A TEST AND EVALUATION OF ROCKET COMBUSTOR LIFE PREDICTION METHODOLOGIES

I.K. Sung, W. Anderson
Purdue University, W. Lafayette, IN, USA

Introduction

Low cycle fatigue (LCF) caused by high thermal and mechanical loading is known as a main life limiting factor for regeneratively cooled rocket combustors. At elevated temperatures, fatigue deformation is accelerated by creep-fatigue interaction. Current life prediction methods are limited by the lack of the exact physical understanding and analysis technique. At present, several theories like dislocation theory are used to explain the creep and fatigue damage, but with limited success. This shortcoming in predictive capability is particularly severe for advanced metals and composites for which little design heritage or basic data exist, therefore phenomenological approach is widely used.

The goal of the work described here is the development of an integrated analytical /experimental approach for life prediction that uses prototypical subscale combustors for low-cost tests. Several life prediction approaches were applied to predict the expected failure mechanism of the gradual thinning and bulging of the cooling passage (the "dog house" effect). The creep-fatigue interaction, strain-life, and visco-plastic modeling approaches were used. Finite element analysis using ABAQUS was adapted to refine thermal structural analysis. In addition to whole liner analysis, 2-D beam section of ligament was analyzed to understand clearly the behavior of liner stress, strain and deformation.

An experimental chamber was also designed to evaluate the analytical approach. A parametric study for two candidate liner materials, copper and steel (SST304), was first done to select the material that would provide the best validation results. The built test article is a water-cooled cylindrical liner with rectangular coolant channels and centerbody to provide a throat. To eliminate stress due to the difference in thermal expansion between the liner and jacket were made from oxygen-free high-conductivity (OFHC) copper and were brazed to each other. A pre-combustor was used to generate hot gas by burning a mixture of hydrogen peroxide and JP-8. The chamber components have been built and will be installed in the test cell after brazing.

Background

In modern high-thrust liquid rocket engines, the temperature and pressure of the combustion gas are around 3,600K (6,000°F) and 20MPa (3,000psi). The throat heat flux can rise to 115-130W/m^2 (70-80 Btu/in^2-s) [1]. At present only copper alloys are used for regenerative cooled liquid engine combustor liner [2]. These materials show good thermal durability, which represents strength against high thermal stress and shock occurring at engine operation. However due to its low melting point (1,350K), this copper liner wall temperature should be kept below 860K (1,100°F) by the regenerative cooling. In the Space Shuttle Main Engine (SSME), for example, the wall thickness is only 0.76mm (0.03"), but the temperature difference is about 200K (360°F) [3]. Because of this high thermal gradient, the stress rises up to 100-150MPa, most of which is over the elastic region and the material deforms plastically.

It is known that creep and fatigue are two main life limiting factors [3]. The major parameters influencing fatigue crack growth rate are frequency, stress ratio and temperature. Under a maintained load, time dependent creep dominates plastic deformation at high temperature. To make matters worse two mechanisms (creep and fatigue) can interact to result in plastic ratcheting, or cyclic-dependent creep. Successive tests of small thrusters by Quentmeyer [3] and Jankovsky et al. [4] at the NASA Lewis Research Center showed that combustor life is determined not only by fatigue but by creep-fatigue interaction, corrosion and sometimes ductile rupture. This process results in progressive deformation and thinning of coolant channel wall.

To investigate creep fatigue interaction, many analytical models like damage fraction rules, linear and cumulative damage rules, strain range partition methods and frequency modified equations were developed. Kasper [5] used a cyclic fatigue and creep analysis approach to estimate combustor life. Porowski et al.[6] attempted a simplified structural model of the coolant channel ligament as a rectangular beam for life prediction. Dai and Ray [7] improved this method by introducing the concepts of equivalent sandwich beam model approximation and a time-dependent viscoplastic model. Walker and Freed developed a hybrid model using Walker's theoretical structure and Miller's methodology, and obtained material parameters for aluminum, copper, nickel and tungsten [8]. Recently Riccius, et al. [9,10] presented some papers to improve rocket engine design using optimization techniques and to investigate material properties for elasto-plastic flow model.

At Purdue, a small scale combustor similar to that used at NASA Lewis Research Center was designed and tested.[11] The test section comprises a plug nozzle and a water-cooled OFHC (CU102) copper liner. Oxidizer was obtained by decomposing hydrogen peroxide (90% H_2O_2 + 10% H_2O by weight), and mixed with JP-8 to create hot combustion gas. An unexpected failure due to coolant leaking to adjacent channel terminated the tests early.

Analytical Approach

- Beam model

Failure of rocket combustors typically represents by "dog-house effect" failures in the cooling channel. This channel has a lower aspect ratio than usual real engine to promote the cyclic damage. Only one channel among 28 channels shown Figure 1 was picked up and this channel was analyzed using the structural beam model theory.

- Linear Damage Model [12]

$$\Sigma \frac{N}{N_f} + \Sigma \frac{t}{t_r} \geq 1 \qquad (1)$$

(1) For given stress determine cyclic life (N_f) and rupture time (t_r).
(2) Calculate applied load and hold time for each cycle.
(3) When left side of equation is bigger than 1, failure occurs.

- Porowski method [6]

This method is applicable to static condition, and predicts life of ligament using rectangular beam model. The procedure is as follows,

(1) Estimate deformation rate per cycle, δ

(2) Compute thinning after N cycles:

$$t_N = \frac{N\delta w}{(\ell + w)} \tag{2}$$

(3) Calculate critical thickness at instability:

$$t_{cr} = 2H\exp(-q) \tag{3}$$

where q is strain hardening exponent and H is material constant.

(4) Assess the predominant phenomenon between creep and fatigue.

(5) When $t_W < t_{cr}$, cyclic life is $N = N_f$

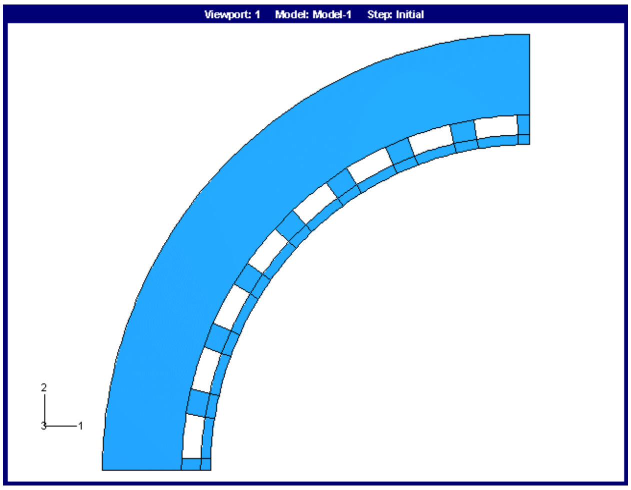

Fig. 1. Cross section of nozzle throat region

- Viscoplastic method [7]

The method developed by Dai and Ray is based on the concepts of a sandwich beam model and visco-plasticity to represent progressive bulging and thinning phenomena in the coolant channel ligament. The total strain rate is the sum of elastic and inelastic strain:

$$\varepsilon_{ij} = \varepsilon_{ij}^{e} + \varepsilon_{ij}^{in} \tag{4}$$

Each strain can be obtained by the integration of the elastic and inelastic strain rate.
Elastic strain rate is given by Hooke's law:

$$\dot{\varepsilon}_{ij}^{e} = \frac{(1+\nu)}{E}\dot{\sigma}_{ij} - \frac{\nu}{E}\dot{\sigma}_{kk}\delta_{ij} \tag{5}$$

where ν is Poisson's ratio and E is Young's modulus. Inelastic strain is calculated using Freed's unified viscoplastic model. Given loading condition such as pressure, temperature and channel configuration of the cooling channel, the time-dependent permanent radial deflection at the hot wall midplane is:

$$w^{p}(x,t) = \frac{1}{d_1 + d_2}\left(\frac{x^2}{2\ell}\int_0^{\ell} \tilde{I}_2^{in}\, d\xi - \int_0^{x}\int_0^{\eta} \tilde{I}_2^{in}\, d\xi\, d\eta \right) \tag{6}$$

where subscripts 1 and 2 denote coolant and hot side thin faces of the beam, respectively. The ligament thinning rate is expressed as follows with radial permanent deflection $w^p(t)$:

$$\bar{\tau}(t) = \frac{\left(\frac{4\ell}{a} + 1\right) w^{p}(t)}{\frac{4\ell}{a}\left(\frac{2\ell}{a} + 1\right)\vartheta_0} \tag{7}$$

where a is rib thickness between channels and θ_0 is the original ligament thickness.

The critical thickness is given by [2]:

$$\theta_{cr} = \theta_0 \exp(-q) \tag{8}$$

where $q = 0.2[(S_u - S_y)/S_y]^{0.6}$
S_u = Ultimate stress
S_y = Yield stress

Finally life is computed as:

$$Life = \frac{\theta_0 - \theta_{cr}}{\bar{\tau}(t)} \tag{9}$$

- Finite Element Analysis (FEA)

A commercial FEA code (ABAQUS) was used to refine analytical prediction. Plastic deformation and progressive thinning and bulging was simulated. From the maximum equivalent plastic strain range total life was determined. Using 2-D model, more detailed isotropic hardening and thermal ratcheting effect was also investigated.

Experimental Approach

Preliminary analysis used 1-D thermal models and empirical stress-strain life curves to design a test section that could show a measurable indication of plastic ratcheting within a reasonable number of cycles. The liner comprised 28 rectangular channels milled into an OFHC cylinder. The hot wall thickness was set at 0.76 mm (0.030"). The rib width was set at 2.69 mm (0.106"). The channel width and height were 3.17 mm (0.125") and 1.778 mm (0.07"), respectively. This configuration was determined to result in a measurable thinning within a reasonable number of cycles at the test conditions. Figures 2, 3, and 4 show the schematic assembly, the water-cooled chamber liner partly inserted into the jacket, and the water-cooled center-body, respectively. The center-body was coated with thermal barrier coating (TBC) to a thickness of 0.254 mm (0.01"). All parts are now ready to test. Test will be conducted in June this year.

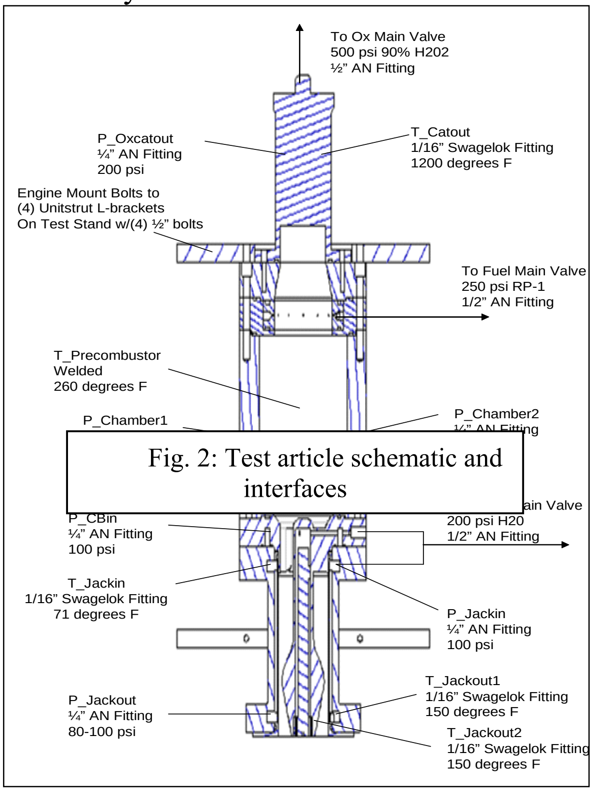

Fig. 2: Test article schematic and interfaces

Detailed Analysis

A one-dimensional code using the Bartz and Seider-Tate correlations for hot- and coolant-side heat transfer coefficients, respectively, was developed and applied. This code was modified to catch side wall effect using fin theory. The coolant flow rate was set to maintain a safe margin from a calculated burnout heat flux of 13.7E6 [W/m^2] (8.49 [Btu/in^2-s]. Pressurized de-ionized water was used as coolant for both the center body and the chamber liner. Figures 5 and 6 show the predicted heat flux and wall temperature. Figure 7, obtained by FE analysis, shows the wall temperature distribution at the throat.

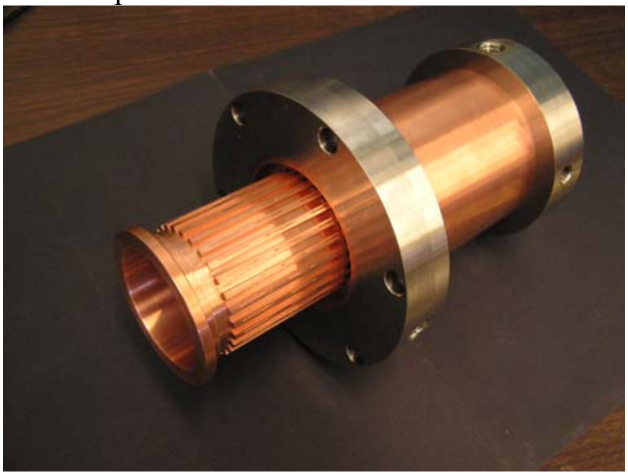

Fig. 3. Chamber liner and jacket before brazing

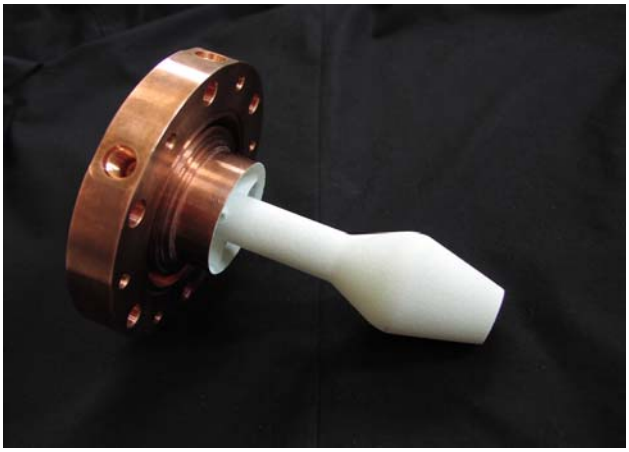

Fig. 4. Center-body after TBC coating

With these calculated loads, a detailed life analysis was done. A finite difference numerical method was used to solve the strain rate equation. Figure 9 shows gradually decreased hoop strain range indicating cyclic hardening of annealed material under constant loading. Figure 10 shows the hysteresis loop and thermal ratcheting during five cycles.

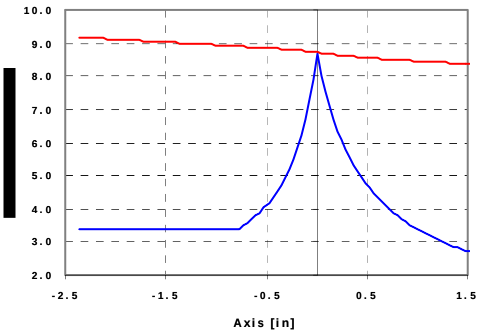

Fig. 5. Predicted chamber heat flux as function of chamber length. Throat is at 0.0 location

Figure 11 shows a total strain of 1.52% resulting in 220 cycles from the S-N curve of OFHC test data. With same condition SST 304 showed 3.02% total strain and 50 life cycles. To eliminate excessive deformation and unusual behavior, OFHC was chosen. Figures 12 and 13 show radial strain variation of first one cycle and progressive strain increasing from 10 to 20 cycles respectively, showing the progressive bulging inward. The thinning rate shown Figure 14 was obtained from viscoplastic theory. From the thinning rate of 1.481E-3 mm/cycle and the critical wall thickness, the life was determined to be 106. Figure 15 represents the deformation after 50 cycles and shows maximum plastic strain at the channel midpoint.

Figure 8 shows the 2-D beam model mesh. The analysis results are shown Figures 9 and 10 for first five cycles.

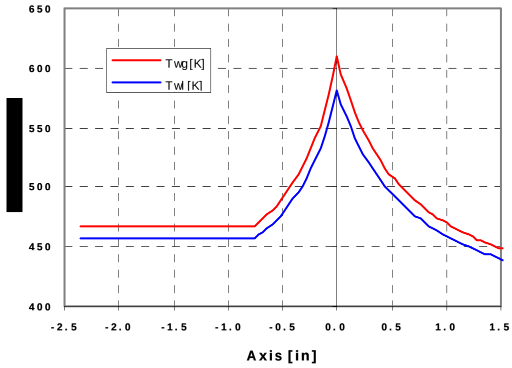

Fig. 6. Predicted gas-side and coolant-side wall temperature as function of test section length

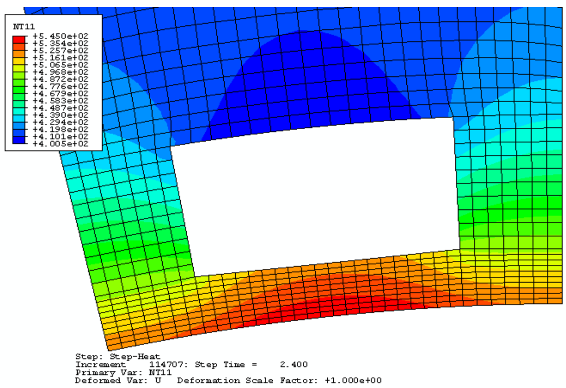

Fig. 7: Wall temperature distribution around rectangular cooling channel

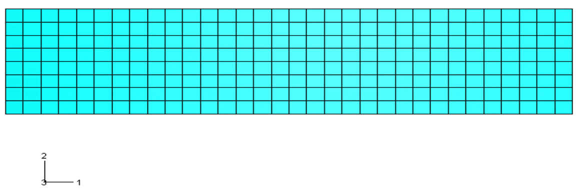

Fig. 8. 2-D beam model of liner ligament. Both sides have fixed boundary conditions

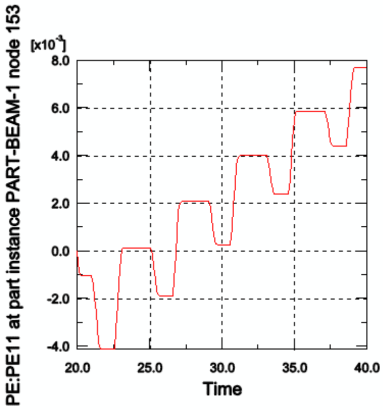

Fig. 9. Time variation of hoop strain at midpoint of hot side wall

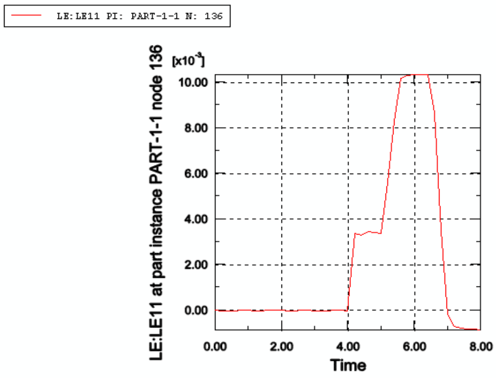

Fig. 12. Radial total strain variation of first one cycle.

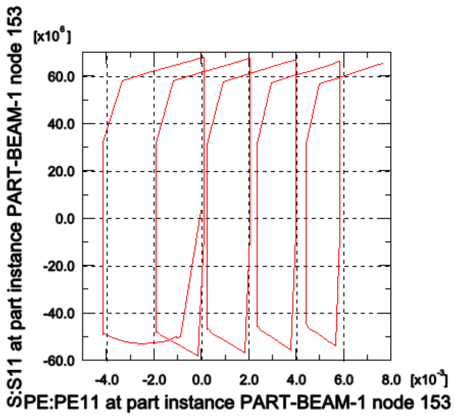

Fig. 10. Hysteresis loop behavior at midpoint of hot side wall

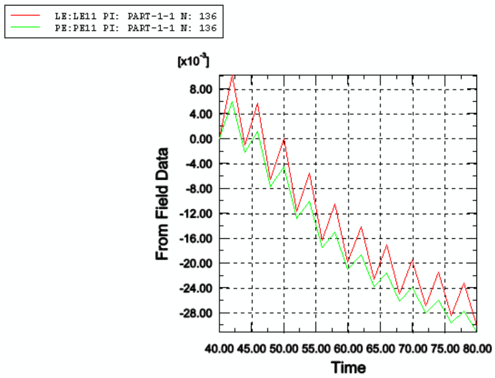

Fig. 13. Predicted radial plastic strain increasing up to 10 cycles.

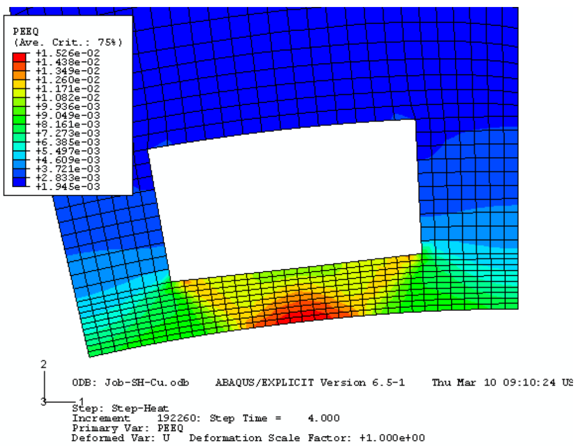

Fig. 11. Equivalent plastic strain distribution of coolant channel

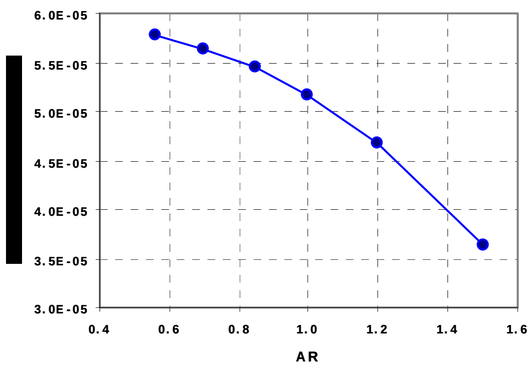

Fig. 14. Thinning rate of coolant channel for different aspect ratio

When using linear damage rule due to lack of OFHC test data, creep did not show meaningful damage fraction (6.0E-4). Only fatigue governed the whole life and showed the same life as strain-life method. The predicted life for each of these methods is summarized in Table 1.

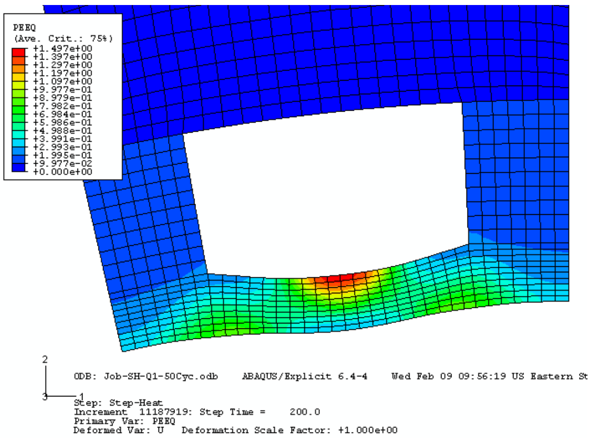

Fig. 15. Channel wall deformation at 50 cycles

Table 1: Predicted Life Summary

Prediction method	Estimated life cycle
Effective stress-strain	200
Porowski Method	67
Viscoplastic Theory	106
ABAQUS	220

Summary

A small-scale rocket combustor was designed to verify life prediction models for low cycle fatigue and fatigue-creep interaction. Several life prediction analytical methods were applied to predict the life of a subscale combustor. Also typical material behavior like cyclic hardening and progressive thinning and bulging at elevated temperature were presented using whole channel and beam configuration. Although creep damage of this subscale model is negligible due to short hold time and small mean stress, typical liquid rocket has long enough time for considering creep damage. Therefore creep-fatigue interaction can not be neglected.

References

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