RESIDUAL LIFE ASSESSMENT OF THE SSME/ATD HPOTP TURNAROUND DUCT (TAD)

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INTRODUCTION

Many of the life-limiting structural problems encountered in high-temperature aircraft and rocket engines result from thermal fatigue behavior. It has been known for over a hundred years that temperature gradients within a structure produces internal stresses. These thermally induced stresses can be as large or larger than the internal stresses generated by the application of external mechanical loads to the structure. Most aircraft and many rocket engines are reusable designs which must be able to withstand cyclic thermal and mechanical stress excursions associated with engine startup and shutdown. For these reusable designs, low cycle thermal fatigue is the life-limiting failure process for certain engine components.

A large body of analytical and experimental work has been produced over the last 50 years concerning the low cycle thermal fatigue behavior of metals. Halford [1] provides a historical review of work in this area starting in the early 1950's and extending into the late 1980's. The field of engineering fracture mechanics grew parallel with this field of low cycle thermal fatigue. From an engineering standpoint, these two fields merge once the component has been exposed to sufficient thermal stress cycles to allow for formation of a discernible crack or cracks.

This paper is concerned with the prediction of the low cycle thermal fatigue behavior of a component in a developmental (ATD) high pressure liquid oxygen turbopump (HPOTP) for the Space Shuttle Main Engine (SSME). This component is called the Turnaround Duct (TAD). The TAD is a complex single piece casting of MAR-M-247 material. Its function is to turn the hot turbine exhaust gas (1200^0 F hydrogen rich gas steam) such that it can exhaust radially out of the turbopump. In very simple terms, the TAD consists of two rings connected axially by 22 hollow airfoil shaped struts with the turning vanes placed at the top, middle, and bottom of each strut. The TAD is attached to the other components of the pump via bolts passing through 14 of the 22 struts. Of the remaining 8 struts, four are equally spaced (90^0 interval) and containing a cooling tube through which liquid hydrogen passes on its way to cool the shaft bearing assemblies. The remaining 4 struts are empty. One of the pump units in the certification test series was destructively examined after 22 test firings. Substantial axial cracking was found in two of the struts which contain cooling tubes. None of the other 20 struts showed any sign of internal cracking. This unusual low cycle thermal fatigue behavior within the two cooling tube struts is the focus of this study.

The fatigue and fracture analysis described in this report closely follows work performed by Sakon et al., [2] on thermally shocked steam turbine pump casings. The investigation procedure follows the outline given below.

A. Establish an approximate analytical relationship between the J-integral for a cracked body under deformation-controlled loading and the strain-based intensity factor K_e.

B. Use a linear finite element analysis (FEA) of the TAD structure to determine the cyclic stress behavior of the "cracked" region. This FEA did not model the crack(s) and only standard solid elements were employed to represent the geometry.

C. Determine the functional form of the cyclic J-integral (ΔJ) in terms of the elliptical crack dimensions using the information from steps (A) and (B).

D. Employ the experimental crack growth data for the MAR-M-247 material to establish the differential crack growth equation

$$da/dN = f(\Delta J).$$ (1)

E. Numerically solve the ordinary, first order, nonlinear, differential equation (1) for the crack length "a" as a function of the number of thermal cycles "N".

ANALYSIS

A. Estimation of Cyclic J-Integral (ΔJ)

A number of investigators [3-4] have examined the use of the strain-based intensity factor to estimate the J-integral value when small scale yielding is occurring in the vicinity of the crack. Sakon and Kaneko [3] proposed that the value of J for the inelastic situation can be approximated by the elastic J-integral, Je, for a deformation-controlled problem, such as thermal fatigue. They compared elastic and inelastic J-integral values for several cracked plate specimen geometry's using the FEM to substantiate the J=Je approximation.

Since the elastic form of the J-integral has been assumed for this problem, the relationship $J_e = K_I^2/E$ may be employed to convert the problem from one of finding the functional form of ΔJ to one of finding the functional form for ΔK, the cyclic stress intensity factor.

B. Linear Finite-Element Analysis of the TAD

As part of the TAD design process, the pump designers at the Pratt and Whitney Division of United Technologies developed a 3-D ANSYS finite element model of a 1/22nd section of the TAD. This initial model consisted of 39,720 tetrahedral (10 noded) elements and 66,639 nodes (=200,000 DOF). Essentially symmetric mechanical and thermal loading conditions on the TAD allowed for the construction of a smaller 1/44th segment model with symmetric boundary conditions.

This 1/44th segment model was used to perform the thermal and structural analyses of the TAD. A transient thermal analysis was done covering the standard Service Life mission at the 109% power level. The highest temperature gradients within the TAD structure were observed to occur during quick acceleration from 0% to the 109% power level and during steep deceleration from the 65% power level to engine shutdown. Steady state operation at the 109% power level produces low thermal gradients within the TAD structure and ,hence, low thermal stresses.

Examination of the transient thermal analysis results by Pratt and Whitney engineers lead to the identification of two acceleration time points and two deceleration time points where the temperature gradients peaked within various locations of the TAD structure. Linearly elastic structural analyses were performed at each of these four time points to determine the TAD internal stress and strain state. This stress (strain) information is necessary to establish the cyclic stress (strain) history experienced by the TAD structure during the Service Life mission.

"Hoop" stress (σ_H) contours acting on the centerline of the strut were constructed for the four time points of interest. Based on these stress contours and the observed fracture behavior, two possible crack "paths" are considered for fracture analysis. The distribution of the "hoop" stress along each of the assumed crack paths was extracted from the FEM results for all four of the time points. The stress range experienced by a given point, A, along the crack path is the difference between the acceleration and deceleration hoop stress values at point A. Since there are two acceleration and two deceleration time points, four stress range combinations are possible:

$$\Delta\sigma_H{}^1 = \sigma_H{}^{7703} - \sigma_H{}^{7203}$$

$$\Delta\sigma_H{}^2 = \sigma_H{}^{7705} - \sigma_H{}^{7203}$$

$$\Delta\sigma_H{}^3 = \sigma_H{}^{7703} - \sigma_H{}^{7205}$$

$$\Delta\sigma_H{}^4 = \sigma_H{}^{7705} - \sigma_H{}^{7205}$$

for each crack path. The largest stress range for any point along crack path #1 is produced by the stress difference created from time points 7705 (deceleration) and 7205 (acceleration). This behavior is true for the other three crack paths and from this point onward in the analysis, the stress range employed to calculate the cyclic stress intensity value, ΔK, is that given by $\Delta\sigma_H = \sigma_H{}^{7705} - \sigma_H{}^{7205}$, for all four crack paths.

C. Functional Form of ΔK in Terms of Cyclic Stress Range and Crack Dimensions

The cyclic stress intensity factor, ΔK can be calculated from the cyclic stress range, $\Delta\sigma$, by use of a method recommended by the ASME Boiler and Pressure Vessel Code, Section XI.

$$\Delta K_I = (M_m \Delta\sigma_m + M_b \Delta\sigma_b)\sqrt{\pi a} \tag{2}$$

M_m - MEMBRANE CRACK SHAPE FACTOR
M_b - BENDING CRACK SHAPE FACTOR
$\Delta\sigma_m$ - MEMBRANE COMPONENT OF THE STRESS RANGE AT CRACK TIP
$\Delta\sigma_b$ - BENDING COMPONENT OF THE STRESS RANGE AT CRACK TIP

The membrane and bending crack shape factors functions of the crack dimensions a (depth) and c (length). The formulas for these shape factors was given by Newman in terms of a and c. From the previously determined stress range along the crack path, $\Delta\sigma$, the membrane and bending stress range components, $\Delta\sigma_m$ and $\Delta\sigma_b$, are known as functions of the crack depth a. Consequently, ΔK is now completely determined as a function of the crack depth a.

D. Experimental Determination of $h(\Delta K)$

Pratt and Whitney engineers have experimentally determined the function $h(\Delta K)$ for the MAR-M-247 material and approximated the function as

$$\log[h(\Delta K)] = C_1\sinh(C_2\log[\Delta K] + C_3) + C_4$$

where C_1, C_2, C_3 and C_4 are experimentally determined constants.

E. Solution of the Crack Growth Equation, da/dN = h(ΔK)

The Crack Growth Equation is a first order, nonlinear, ordinary differential equation which was solved using the MATLAB software (Runge-Kutta, 2-3) for the crack depth a(N).

CONCLUSIONS

1) The present analysis method cannot completely predict the low-cycle thermal fatigue cracking observed in the cooling tube struts of Unit #9.

   a) During thermal cycling the analysis predicts periods of rapid crack growth, but the total crack length is less than that observed in service.
   b) Prediction accuracy could be improved by defining how the hoop stress varies across the "net" section as the crack grows.

2) The linear elastic FEM analysis indicates that a sufficient thermal stress cycling occurs to cause substantial low-cycle crack growth, if an initial flaw exists.

3) More complete knowledge of the thermal environment on the interior of the strut is necessary to improve the fatigue behavior prediction.

REFERENCES

1. Halford, A. G, in *Thermal Stresses II*, edited by Richard B. Heinarski, published by North-Holland, 1987.

2. Sakon, T., Fujiharu, M., and Sada, T..,in *Thermo-mechanical Fatigue Behavior of Materials*, ASTM STP 1186, 1993, pp. 239-252.

3. Sakon, T., and Kaneko, H., in *Proceedings of the Fifth International Conference on Creep of Materials*, May 18-21, 1992, pp. 227-233.

4. Rau, C. A., Jr., Gemma, A. E., and Leverant, G. R., in *Fatigue at Elevated Temperatures*, ASTM STP 520, 1973, pp 166-178.