A MECHANISTICALLY BASED MODEL FOR
HIGH TEMPERATURE LCF OF NI BASE SUPERALLOYS

Stephen D. Antolovich*, R. Baur** and S. Liu*

* Department of Materials Science, University of Cincinnati
Cincinnati, OH 45221

** General Electric Co.
Evendale, OH 45215

ABSTRACT

Low cycle fatigue of as-heat treated René 80 was studied with temperature range 760°C-982°C. The fatigue life at 871°C and 982°C increased with decreasing frequency. In addition some specimens were tested at 871°C after exposure for 100h at 982°C either stress free or at stress of 97MPa. The effect of stress exposure was to markedly reduce the fatigue life compared to the as-heat treated condition. At 760°C the structure was stable relative to cyclic plastic deformation while at 871°C and 972°C considerable precipitate coarsening occurred and the precipitates developed interfacial arrays of edge dislocations. At the higher test temperatures, cracking generally occurred along oxidized, surface-connected grain boundaries. Using the concept of a critical combination of oxidation depth and peak stress, an expression for the fatigue life was developed that includes temperature, frequency and cyclic stress/strain parameters as variables.

I. INTRODUCTION

The combination of high stresses, temperatures and long lives for jet engine components places them in the régime where failure due to low cycle fatigue (LCF) becomes an important design consideration. Due to the expense and increasing scarcity of basic materials⁽¹⁾ for these components, there is now a major incentive to implement the "retirement for cause" philosophy⁽²⁾. Adoption of this approach, while posing significant technological problems, is clearly desirable; however, its implementation is limited by a lack of understanding of what constitutes damage. This is apparent when one considers various approaches to LCF prediction at elevated temperatures.⁽³⁻⁶⁾ While these approaches all predict lives quite accurately for certain materials and

temperature régimes, they are not universally applicable. Furthermore they are not usually formulated in terms of precise damage mechanisms and consequently their limits of applicability are not defined. It is the authors' strong belief that life prediction methodology should be formulated in terms of mechanism and that eventually a system should be developed correlating life prediction models to specific mechanisms. Such information could then be given to designers in terms of appropriate models for a given material with well-defined limits of temperature, stress, strain, etc.

The goal of this project was to characterize the LCF behavior of René 80, to study possible damage accumulation mechanisms, and finally to develop a mechanistically based model. René 80 is a cast Ni base superalloy currently used in jet aircraft turbine blades.

II. EXPERIMENTAL PROCEDURE

A. Materials and Test Procedure

René 80 LCF test bars were cast to shape. The composition (wt%) is 3.0Al, 5.0Ti, 14.0Cr, 3.9W, 4.0Mo, 9.8Co, 0.17C, Ni bal. The heat-treatment has been described elsewhere⁽⁷⁾ and results in the structure shown in Fig. 1. Specimens were machined by low stress grinding and tested in longitudinal strain control at 760°C, 871°C and 982°C at $R_c=0.05$. Testing was done so as to maintain a nominal ramp rate of either 0.5%/min or 50%/min with a 90s hold time imposed at either maximum or minimum strain for some tests. In addition, after heat treatment but before testing, some specimens were coarsened for 100h at 982°C either stress-free or at 97MPa ($\sim 1/3$ yield). These specimens were either tested directly to simulate engine conditions or were tested after machining the surface layer away to determine the effect of the environment.

B. Metallography

Detailed metallographic studies were carried out to characterize microstructure, crack path, oxidation kinetics, and evolution of the dislocation substructure since all of these play an important role in damage processes. Light optical, scanning (SEM) and transmission (TEM) microscopy techniques were used.

Fig.1 Microstructure of René 80 by (a) light optical microscopy and (b) dark field transmission electron microscopy.

III. RESULTS AND DISCUSSION

A. Cumulative Glide and Cyclic Stress Strain Behavior

An important feature of the LCF process is the evolution of the stress response with cycle number and plastic strain. The cumulative glide behavior for as-heat treated specimens has been studied elsewhere.⁽⁸⁾ At 871°C and 982°C there is an initial period of rapid softening followed by saturation. At 760°C the softening is less pronounced. Finally towards the end of the test, as cracks initiate, the stress drops off very rapidly for all test conditions. The softening at 871°C and 982°C is associated with rapid coarsening of the large γ' precipitates, development of interfacial dislocations on the γ' , and dissolution of the small γ' particles. The microstructures after testing are shown in Fig. 2. Note that at 871°C and 982°C there are relatively few dislocations in the matrix while at 760°C the precipitate structure is unchanged and slip bands have formed. Slip band formation was not seen at the higher test temperatures. While the dislocation arrangements observed at 760°C certainly constitute a form of damage, it is difficult to draw the same conclusion for the higher test temperatures. In fact the interfacial dislocations have been shown to be near-edge character⁽⁷⁾ and of such a sign as to take up the mismatch between matrix and precipitate thereby reducing the energy of the system. Also, the coarsened precipitates facilitate deformation and thus lead to increased ductility. Both of these effects would be expected to extend the fatigue life.

Fig.2 Transmission electron micrographs showing typical structures for low rate tests:

- a) 760°C, 535 cycles
- b) 871°C, 732 cycles
- c) 871°C, 90s hold, 929 cycles
- d) 982°C, 877 cycles
- e) 982°C, 90s hold, 573 cycles

The plateau stresses as a function of plastic strain range obeyed our equation of the form:

$$\Delta\sigma/2 = K(\Delta\varepsilon_p/2)^{n'} \quad \dots (1)$$

where the symbols have their usual meaning. Values of K and n' are given elsewhere.⁽⁸⁾

B. LCF

The effect of prior exposure at 982°C can be seen in Fig. 3. The fatigue life was moderately reduced by stress free

exposure and radically reduced by stress exposure. The life was significantly increased when the surface layer was machined away, indicating that the major effect of prior exposure was to introduce damage in the near surface region rather than to effect detrimental metallurgical phase changes in the bulk. The stress exposed test results should be considered seriously by designers since these results tend to approximate engine conditions while most data is obtained using as-heat treated and machined specimens.

Fig. 3. LCF behavior of René 80 at 871°C as affected by prior exposure.

The remaining test results are shown in Figs. 4-6. Note the increased life at both 871°C and 982°C when the frequency was decreased or a hold time was imposed compared to the continuous cycling data. The increases tend to be most pronounced for the lowest strain levels. Such increases are not generally expected if one thinks in terms of a negative creep/fatigue interaction but they have been observed by other investigators for this alloy.^(9,10)

The fracture surfaces were examined by SEM and crack initiation usually occurred at the surface. Only for the case of rapid ramp rates and hold times was any internal initiation observed and even in these cases surface initiation sites were always present to a significant degree.

Crack formation was usually observed in surface connected grain boundaries as shown in Fig. 7. Based on both the LCF test results and metallographic observations, environmental reactions at the surface appears to be the principal damage mode at least at 871°C and 982°C. If this is true, then the LCF test results can be explained qualitatively by assuming that crack formation occurs at a critical combination of stress and environmental damage such that the lower the stress, the more extensive the environmental damage can be before crack initiation. There is then a trade-off between the structural coarsening which is driven by the fatigue deformation and environmental damage which is driven primarily by temperature and time. The

Fig. 4. LCF behavior of René 80 at 760°C

Fig. 5. LCF behavior of René 80 at 871°C

Fig. 6. LCF behavior of René 80 at 982°C

environmental damage could take the form of oxide formation or penetration of oxygen along boundaries and interdendritic regions. (7)

C. Oxidation Kinetics

Specimens were oxidized at 760°C and 982°C between 16 and 500h. The depth of apparent oxidation was measured metallographically and the data were found to fit an equation of the form:

$$l = (Dt)^{1/2} \quad \dots (2)$$

where l = depth of oxidation,
 D = diffusion constant,
 t = time

The diffusion constant can be represented by the equation:

$$D = D_0 \exp(-Q/RT) \quad \dots (3)$$

where all symbols have their usual meaning with $Q = 9.6$ k-cal/mol and $D_0 = 1.66 \text{ m}^2/\text{s}$ as measured from the data. This information will be used in the development of a mechanistically based model.

D. Model Development

In order to test the ideas put forth previously, the maximum stress at initiation in an LCF test was plotted as a function of the computed oxide spike depth assuming that oxide spikes obeyed the same kinetics (with perhaps different constants) given by eq. 2. The spike depth for the shortest test time was arbitrarily taken as unity. This means that the spike depth for all other tests is given by:

$$l_i = (t_i/t_o)^{1/2} \quad \dots (4)$$

where l_i = spike depth for test of duration t_i , and t_o = shortest test time. The data are plotted in Figs. 8 and 9 for 871°C and 982°C and are well-represented by an equation of the form:

$$\sigma_i^{\max} \cdot l_i^{1/4} = C_o \quad \dots (5)$$

where $\sigma_i^{\max}$ = max. stress at initiation, l_i = spike depth, C_o = material constant. An expression for the fatigue life in terms of more familiar variables can be developed using the following equations:

$$\sigma_i^{\max} = \bar{\sigma} + K(\Delta \epsilon_p/2)^{n'} \quad \dots (6)$$

Fig. 7. Crack formation along oxidized grain boundary for specimen tested at (a) 871°C and (b) 982°C

$$t_i = t_e + (1/\nu + t_h) N_i \quad \dots (7)$$

where $\bar{\sigma}$ = mean stress, t_e = time of prior exposure (if any) ν = continuous cycle frequency, t_h = hold time (if any) N_i = cycles to initiation. Substitution of equations 2, 6 and 7 into (5) gives the following result:

$$\left[\bar{\sigma} + K(\Delta \epsilon_p / 2)^{n'} \right]^8 D \left[t_e + (1/\nu + t_h) \right] N_i = C_i \quad \dots (8)$$

The René data at 871°C and 982°C were essentially fit to this expression. While the high temperature data fit the model very well, the same was not true at 760°C, the coefficient of determination being only 0.46. The reason for this can be understood in terms of a different deformation mode and a complete lack of structural coarsening. It is probable that while environmental effects are important at 760°C, more complex synergistic interactions between deformation mode and environment are occurring.

In many cases stable systems are tested in fully reversed fatigue. For this situation eq. 8 reduces to:

$$N_i = C_2 (\nu / (1 + \nu t_h)) \exp \left(\frac{Q}{RT} \right) \cdot \Delta \epsilon_p^{-8n'} \quad \dots (9)$$

where eq. 3 has been substituted into eq. 8. It is

Fig. 8. Stress at initiation vs. oxide spike depth for specimens tested at 871°C.

Fig. 9. Stress at initiation vs. oxide spike depth for specimens tested at 982°C.

interesting that eq. 9 has the form of Coffin's⁽⁴⁾ frequency modified fatigue life with an explicit expression for the frequency and temperature dependence terms and the Coffin-Manson exponent β , given by $1/8n'$. Equation (9) predicts that for stable materials, tested in fully reversed fatigue, the life will decrease for low frequency, long hold time and high temperature. Such behavior is, in fact, observed. Moreover, values of n' are frequently in the range of 0.15 to 0.20 which according to eq. (10) implies Coffin-Manson exponents on the order of 0.6 to 0.8. Again such values are commonly observed.

Finally we can conclude, based on the development of the above model, that agreement of the data with a Coffin-Manson representation does not necessarily imply damage accumulation by deformation debris as has been frequently assumed.

IV. Conclusions

1. The LCF life of as heat-treated René 80 at 871°C and 982°C increases with decreasing frequency, which is not usually accounted for in most high temperature LCF models.

2. The effect of exposure at 982°C for 100h prior to testing is to reduce the fatigue life, this reduction being most pronounced when pre-exposure took place under a stress of 97MPa. Subsequent machining restored the fatigue life to levels at least equal to the as-heat treated condition.

3. The imposed LCF deformation at 871°C and 982°C provided a driving force for coarsening of the γ' precipitate, which was accompanied by development of a network of interfacial edge dislocations. At 760°C the precipitate structure was stable and deformation bands were clearly visible.

4. Cracks were usually associated with oxidized, surface-connected grain boundaries. Only for the high ramp rate hold time specimens was any internal initiation observed. Even in this case surface initiation predominated.

5. Oxidation was well-represented by parabolic kinetics and an activation energy of 9.6 k-cal/mol.

6. Based on metallographic observations and LCF test results an expression for the fatigue life was developed for 871°C and 982°C which has the form of Coffin's frequency modified fatigue life.

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