INITIATION AND GROWTH OF FATIGUE CRACKS AT HIGH TEMPERATURE

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ABSTRACT

A series of fully reversed cyclic tests were carried out on Sanicro 31 (Alloy 800) specimens at 600°C. The majority of these tests were conducted on axially loaded smooth specimens at various strain levels using a high strain rate of 2.64×10^{-1} sec^{-1}, supplemented by tests carried out at a low strain rate of 1.32×10^{-4} sec^{-1}. Fatigue (transcrystalline) cracks formed in several small and localized areas on the surface at the high cyclic strain rate. Coalescence of these small cracks forming a common crack front occurred at approximately half life ($0.5N_F$). Once this life fraction had been exceeded, imposition of low strain rate cycles causing intercrystalline cracking resulted in interaction between these two damage mechanisms.

Stress response measurements allowed the concept of non-linear damage accumulation to be applied to this work. The damage accumulation rate (dD/dN) was found to be directly related to the fatigue crack growth rate (da/dN).

KEYWORDS

High temperature fatigue, damage accumulation, fatigue crack growth rate at high temperature, Alloy 800.

INTRODUCTION

Damage concepts have been successfully applied to life prediction at high temperature (Lemaitre and Chaboche, 1974). Such applications must, of course, deal with monotonic creep-fatigue or cyclic creep-fatigue interaction.

In many practical applications the material is subjected to strain controlled conditions. Lemaitre and Plumtree (1979) have considered the damage evolution for such cases and its non-linear accumulation may be written:

$$D_F = 1 - \{1 - N/N_F\}^{1/(p+1)} \tag{1}$$

where D_F is the fatigue (high frequency) damage accumulated in a given life fraction, N/N_F, and p is a material constant. A similar non-linear equation for cyclic creep (very low frequency) damage may be written:

$$D_C = 1 - \{1 - N/N_C\}^{1/(q'+1)} \tag{2}$$

where N/N_C is the life fraction and q' is a material constant.

The present work was carried out to establish a relationship between damage, as in the context above, and the formation and growth of cracks occurring in an austenitic iron-nickel - chromium alloy subjected to cyclic strain controlled conditions at 600°C.

MATERIALS AND EXPERIMENTAL PROCEDURE

The material used in this investigation was Sanicro 31 (trade name of Sandvik AB). This alloy is a high temperature alloy, similar to Alloy 800, which is used where corrosion resistance and strength are required at elevated temperatures. The chemical composition of the cast used was 0.043%C, 21.7%Cr, 33.2%Ni, 0.33%Ti and 0.20%Al.

Specimens were taken from 16 mm. bar stock and solution heat treated at 1150°C for 10 minutes in an argon atmosphere followed by a water quench, resulting in a grain size of 50 ± μm. The specimens were then machined with threaded ends for gripping and a reduced diameter of 4.85 mm. over a gauge length of 7.5 mm.

Cyclic testing was performed on a closed loop electro-hydraulic servocontrolled testing machine. The tests were carried out under strain control. The testing procedure for controlling strain was similar to that used by Abdel-Raouf, Plumtree and Topper (1973). Strain range and frequency were the testing variables with temperature being held constant at 600°C.

In order to determine cyclic characteristics (ie. life, material constants, etc.) it was necessary to perform several reference tests by keeping the strain rate constant according to $\dot{\varepsilon} = 2\Delta\varepsilon_T\nu$. The conditions for the reference tests were selected such that for the high frequencies (ν=5Hz and 10Hz) life was independent of frequency as well as time, resulting in transgranular failure. At the low frequencies (ν=0.0025Hz) the life was time and frequency dependent, resulting in an intergranular failure.

Block tests were carried out to determine whether a critical crack size existed which corresponded to a given number of cycles (N^*) beyond which interaction of fatigue and creep damage mechanisms occurred. These tests consisted of cycling the specimen at ν=5 Hz ($\Delta\varepsilon_T$=2.64%) for a predetermined number of cycles (specific life fraction) then switching to sequential mixing of low and high frequency cycles of ν = 0.0025 Hz ($\Delta\varepsilon_T$=2.64%) and ν = 5 Hz ($\Delta\varepsilon_T$=2.64%) respectively.

A series of high frequency tests (ν=5Hz) was also carried out to determine the crack size at various life fractions for two different strain ranges, $\Delta\varepsilon_T$ = 2.2% and $\Delta\varepsilon_T$ = 1.54%. The procedure was to stop the test at a predetermined life fraction and examine the specimen for surface cracks and evaluate their size. The technique for crack detection and observation has been described by Douglas and Plumtree (1979). It was hoped that these tests would indicate if any possible relationship existed between crack growth rate and fatigue damage accumulation rate.

Fracture surfaces from various reference and mixing tests were examined using an ISI III Scanning Electron Microscope. The fracture surfaces were cut from the gauge lengths of the specimens, ultrasonically cleaned in acetone and then rinsed in alcohol before examination.

RESULTS AND DISCUSSION

High and low frequency cycling reference test results were carried out so that the relationship between the strain range ($\Delta\varepsilon_T$) and number of cycles to failure ($N_{F/C}$) was established. A total strain range of $\Delta\varepsilon_T$ = 2.64% was chosen for the majority of the tests at both frequencies. Under these conditions the two specimens cycled at the high frequency of ν = 5 Hz ($\dot{\varepsilon}_H$ = 2.64 X 10^{-1} sec^{-1}) possessed lives of 534 and 566 cycles. The average of 550 cycles was considered as the cyclic life (N_F) of the material for this strain level and frequency. Two low frequency tests at ν = 0.0025 Hz ($\dot{\varepsilon}_L$ = 1.32 X 10^{-4} sec^{-1}) resulted in lives of 193 and 204 cycles. The average of 198 cycles was considered to be the cyclic life (N_C) of the material for this imposed strain level and frequency. The results of these tests served as a base for the subsequent block tests in which the number of cycles in the high frequency or low frequency sequence was expressed as some fraction of the appropriate life.

In order to show the time and frequency independency of the fatigue damage, two tests (T1 and T10) were conducted at a strain range of $\Delta\varepsilon_T$ = 2.4%. Specimen T1 was cycled at ν = 10 Hz and specimen T10 was cycled at ν = 5 Hz, both tests resulted in approximately the same lives (700 and 739 respectively). High frequency reference tests conducted at strain ranges of $\Delta\varepsilon_T$ = 1.54% and $\Delta\varepsilon_T$ = 2.2% produced average cyclic lives of 2700 cycles and 900 cycles respectively ($\dot{\varepsilon}$ = 2.64 X 10^{-1} sec^{-1}). This information served as a base for the crack size determination tests, in which the crack size was recorded for various life fractions.

For constant strain, damage evolution given in Equations 1 and 2 requires that the exponents p and q' are known. These may be determined by monitoring the stiffness change as a crack forms and grows through the specimen. More simply, the change of load (or stress amplitude) for a given displacement (or strain) will also yield the change in stiffness. Hence, by following the stress response of the high and low frequency reference tests it was possible to derive the damage evolution. Under steady-state conditions the stress response, $\Delta\sigma^*$, was monitored and once the stiffness of the specimen decreased due to the presence of a crack, the stress response, $\Delta\sigma$, for any particular number of cycles, N or life fraction, was recorded allowing the amount of damage to be determined according to:

$$D = 1 - \Delta\sigma/\Delta\sigma^* \tag{3}$$

The derivation of Equation 3 may be found in the work of Lemaitre and Plumtree (1979). This allows the value of p to be determined for a given set of testing conditions since a log-log plot of (1-D) [from Equation 3] versus ($1-N/N_F$) will give 1/(p+1) as the slope [from Equation 1]. For $\Delta\varepsilon_T$ = 2.64% the value of p was 27. Damage versus life fraction is plotted in Fig. 1 using this exponent. The value of q'(=15) was determined using low frequency cycling stress response data and the corresponding damage evolution [Equation 2] is also plotted in Fig. 1.

Block tests consisting of initial high frequency cycles followed by a sequence of 5 low and 11 high frequency cycles, which was then repeated to failure, showed clearly that once the initial high frequency cycles exceeded half life ($N > 0.5\ N_F$) the number of sequences to failure was drastically reduced. The results are given in Fig. 2. This shows that a critical amount of damage in high frequency cycling (corresponding to a critical number of cycles, N^*) is required for interaction, which occurred at approximately half of the life (ie. $N^* = 0.5\ N_F$).

The results of measuring the surface crack length, ℓ, against the crack depth, a, for various life ratios at high frequency are shown in Fig. 3. It appears that a critical crack length, ℓ^*, exists below which the crack size or depth, a, is very small and does not increase significantly with an increase in ℓ.

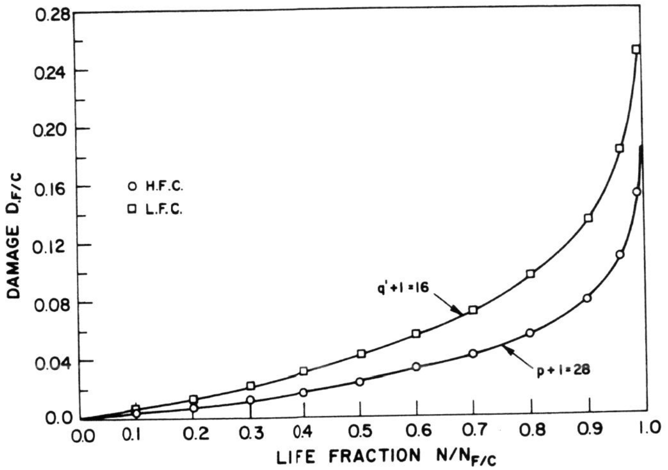

Fig. 1. H.F.C. and L.F.C. damage evolution at 600°C.

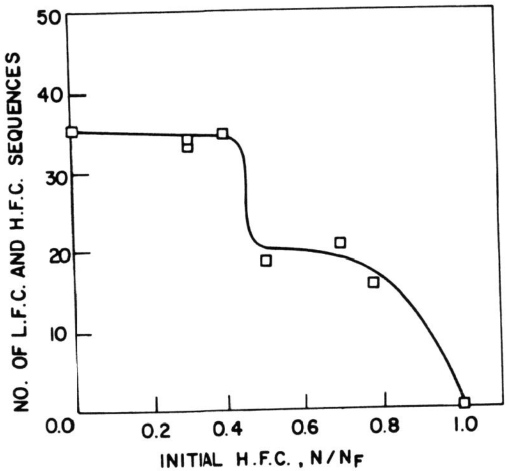

Fig. 2. Block test results. Temp =600°C. Total strain range=2.64%.

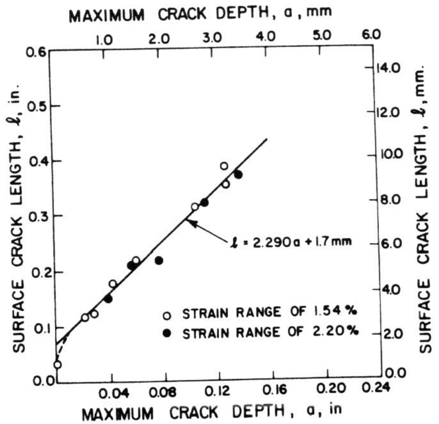

Fig. 3. Relationship between surface crack length and maximum crack depth at 600°C.

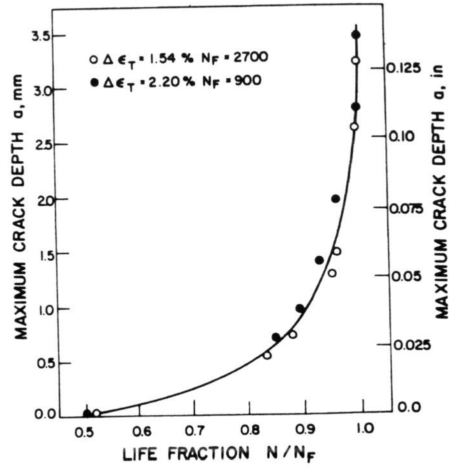

Fig. 4. Variation of maximum crack depth with life fraction at 600°C.

The plot of crack depth for a given life ratio, shown in Fig. 4 tends to indicate that the crack depth had a slight dependency upon strain level. At life ratios of $N/N_F < 0.5$ the cracks or damaged areas were extremely small and localized to surface regions. For $N/N_F > 0.5$ these localized cracks began to link together and form a common crack front which then penetrated into the specimen. Stopping the test prior to 0.5 N_F resulted in difficulty in repropagating the small cracks associated with the damaged regions.

In order to clarify the definition of damage it was necessary to determine whether a relationship existed between the damage accumulation rate (dD/dN) and the fatigue (high frequency) crack growth rate (da/dN). This required that the two be correlated using an elastic-plastic fracture mechanics analysis. Rather than using ΔK, it was decided to use ΔJ (Rice, 1968), since the crack-tip plastic zone could not be considered as being relatively small.

The J integral has shown great promise as a correlation factor for fatigue crack growth under plastic conditions (Dowling, 1977). For the elastic-plastic case J gives a measure of the crack-tip strain field. In the present study, the derivation of J was similar to that used by Dowling (1977). Douglas and Plumtree (1979) have calculated ΔJ for the present specimens at 600°C, ie:

$$\Delta J = 7.88\ a\ \Delta W_e + 8.76\ a\ \Delta W_p \tag{4}$$

where ΔW_e and ΔW_p are the elastic and plastic strain energies respectively.

Crack growth data was obtained from Fig. 4 (a vs. N/N_F) by the difference method. This data was then correlated with the J integral. The plot of log (da/dN or dD/dN) versus ΔJ shown in Fig. 5 indicates that a Paris-type relationship is obeyed such that, $da/dN = C(\Delta J)^n$ where C and n are material constants. For the present study the values of C and n are given in Fig. 5. It follows that given $D = f(a)$ and using the difference method to obtain the slope of the experimental damage curve for a given number of cycles (similar to Fig. 1), then the damage accumulation rate dD/dN is directly proportional to the fatigue crack growth rate, which is shown in

Fig. 5. Combining the equations for dD/dN and da/dN gives:

$$dD/dN = 2.7 \times 10^{-5}\ da/dN\ \text{(m/cycle)} \quad (5)$$

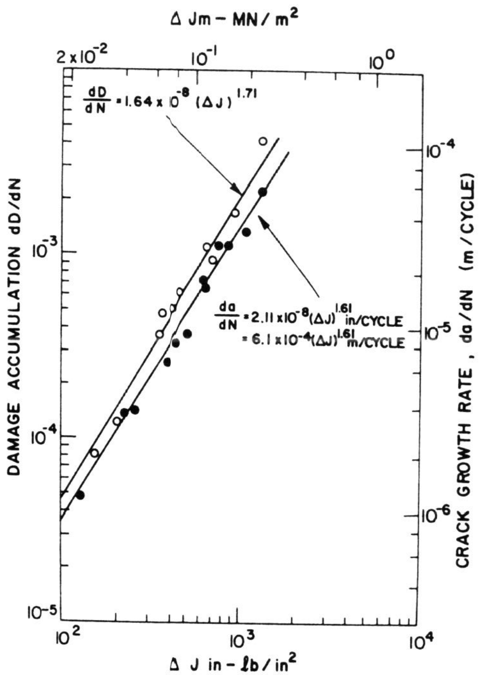

Fig. 5. Relationship between crack growth rate (da/dN) damage accumulation rate (dD/dN) and ΔJ.

Both the stress response (or stiffness) and crack measurements indicated that below a certain number of high frequency cycles (~0.5 N_F), the amount of damage was extremely small. In fact, it appears that significant interaction with low frequency or creep-type damage occurs only after a critical amount of high frequency or fatigue damage has been imposed. Besides being observed in the present work, Plumtree and Persson (1978) independently verified this phenomenon by subjecting Alloy 800 to monotonic creep after varying numbers of cycles in fatigue at 600°C. A complete and unaffected creep life resulted when the amount of prior fatigue was less than or equal to 0.5 N_F.

It is suggested then that the damage occurring during the block tests may be divided into two regimes. First, when ($N/N_F < 0.5$), several small and localized cracks form with surface lengths of about 0.5 to 0.8 mm. The second regime ($N/N_F \geqslant 0.5$) corresponds to the development and growth of a common crack front when the smaller cracks link together and the resulting main crack penetrates into the specimen, eventually causing failure. It is within this regime that the imposition of low frequency cycles (creep-type damage) becomes extremely detrimental since the two damage mechanisms interact in a synergistic manner.

CONCLUSIONS

A relationship between fatigue crack growth rate and damage accumulation rate, obtained by using concepts of non-linear damage accumulation, has been established for smooth specimens of Sanicro 31 (Alloy 800) at 600°C.

Interaction of damage due to low frequency strain cycling with that caused by high frequency strain cycling occurred after about half the high frequency life had been exceeded. This corresponded to the coalescence of several small and localized surface cracks forming a common fatigue crack front.

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REFERENCES

Abdel-Raouf, H.A., A. Plumtree and T.H. Topper (1973). Effects of temperature and deformation rate on cyclic strength and fracture of low-carbon steel. In Cyclic Stress-Strain Behavior Analysis, Experimentation and Failure Prediction, STP 519, ASTM, Philadelphia, 28-57.

Douglas, M.J. and A. Plumtree (1979). Application of fracture mechanics to damage accumulation in high temperature fatigue. In Ed. Smith, C.W., Fracture Mechanics, STP 677, ASTM, Philadelphia, 68-84.

Dowling, N.E., (1977). Crack growth during low-cycle fatigue of smooth axial specimens. In Cyclic Stress-Strain and Plastic Deformation Aspects of Fatigue Crack Growth, STP 637, ASTM, Philadelphia, 97-121.

Lemaitre, J. and J-L. Chaboche (1974). A non-linear model of creep-fatigue damage accumulation and interaction. Proc. IUTAM Symposium Mech. of Visco-elastic Media and Bodies, Gothenburg. Office National D'Etudes et de Recherches Aerospatiales, Chatillon, TT No 1394.

Lemaitre, J. and A. Plumtree (1979). Application of damage concepts to predict creep-fatigue failures. Trans. ASME, J. Engineering Mat. and Technology, 101, 284-292.

Plumtree, A. and N-G. Persson (1978). Creep-fatigue interaction in an austentic Fe-Ni-Cr Alloy at 600°C. In D.M.R. Taplin (Ed), Advances in Research on the Strength and Fracture of Materials, Vol. 2B, Pergamon, N.Y., 821-829.

Rice, J.R. (1968). A path independent integral and the approximate analysis of strain concentration by notches and cracks. Trans ASME, J. Appl. Mechanics, 35, 376-386.