Fatigue Failure of Space Shuttle Main Engine Turbine Blades

Gregory R. Swanson
Aerospace Engineer
ED22/ Structural Mechanics Team
NASA, Marshall Space Flight Center
MSFC, AL

Nagaraj K. Arakere
Associate Professor
Mechanical Engineering Department
The University of Florida
Gainesville, FL

Abstract

Experimental validation of finite element modeling of single crystal turbine blades is presented. Experimental results from uniaxial high cycle fatigue (HCF) test specimens and full scale Space Shuttle Main Engine test firings with the High Pressure Fuel Turbopump Alternate Turbopump (HPFTP/AT) provide the data used for the validation. The conclusions show the significant contribution of the crystal orientation within the blade on the resulting life of the component, that the analysis can predict this variation, and that experimental testing demonstrates it.

Introduction

Objectives for this study, enumerated below, are motivated by the need for developing failure criteria and fatigue life evaluation procedures for high temperature single crystal components, using available fatigue data, finite element modeling of turbine blades, and engine test data

1. Develop fatigue failure criteria for single crystal material. Apply the proposed criteria for uniaxial LCF test data. Determine a lifing equation based on the curve fit of the failure parameter with LCF test data.
2. Describe finite element modeling of single crystal SSME turbine blades, including the effects of variation of primary and secondary crystal orientations.
3. Using the FE stress analysis results and the fatigue life relations developed, determine the effect of variation of primary and secondary crystal orientations on life, at critical blade locations.
4. Determine the most advantageous secondary crystal orientation for a given blade design and compare with engine test results.

Single crystal superalloys have highly orthotropic material properties that vary significantly with direction relative to the crystal lattice. The majority of material testing focuses on two key crystallographic orientations, <001> and <111>, which have the largest variation in capabilities relative to each other. Limited additional data is available for other orientations. To analyze test results for material that is not isotropic not only must the stress and strain be transformed from one coordinate system to another, but also the constitutive relations must be transformed.

Coordinate Transformations for Orthotropic Material

Transformation of the stress and strain tensors between the material and specimen coordinate systems is necessary for implementing the failure criteria outlined. These transformations are based on the derivations by Lekhnitskii [1]. The components of stresses in the (x', y', z') system in terms of the (x, y, z) system is given by

$$\{\sigma'\} = [Q']\{\sigma\} \tag{1}$$

$$\{\sigma\} = [Q']^{-1}\{\sigma'\} = [Q]\{\sigma'\} \tag{2}$$

The strain vector transformation matrix is different from [***Q***] because $\gamma_{xy} = 2\varepsilon_{xy}$, $\gamma_{zx} = 2\varepsilon_{zx}$, and $\gamma_{yz} = 2\varepsilon_{yz}$, which accounts for engineering vs. tensor shear strain components.

$$\{\varepsilon'\} = [Q'_\varepsilon]\{\varepsilon\} \tag{3}$$

The generalized Hooke's law for a homogeneous anisotropic body in Cartesian coordinates (x, y, z) is given below [1].

$$\{\varepsilon\} = [a_{ij}]\{\sigma\} \tag{4}$$

[$\boldsymbol{a}_{ij}$] is the matrix of 36 elastic coefficients, of which only 21 are independent.

The elastic properties of FCC crystals exhibit cubic symmetry, also described as cubic syngony. Materials with cubic symmetry have only three independent elastic constants designated as the elastic modulus, shear modulus, and Poisson ratio [2]. Invoking the rules of elastic symmetry for a material exhibiting cubic syngony [1] we see that $[a_{ij}]$ has only 3 independent elastic constants,

$$a_{11} = \frac{1}{E_{xx}},\ a_{44} = \frac{1}{G_{yz}},\ a_{12} = -\frac{\nu_{yx}}{E_{xx}} = -\frac{\nu_{xy}}{E_{yy}}$$

Unlike isotropic materials, the components of $[a_{ij}]$ are a function of orientation.

The Transformation of Elastic Constants under a Coordinate System Transformation

Transformation of 2nd order tensors under a coordinate system transformation is described in detail by Lekhnitskii [1] and only the final results are presented here.

The Hooke's law in the (x, y, z) coordinate system is given by Eq. (5).

$$\{\varepsilon\} = [a_{ij}]\{\sigma\} \qquad (5)$$

The Hooke's law in the (x`, y`, z`) coordinate system is given by Eq. (6).

$$\{\varepsilon'\} = [a'_{ij}]\{\sigma'\} \qquad (6)$$

The elastic constant matrix transforms as follows:

$$[a'_{ij}] = [Q]^T [a_{ij}][Q] = \sum_{m=1}^{6}\sum_{n=1}^{6} a_{mn} Q_{mi} Q_{nj} \qquad (7)$$
$$(i, j = 1, 2, \ldots\ldots, 6)$$

We can now transform the elastic constants and hence the stresses and strains between the material coordinate system (x, y, z) and the specimen coordinate system (x`, y`, z`).

Uniaxial Fatigue Test Data and Fatigue Failure Criteria

Uniaxial fatigue test data for PWA1493 at 1200 F was used to develop the fatigue failure criteria. Four different orientations of the crystal relative to the loading direction of the specimen were tested. These were <001>, <111>, <213>, and <011>. Figure 1 shows the cyclic strain amplitude Vs. The cycles to failure. There is considerable scatter in this data. Many possible fatigue failure criteria were tried in the course of this study, including polycrystalline and single crystal specific, with the resolved $\Delta\tau_{max}$ criteria selected based both on performance and simplicity. This criteria is based on finding the maximum resolved shear stress amplitude among the 30 slip systems possibly active in deformation of a FCC crystal [2]. Equation 8 is the best fit for this criteria to the uniaxial data, and figure 2 is a plot of resolved $\Delta\tau_{max}$ Vs. cycles to failure.

$$\text{resolved } \Delta\tau_{max} = 397{,}758\ N^{-0.1598} \qquad (8)$$

Equation 8 gives a useful relation that can be used to calculate fatigue life for PWA1493 at 1200F. This relation will be used to calculate fatigue life at a critical blade tip location for the SSME turbine blade.

Application of Fatigue Failure Criteria to Finite Element Stress Analysis Results of Single Crystal Nickel Turbine Blades

Turbine blades used in the High Pressure Fuel Turbopump Alternate Turbopump (HPFTP/AT) are fabricated from single crystal nickel PWA1493 material. In September of 1997 an HPFTP/AT for the Space Shuttle Main Engine (SSME) suffered a turbine blade failure during development testing [3,4,5]. Cause of the blade failure in the HPFTP/AT was determined to be the initiation and propagation of fatigue cracks from an area of high concentrated stress at the blade tip leading edge. Inspection of blades from other units in the test program revealed the presence of similar cracks in the turbine blades. When the size of the fatigue cracks for the population of blades inspected was compared with the secondary crystallographic orientation β a definite relationship was apparent [3,4].

Primary crystallographic orientation of a turbine blade, commonly referred to as α, is defined as the relative angle between the airfoil stacking line and the <001> direction. Figure 3 shows the finite element model of the first stage turbine blade and the coordinate system defined at the bottom of the attachment. The negative z axis is the stacking axis. Current manufacturing capability permits control of α to within 5° of the stacking line. The SSME AT blades are allowed to have a maximum α variation of 15° [5].

Secondary orientation, commonly referred to as β, defines the angle of the <100> orientation relative to the blade geometry. The reference location on the blade geometry for establishing 0° β is a line parallel to the blade attachment as shown in Fig 3. In most turbine blade castings the secondary orientation β is neither specified nor controlled during the manufacturing process. Because each blade can have a different secondary orientation, finite element stress analysis of the blades has to account for a range of β orientations between 0 – 90 degrees.

Description of the Finite Element Model

The HPFTP/AT first stage blade ANSYS finite element model (FEM) was cut from a large 3D cyclic symmetry model that includes the first and second stage blades and retainers, interstage spacer, disk and shaft, and the disk covers. The models are geometrically nonlinear due to the contact surfaces between the separate components. The large model was developed by ADAPCO for P&W as part of the Critical Design Review (CDR) for the HPFTP/AT [5]. Due to the large size of the global model cutting the first stage blade from it was necessary to reduce the computer run time and file size required for the multiple runs needed to study the effect of material orientation.

The element type used for the blade material is the ANSYS SOLID45, an 8-node 3D solid isoparametric element with internal extra shape functions. Anisotropic material properties are allowed with this element type, the ANSYS program aligns the material coordinate system with the element coordinate system. To generate the 297 material coordinate systems used for this study local coordinate systems were generated and the element coordinate systems aligned with them [4]. Two angles, Δ and γ, locate the primary material axis relative to the casting axis, the third angle, β, is the clocking of the secondary material axis about the primary material axis. Figure 4 shows the distribution of the 297 different material coordinate systems within the allowed 15 degree maximum deviation from the casting axis.

The boundary conditions represent full power mainstage operation of the Space Shuttle Main Engine, referred to as 109% RPL SL (Rated Power Level Service Life). The shaft speed is 37,355 rpm, the airfoil temperature is approximately 1200 F, forces representing the blade damper radial sling load are applied to the blade platform, and pressures are applied to the blade surfaces and internal core.

The 297 finite element results files presented a difficult challenge to post process. Two FORTRAN codes, developed at MSFC, were employed for this effort [4]. The first strips the element results from the coded binary output files and places them into ASCII text files. The second program processes the ASCII files to calculate averaged nodal results, the resolved shear stresses and strains and the normal stresses and strains in the single crystal material coordinate system. It then calculates the parameters chosen for study and sorts them based on user set criteria.

Effect of Secondary Crystal Orientation on Blade Tip Stress Response

Variation of secondary crystal orientation on stress response at the blade tip critical point prone to cracking (tip point on inside radius) was examined by analyzing the results from the 297 FE model runs. The FE node at the critical point was isolated and critical failure parameter value ($\Delta\tau_{max}$) computed on the 30 slip systems. Using the fatigue life equation based on the $\Delta\tau_{max}$ curve fit of LCF test data, Equation 8, we can obtain a contour plot of dimensionless life at the critical point as a function of primary and secondary orientation, as shown in Figure 5. The maximum life is obtained for β = 50 degrees, and Δ = 0 degrees and γ = 7.5 degrees, and Δ = 5.74 degrees and γ = 13.86 degrees.

The test history for blade tip cracking is shown in the contour plot in Figure 6. Data from 100 blades is plotted with crack length (as measured from the inside of the core across the wall at the tip) setting the contour shading against the case number, defined in Figure 4, and secondary angle, β. The largest cracks were completely through the airfoil and had propagated to the point that sections of the blade separated. The largest cracks are in the region of lowest life, and none of the large cracks are in the region of high normalized life.

Conclusions

Fatigue failure in PWA1480/1493, a single crystal nickel base turbine blade superalloy, is investigated using a combination of experimental LCF fatigue data and 3D FE modeling of HPFTP/AT SSME turbine blades. Several failure criteria, based on the normal and shear stresses and strains on the 24 octahedral and 6 cube slip systems for a FCC crystal, are evaluated for strain controlled uniaxial LCF data (1200 F in air). The maximum shear stress amplitude, $\Delta\tau_{max}$, on the 30 slip systems was found to be an effective fatigue failure criterion, based on the curve fit between $\Delta\tau_{max}$ and cycles to failure.

Investigation of leading edge tip cracks in operational SSME turbine blades had revealed that secondary crystal orientation appeared to influence whether a crack initiated and arrested or continued to grow until failure of the blade airfoil. The turbine blade was modeled using 3D FEA that is capable of accounting for material orthotrophy and variation in primary and secondary crystal orientation. Effects of variation in crystal orientation on blade stress response were studied based on 297 FE model runs. Fatigue life at the critical locations in blade was computed using FE stress results and failure criterion developed. Detailed analysis of the results revealed that secondary crystal orientation had a pronounced effect on fatigue life. The optimum value of secondary orientation $\beta = 50^\circ$ computed corresponds very closely to the optimum value of β indicated in the failed population of blades. Control of secondary and primary crystallographic orientation has the potential to significantly increase a component's resistance to fatigue crack growth without adding additional weight or cost.

References:

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[3] Moroso, J, "Effect of secondary crystal orientation on fatigue crack growth in single crystal nickel turbine blade superalloys," *M. S. Thesis*, Mechanical Engineering Department, University of Florida, Gainesville, FL, May 1999.

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[5] Pratt and Whitney, "SSME Alternate Turbopump Development Program HPFTP Critical Design Review," P&W FR24581-1 December 23, 1996. NASA Contract NAS8-36801.

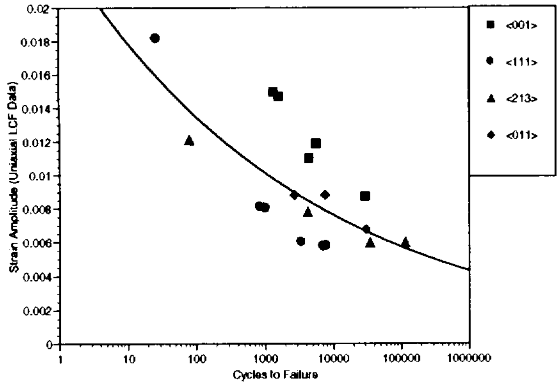

Figure 1. Strain range Vs. Cycles to Failure for LCF test data (PWA1493 at 1200F)

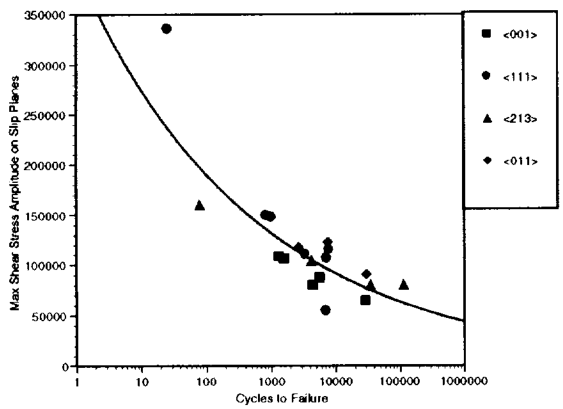

Figure 2. Shear Stress Amplitude [$\Delta\tau_{max}$] Vs. N

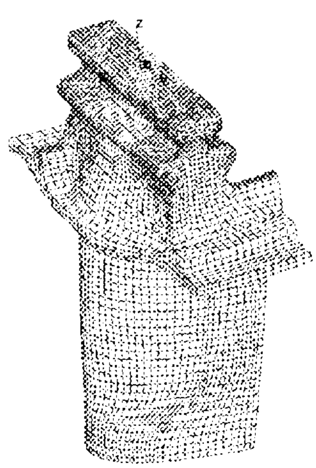

Figure 3. First Stage Blade Casting Coordinate

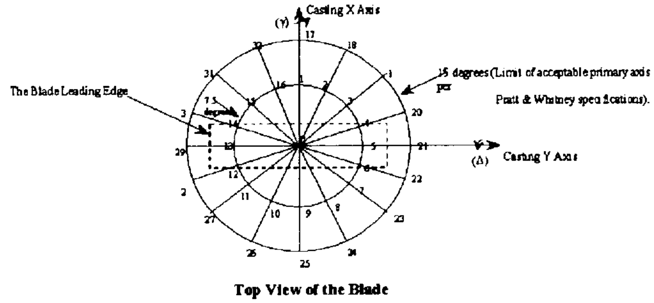

Figure 4. 33 primary axis cases with 9 secondary cases each, a total of 297 material

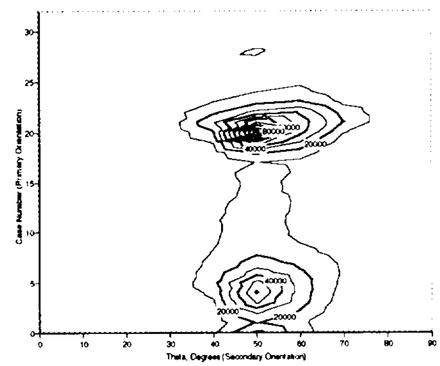

Figure 5. Normalized HCF life at blade tip

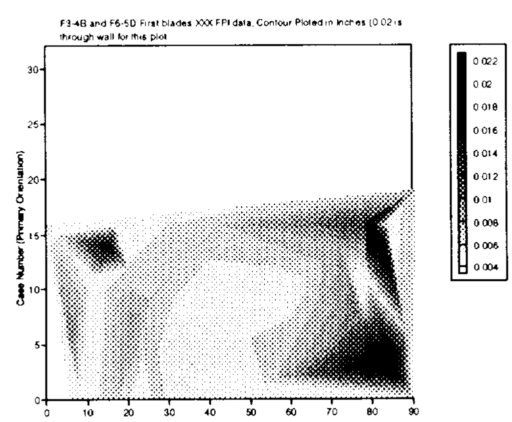

Figure 6. Actual crack sizes from engine test data

ABSTRACT

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High Cycle Fatigue (HCF) induced failures in aircraft gas turbine and rocket engine turbopump blades is a pervasive problem. Single crystal nickel superalloy turbine blades are used because of their superior creep, stress rupture, melt resistance, and thermomechanical fatigue capabilities over polycrystalline materials. Currently he most widely used superalloys are PWA 1480, PWA 1484, and PWA 1493. Single crystal materials have highly orthotropic properties making the orientation of the crystal lattice within the parts geometry a significant factor in the overall analysis.

Experimental validation of finite element modeling of single crystal turbine blades is presented. Experimental results from uniaxial high cycle fatigue (HCF) test specimens and full scale Space Shuttle Main Engine test firings with the High Pressure Fuel Turbopump Alternate Turbopump (HPFTP/AT) provide the data used for the validation. The conclusions show the significant contribution of the crystal orientation within the blade on the resulting life of the component, that the analysis can predict this variation, and that experimental testing demonstrates it.

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