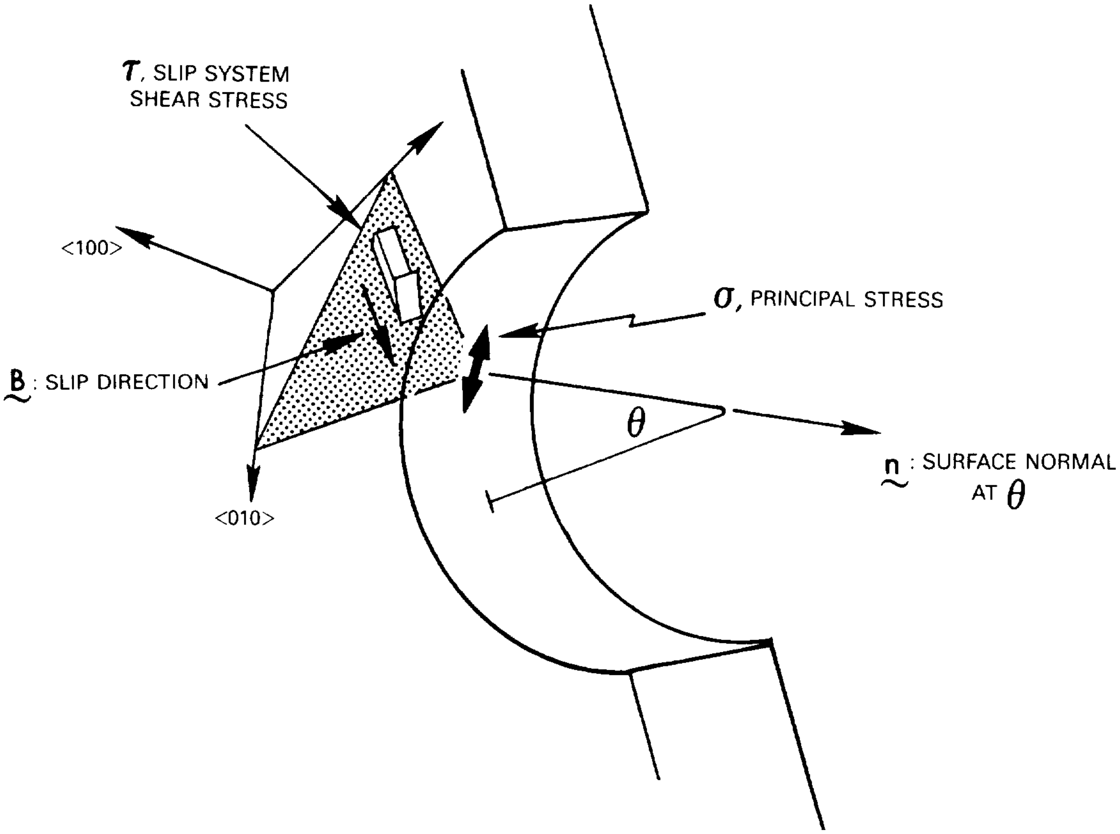

FIGURE 3 GLOBAL AND SLIP SYSTEM STRESSES IN THE NOTCH

TABLE 1

Global and Slip System Parameters for Thin, Mild Notched Specimens

Orientation		Principal Strain		Principal Stress		Maximum Slip System Shear Stress		
Primary	Secondary	θ	ϵ/E	θ	σ/S	θ	τ/S	$\underset{\sim}{B} \cdot \underset{\sim}{n}$
<001>	<100>	0	1.5	23	1.8	23	.76	.28
<001>	<210>	0	1.5	23	1.8	23	.79	.00
<101>	<10$\bar{1}$>	0	1.9	0	2.0	0	.77	.48
<101>	<1$\sqrt{2}\bar{1}$>	0	1.9	0	2.0	0	.72	.17
<111>	<01$\bar{1}$>	0	2.0	0	2.0	16	.57	.22

θ = anglular location in the notch measured from the minimum section (degrees)
S = net section stress
E = net section strain
σ = maximum principal stress in the notch
ϵ = maximum principal strain in the notch
τ = shear stress on the most highly stressed octahedral slip system
$\underset{\sim}{B}$ = slip direction of the most highly stressed octahedral slip system
$\underset{\sim}{n}$ = surface normal

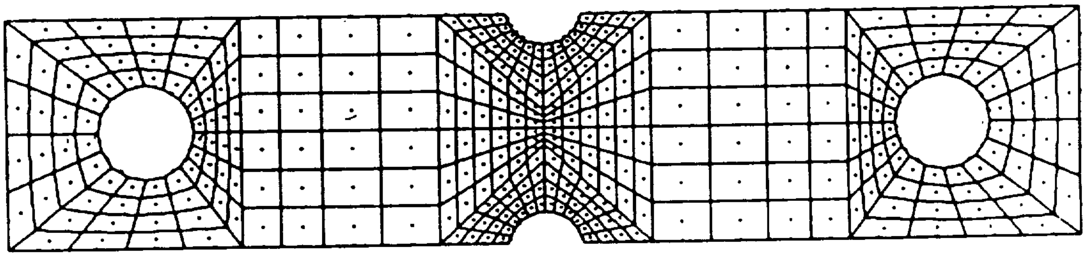

FIGURE 4 THREE DIMENSIONAL FINITE ELEMENT MESH USED IN SPECIMEN ANALYSIS

The location of the maximum principal stress and the maximum strain do not coincide for all orientations being tested. In addition, the maximum slip system shear stress and the maximum principal stress do not change in constant proportion from one orientation to another and do not even occur at the same location in the notch for the <111><01$\bar{1}$> orientation.

The results shown in Table 1 are from elastic finite element analyses. However at the stress levels of interest to this program, the region around the notch yields. The test data clearly shows slip lines being formed at the fatigue loads. A constitutive model for this nonlinear material behavior is being developed to permit nonlinear stress analysis. Such a model was developed in the Base Program with emphasis on high temperature behavior (Swanson et. al., 1987), and will be refined as necessary for the lower temperature regime of interest in this program. This model uses the unified approach for computing all inelastic strains simultaneously rather than the conventional approach of separating plastic and creep strains. Global stresses are resolved onto the twelve octahedral and six cube slip systems and then used in a viscoplastic formulation to calculate inelastic strains on each slip system. The strains in the global coordinate system are then obtained by summing the slip system shear strains. The model constants were determined from approximately forty cyclic constitutive tests on uniaxial strain controlled specimens tested at several temperatures between 800F and 2200F. Specimens were oriented in the <001>, <101>, <111> and <213> directions. These test showed that the material is only moderately strain rate sensitive at 1400F and is very insensitive at 1200F and below.

Fatigue tests have just recently begun on thin, mild notched specimens. Tests have been conducted at room temperature, 1200F and 1400F at 1 cycle per second under load control. There is insufficient data to date to report clear life versus stress trends, however some information regarding crack initiation sites and crack morphology is available. In general, cracks were found to initiate from casting micropores in un-HIP'd material and at locations corresponding to the maximum principal stress rather than the maximum principal strain. For the orientations tested to date this initiation site also coincides with the maximum slip system shear stress, so that it is not possible to conclude which of these two paramters is more important. Figure 5 is an overall view of a <001><100> specimen cycled between 6 and 115 Ksi. nominal stress at 1400F. Life to failure was 2976 cycles. Fatigue cracks initiated in both notches near the maximum stress location and in the latter stage of growth, progressed along a {111} plane intersecting the specimen surface at an angle of 48 degrees from a line connecting the notch centers. For a perfectly aligned <001><100> specimen, the slip system with the highest shear stress intersects the specimen surface at 45 degrees from a line connecting

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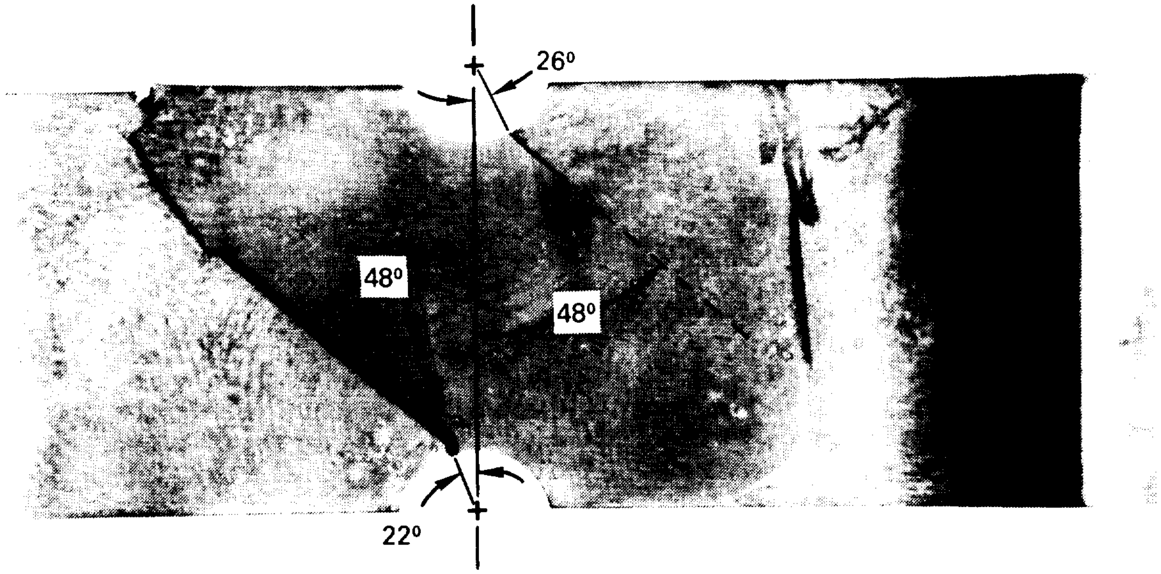

FIGURE 5 FATIGUE CRACKS IN <001> <100> MILD NOTCHED SPECIMEN

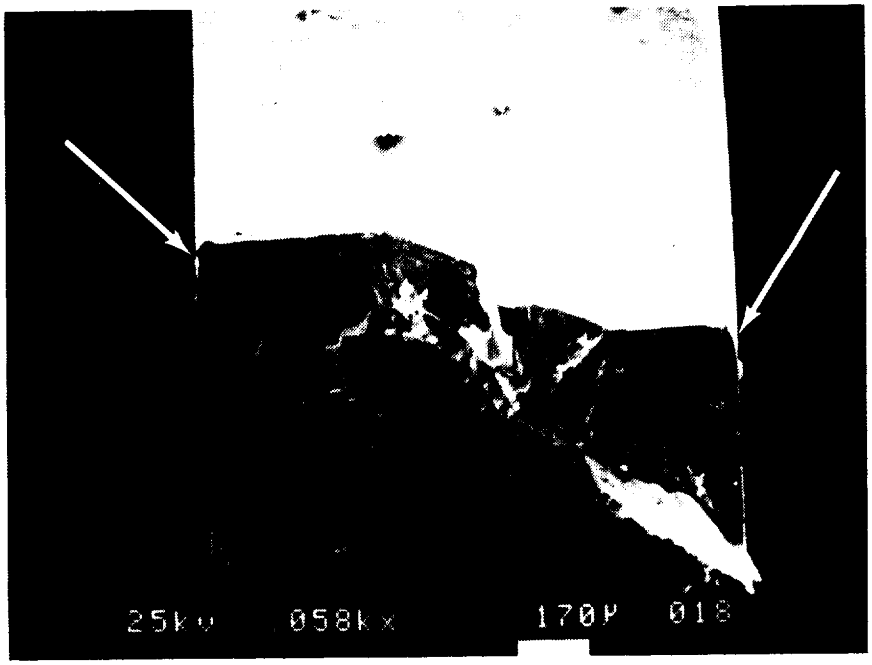

FIGURE 6 FATIGUE CRACK ORIGINS AT CASTING MICROPORES LOCATED NEAR THE MAXIMUM STRESS/MAXIMUM SLIP SYSTEM SHEAR STRESS

the notch centers. Figure 6 shows the initiation sites in the primary crack in more detail. Cracks initiated from two separate pores which were located at angles of 22 and 30 degrees from the minimum specicimen dimension. The maximum stress location in this orientation is calculated to be 23 degrees from the notch bottom. The crack planes near the initiation sites were perpendicular to the maximum stress direction rather than along a single {111} plane. However a closer examination of similar pore initiated cracks by Anton in 1987 showed that the crack plane was formed by crack growth along several intersecting octahedral planes. So even though the general plane of the crack is perpendicular to the principal stress, it cannot be concluded that the principal stress is the controlling fatigue paramenter. The three dimensional stress state in the vicinity of the pore will lead to several slip systems having high stress and may promote cracking on more than one plane at a time. In a similar fashion, the transverse "constriction" stress in the thick specimens to be tested may lead to multiple plane cracks.

After an initial region of "non-crystallographic" growth, the cracks turn abruptly and proceed along a single {111} plane. Critical crack sizes for this transition are being determined. Detailed crack growth measurements in the early stages of crack growth are being taken in room temperature tests to provide additional data for model development. Figure 7 shows crack growth data obtained by periodic inspection at 100X magnification with the specimen unloaded.

Hot isostatic pressing eliminates microporosity so that the initiation processes and lives are expected to be different than in the un-HIP'd specimens. Fatigue studies in superalloy single crystals by Giamei and Anton (1986) showed that cracks initiated due to slip steps formed at the intersection of slip planes and the surface. In the absence of micropores, surface initiation is anticipated. In anticipation that slip step height may be an important initiation parameter in HIP'd material, two of the secondary orientations were chosen to vary the angle at which the most highly stressed slip system intersects the notch surface. The angle of intersection with the notch surface can be quantified by the dot product of a vector in the slip direction, $\underline{B}$, and a vector normal to the surface, $\underset{\sim}{n}$. A dot product of 1 indicates that the slip direction is perpendicular to the surface (resulting in a large slip step) while a dot product of 0 indicates that the slip direction is parallel to the surface (producing no slip step). Table 1 shows how this parameter varies with secondary orientation in the <001> and <101> primary orientation specimens.

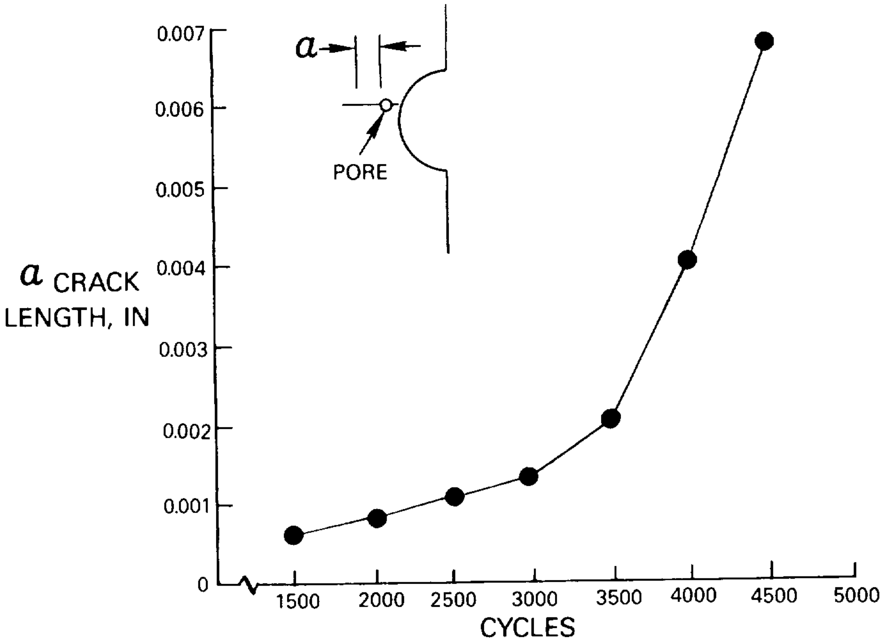

FIGURE 7 FATIGUE CRACK GROWTH FROM MICROPORE

CONCLUSIONS

The analytical and test program described above is a multiyear effort intended to develop constitutive and fatigue life prediction models for single crystal materials with application to the lower temperature uncoated and notched regions of turbine airfoils. Specimen configurations and orientations have been chosen to span the range of possible attachment configurations while testing possible fatigue paramenters in a systematic way. Initial test indicate that the in thin un-HIP'd notches fatigue cracks are initiated at casting micropores near the maximum stress location. This preliminary data suggests that the maximum strain is not the best fatigue parameter.

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