A New Creep-Fatigue Life Prediction Model

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ABSTRACT

A published creep-fatigue life prediction model is modified in this paper and assessed with data on Inconel 718 under different test conditions. It has been shown that the method developed within the viscosity concepts correlates the low-cycle fatigue data well. This paper reports the modification over the previous model.

INTRODUCTION

Creep-fatigue life prediction methods have been developed for the last two decades, yet no method has been widely accepted as a design code for high temperature applications. The damage summation approach (DSA) /1/, frequency modified approach (FMA) and their subsequent modifications /2,3/, strain range partitioning (SRP) and subsequent modifications /4-6/, damage rate approach (DRA) /7/, damage function approach (DFA) /8/, damage parameter approach (DPA) /9/, ductility exhaustion approach (DEA) /10,11/, Code R-5 /12/ and other methods have been developed to correlate "cast specific" strain versus life data. These methods were capable of predicting life only in a range of test temperatures /1/, strain ranges and rates /4-7/, heat treatment conditions and other parameters.

The material toughness was accounted for in the new model /13/ in the expression for life. The dynamic viscosity which causes flow in the material is a rate of damage accumulation. Since the low-cycle fatigue process is a time-dependent, plastic strain dominated behavior, cycle time was incorporated in the model. A product of stress and cycle time that has units of stress/sec., known as dynamic viscosity, was used with the cyclic stress-strain equation. Dynamic viscosity under creep-fatigue tests when equated with material toughness, which is a product of ductility and strength, determined life. The cyclic life expression was developed from the two terms where fatigue ductility was a product of plastic strain range and life. This method may be extended under creep conditions if creep deformation dominates the failure mechanisms by replacing the fatigue ductility with creep ductility. Applicability of the new method so developed was assessed with creep-fatigue data on Inconel 718 at 600°C generated in various European laboratories during a NATO activity through the Advisory Group on Aerospace Research and Development (AGARD), reported in AGARD WS 26 /14/.

TEST REQUIREMENTS OF THE METHODS

The methods discussed in /1-12/ require several tests such as continuous fatigue, hold time tests, variable strain rate tests, creep rupture tests at several temperatures and stresses. Creep rupture properties are needed at the conditions of creep-fatigue tests to predict life if DSA /1/ is used. Creep rupture behavior depends upon a range of stress in which a bilinear relationship is often observed. Coffin-Manson relationships are required by most methods /2-6,8,12/ which relate plastic strain range with life and components of partitioned total strain in elastic and plastic ranges. A stress-strain relationship or the Basquin equation is required in several methods /2,3,8,12/. Ductility has also been used in /6,10-12/, where it is not very well known how to determine ductility in fatigue and creep in the tension and compression directions. Therefore, the concepts such as exhaustion of ductility under creep-fatigue greatly depend upon how ductility was defined in the tension and compression directions. Theoretically, exhaustion of ductility under compression dwells, equal tension and compression dwells and unequal tension and compression dwells cannot be determined as compressive properties are unknown or very little known; therefore, care needs to be taken to predict life with the methods shown in /10-12/. The ductility depends not only upon the stress range, strain rate, temperature and microstructure, but also upon impurity content, cavities per grain, grain size, texture, relaxed stresses, compressive stress ranges and other phenomena, such as work hardening, recovery, recrystallization, grain boundary precipitations, dislocation density and their mobility for cell formation. Most methods assume the tensile rate of stress/strain relaxation for compressive dwells /1,12/, whereas compressive softening and hardening behavior are not the same as tensile /15/. As a result, a number of assumptions were made in the previous life prediction methods /1-12/, which raise a number of questions discussed above.

Since each life prediction method requires a number of parameters which are determined from specialized tests where the data are fitted in terms of a least square best fit equation, these parameters are used extensively in the phenomenological methods of life prediction discussed in /1-12/. Though the new method also is phenomenological, it uses very few parameters, such as the Basquin equation and log strain range to strain rate ratio and log life; their behavior is discussed below.

DEVELOPMENT OF THE NEW METHOD

The new method is developed on the premise that under creep-fatigue conditions a material flows with the application of loads. When the dynamic viscosity, which describes such a flow behavior, equals the material toughness, failure occurs. This was achieved in terms of a stress profile with respect to time, where dynamic viscosity was derived from equation (1) below:

$$\text{Dynamic viscosity} = (\text{semi-stress range})\text{x}(\text{cycle time})$$

$$= \Delta\sigma \, . \, (\Delta\varepsilon_t / \dot{\varepsilon})^{m} \qquad (1)$$

where $\Delta\sigma$ is the tensile stress range, $\Delta\varepsilon_t$ is the total strain range, $\dot{\varepsilon}$ is the strain rate and m is the slope of $\log(\Delta\varepsilon_t/\dot{\varepsilon})$ and log N_f.

Material toughness was determined from the product of ductility and strength. Ductility was derived from the expression used widely as a product of plastic strain range and cyclic life /10,11/. The strength under monotonic conditions is a simpler term than the strength under creep-fatigue conditions, which requires knowledge of the gradual increase or decrease in strength with an increase in the number of creep-fatigue cycles. The residual strength values with respect to the number of cycles are not digitized and determined; therefore, the strength was assumed to be the saturated tensile stress at half life. Following this assumption, the toughness equation was represented as follows:

$$\text{Toughness} = (\text{ductility}) \text{ x } (\text{strength})$$

$$= \Delta\varepsilon_p . N_f . \Delta\sigma_t \qquad (2)$$

where $\Delta\varepsilon_p$ is the plastic strain range, N_f is the number of cycles to failure and $\Delta\sigma_t$ is the saturated tensile stress range at half life.

When equations (1) and (2) are equated, the following cyclic life relation was evolved:

$$N_f = \{\Delta\sigma \, . \, (\Delta\varepsilon_t / \dot{\varepsilon})^{m}\} / \{\Delta\varepsilon_p \, . \, \Delta\sigma_t\} \qquad (3)$$

The Basquin equation was used to replace the semi-stress range with the plastic strain range in equation (4) as follows:

$$N_f = \{K\,(\Delta\varepsilon_p)^n \cdot (\Delta\varepsilon_t/\,\dot{\varepsilon}\,)^m\} \,/\, \{\Delta\varepsilon_p \cdot \Delta\sigma_t\} \qquad (4)$$

Rearrangement of the above equation reduces it to equation (5) below:

$$N_f = \{(\,K\,/\Delta\sigma_t\,)\,(\Delta\varepsilon_p)^{n-1} \cdot (\Delta\varepsilon_t/\,\dot{\varepsilon}\,)^m\} \qquad (5)$$

where K and n are the parameters of the stress-strain equation.

It is apparent from equation (5) that it uses only the parameters determined from the continuous fatigue data; hold times are accounted for in terms of strain rates. Therefore, knowledge of the stress-strain behavior and m is required in the creep-fatigue life prediction by the proposed new method. All the strain range terms are used in their absolute values (i.e., 1% = 0.01) and strain rate is used in terms of %/sec units. Since the value of K depends upon the test parameters which were unspecified, the same ratio of ($K/\Delta\sigma_t$) was assumed to result under different test conditions.

MATERIAL AND TESTING

The material selected in this study is a nickel-based superalloy, Inconel 718, extensively used in the gas turbine engine industry as a material for hot section disks. As a result, NATO initiated a testing program through AGARD /14/ to test creep fatigue at the Rolls Royce, Pisa University, METU Germany, CNR ITM, DRA U.K., NAE Canada, CEAT and NLR laboratories. Not all the details of test parameters, data and materials have yet been published; however, in a separate study /16/ conducted in NLR a few mechanical properties were published /16 and are tabulated in Table 1.

APPLICABILITY OF NEW METHOD WITH INCONEL 718

The life prediction of "cast specific" creep-fatigue data was carried out for 33 continuous fatigue tests performed at six laboratories. Six data points were used to determine the parameters of the Coffin-Manson equation. Later the value of K was determined empirically from these values. The parameters of the life prediction equation (5) are tabulated in Table 2.

The above parameters were used in equation (5) and assessed with 33 continuous fatigue data generated with a triangular waveform. In addition to the continuous fatigue tests, 17 hold-time tests were conducted under load control with a 3-sec. ramp rate and a 120-sec. hold applied in the peak tensile direction. However, only in a few cases were complete test details available that

Table 1

Material properties and summary of tests /14,16/

0.2% σ_y 600°C	σ_{ts} 600°C	% Reduction	Grain size	Hold times	Pure fatigue
1030 MPa	1230 MPa	23	< 22 microns	120 sec.	
				load control	strain control

Table 2

A summary of parameters used in the new life prediction equation

K	m	n	Strain rate	K/σ_t	R
994 MPa	-0.19	-0.3	0.1%/sec	1.53	0.997

impaired the applicability of this method with holds. With a probability-of-failure curve with respect to the ratio of predicted life to observed life, if maintained within a factor of ± ×2, a high confidence of 95% was found in the life prediction in /1-12/ and other studies, taken as a reference in this study.

ASSESSMENT WITH CONTINUOUS FATIGUE DATA

The continuous fatigue behavior of Inconel 718 is shown in Fig. 1 /14/. It is evident that cyclic life ranged from a few hundred cycles to several hundred thousand cycles. These data are "cast specific", not analyzed statistically, whereas -3σ data are used in the design of engine components. Only one test was conducted for each condition and no test was duplicated under the same laboratory conditions for the same test parameters; it will be very difficult to comment on the life predicted by the new method against experimental data. Therefore, the life prediction method must be conservative and predict life lower than the "cast specific" data to account for minimum or -3σ lives.

Six tests conducted at NAE were predicted by the new method within a factor of ± x 2. Six tests conducted at IABG were predicted within a factor of ± x 2. Six tests conducted at DRA, in which cyclic lives of two tests were in a range of 3.13 x 10^5 cycles, were predicted very conservatively within a factor of 9. The rest of the data, in which cyclic life ranged from 500 to 4100 cycles, were predicted within a factor of ± x 2. Six tests conducted at Pisa exhibit an experimental anomaly in that the cyclic life at 1.2% total strain range was nearly four times shorter than at 1.26% total strain range, as shown in Fig. 2. Therefore, if the experimental error in one Pisa data point was accounted for, all six data points were predicted within a factor of ± x 2. Six tests conducted at CEAT were predicted within a factor of ± x 2. Three tests conducted at CNR ITM were predicted conservatively. Therefore, 100% of the test data were predicted conservatively as shown in Fig. 2.

ASSESSMENT WITH HOLD TIME DATA

The hold time tests were in progress when the data pack was prepared /14/ and as a result complete details of the data were not reported. Only in one case details of six hold time tests conducted at DRA were partially compiled /14/. All the six data points were predicted conservatively as shown in Fig. 3.

The mean stresses at half life were compressive in most cases, developing in all strain ranges. Mean

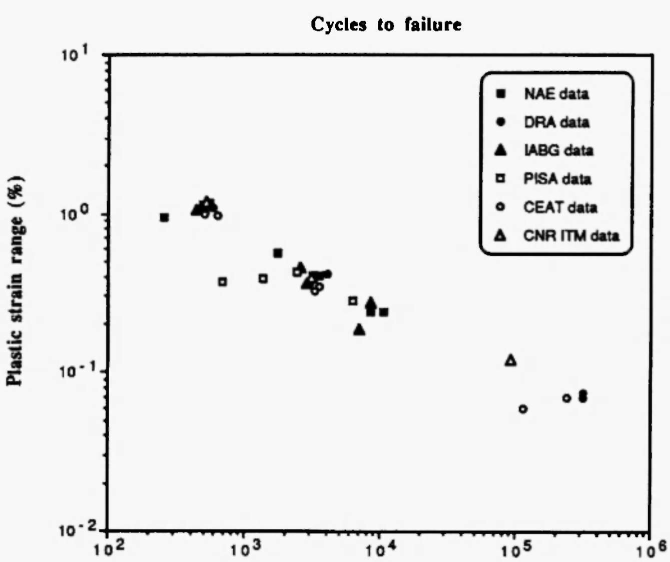

Fig. 1: Continuous fatigue behavior of Inconel 718 at 600°C /14/.

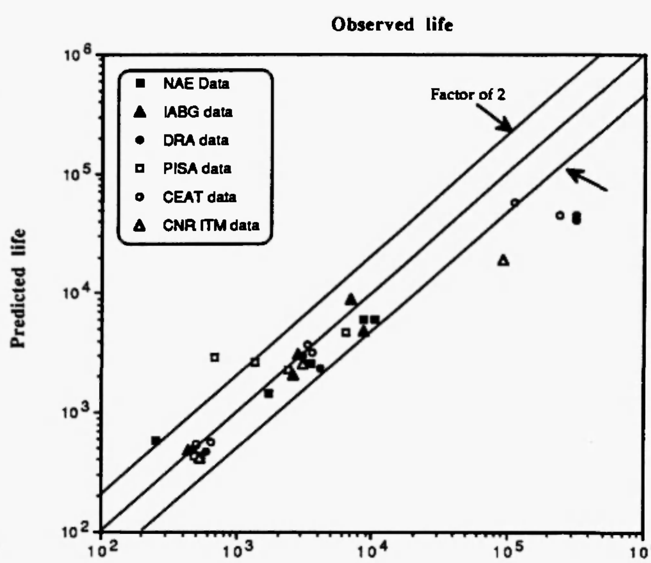

Fig. 2: Life prediction of Inconel 718 under continuous fatigue by new method.

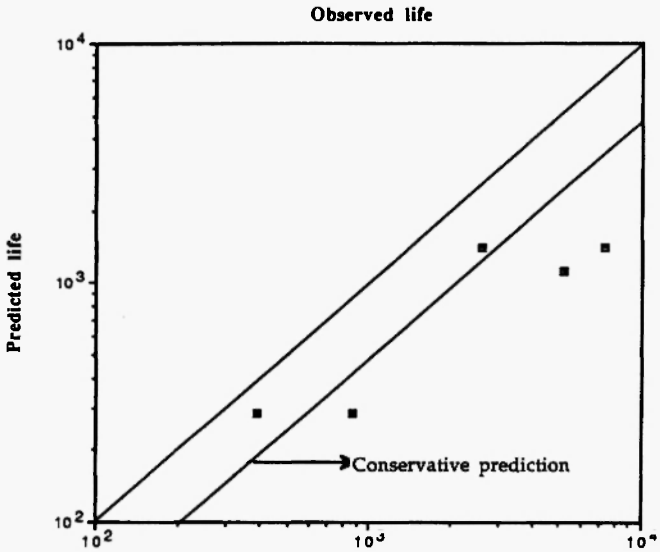

Fig. 3: Prediction of hold time data by the new model for Inconel 718.

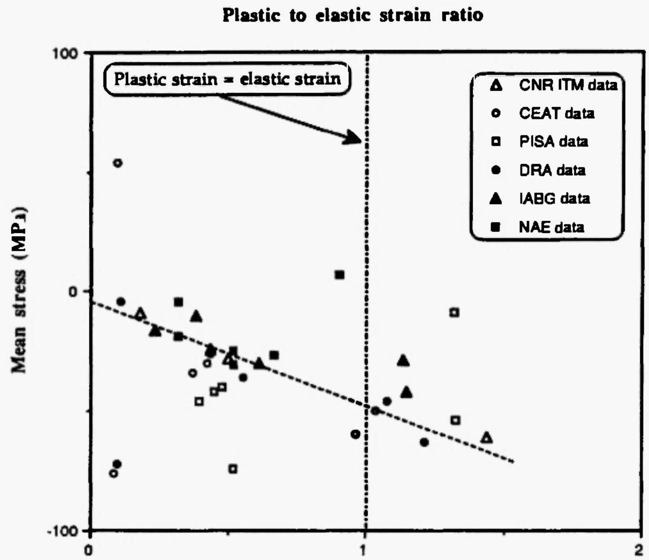

Fig. 4: Mean stress development under continuous fatigue in Inconel 718.

stresses developed in continuous fatigue conditions were plotted in Fig. 4 with respect to the ratio of plastic to elastic strain ranges. It was shown in Fig. 4 that, with the increase in elastic strain range, compressive mean stresses increase, which is expected to exhibit a crossover in the behavior with a critical value of plastic strain that may develop tensile mean stresses. A mean line is drawn in Fig. 4 to show this behavior; it may be noted that only one point of the CEAT data exhibits tensile mean stresses for which tensile and compressive stress ranges are determined 100 MPa lower than the reported stress range /14/. Life prediction of both the continuous fatigue and dwell time conditions are predicted conservatively within a factor of ± x 2 which will account for the lower bound data.

CONCLUSION

The new life prediction method is developed under the premise that a creep-fatigue cycle generates material flow which can be represented by dynamic viscosity. When the dynamic viscosity equals the material toughness a specimen fails.

The new method was assessed with the continuous fatigue data as well as the hold time data. The prediction was found to be conservative for all cases; therefore, this method has a potential for further assessment and analysis before being recommended for use.

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