FATIGUE CRACK PROPAGATION RATE OF AISI TYPE 304 STAINLESS STEEL AT 570°C IN AIR

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INTRODUCTION

Low cycle fatigue at elevated temperature is an important consideration in the design and operation of structural components for many applications such as in liquid metal fast breeder power stations, turbine blades, petroleum and chemistry process equipment. In order to find an accurate way to predict component lives a thorough understanding is needed of the behaviour of material under fatigue and creep or environmental interaction. The current study is concerned with crack growth of stainless steel subjected to cyclic loading conditions at high temperature since propagation is the dominant process of short life fatigue of structural components. It is also concerned with investigating the influence of cyclic waveform on crack growth rate at high temperature.

EXPERIMENTAL PROCEDURE

The present experiments were conducted at 570°C in air on AISI type 304 stainless steel single edge notch specimens (50.8 mm wide and 4.84 mm thick) using a servo-controlled electro-hydraulic test machine. The temperature was measured by a thermocouple attached to the specimen. A second thermocouple was used to control the high frequency generator. The induction heating coil was constructed with two loops wound in counter-direction on either side of the specimen. Each loop consisted of two turns. All the tests were carried out under load control. The notch was 14 mm long and crack measurements were not started until a fatigue crack of about 1.5 - 1.8 mm had formed at a frequency of 5 Hz with a triangular waveform, afterwhich the intended frequency and waveform were applied.

Several types of tests were performed. The first was a series using a triangular waveform at frequencies of 0.005, 0.05, 0.135 and 5 Hz. The second set was designed to investigate the effect of waveform on crack propagation rate. In this case, four waveforms at a constant frequency of 0.135 Hz were considered. These were: equal-equal, involving equal ramp-up and ramp-down times of 3.7 secs (i.e., a balanced triangular wave of frequency 0.135 Hz); fast-hold-fast, involving a short loading time (0.1 sec) with a hold period at maximum load of 7.2 secs followed by a short unloading time of 0.1 sec; slow-fast, involving a long loading period of 7.3 secs followed by a short unloading time of 0.1 sec; fast-slow, involving a short loading period of 0.1 sec and a long unloading period of 7.3 secs. The third series of tests dealt with the effect of different tensile ramp times of 0.3, 1, and 14.6 secs. The unloading time was kept the same at 0.1 sec.

The crack length (a) was measured using an optical microscope attached to a Vernier scale and the crack propagation rate (da/dn) was determined from the tangent of the corresponding a versus n curve (where n is the number of cycles).

Following cyclic testing, the fracture surfaces were examined using scanning microscope and optical microscope techniques. In some cases, the internal structure was examined by first plating the surface with nickel and then mounting, lapping, polishing and etching the specimens.

RESULTS

The effect of varying frequency from 0.005 Hz to 5 Hz on the crack propagation rate is seen in Fig. 1. As the frequency decreased below 1 Hz the crack growth rate increased and the effect could be expressed by the following power law:

$$da/dn = C\Delta K^{\alpha} f^{-\beta} \tag{1}$$

where ΔK is the stress intensity factor range (in the present case $\Delta K = K$ since K_{min} was zero), f is the frequency and C, α and β are material constants ($C = 3.54 \times 10^{-6}$, $n = 1.53$ and $\beta = 0.124$).

$$\text{Hence } da/dn = 3.54 \times 10^{-6} \Delta K^{1.53} f^{-0.124} \tag{1a}$$

This type of relationship has been observed by Guinemer and Plumtree [1] and Solomon and Coffin [2].

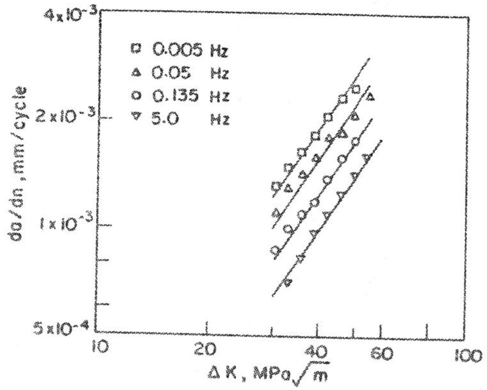

Fig. 1. Crack Growth Rate (da/dn) versus stress intensity factor range (ΔK) plot for different frequency tests.

Examination of the fracture surfaces of specimens tested at 5 Hz and 0.5 Hz revealed the presence of striations especially at high ΔK levels. At low ΔK levels, poorly defined striations were observed. With a decrease in frequency, an increasing amount of intergranular fracture was observed. For the specimens tested at 0.135 Hz and 0.05 Hz, a mixed fracture was evident at low ΔK values whereas transgranular fracture dominated at high ΔK values. However, intergranular fracture dominated the surface of the specimen tested at 0.005 Hz in the low ΔK regime. At high ΔK values, a mixed fracture mode was seen.

Considering the effect of waveform at a constant frequency of 0.135 Hz, it became apparent that the slow-fast waveform increased the crack propagation rate significantly as seen in Fig. 2. The fast-hold-fast and the equal-equal waveforms resulted in similar crack propagation rates, the former giving a slightly greater growth rate. The fast-slow waveform had the lowest crack propagation rate of this group of tests, in fact its growth rate was about the same to that of the 5 Hz frequency test carried out with a triangular waveform. These results are in agreement with those of Yamaguchi and Kanagawa [3] who performed a series of fatigue tests on AISI type 316 stainless steel at 600°C and 700°C.

On metallurgical examination of this group of specimens subjected to different waveforms it was clear that there was more wedge-type cavitation at the grain boundaries when the waveform was slow-fast or fast-hold-fast. A large amount of intergranular fracture was noted. On the other hand, the fracture surface of the specimen tested with a fast-slow waveform was completely covered with ductile striations and the main crack and branch cracks were transgranular.

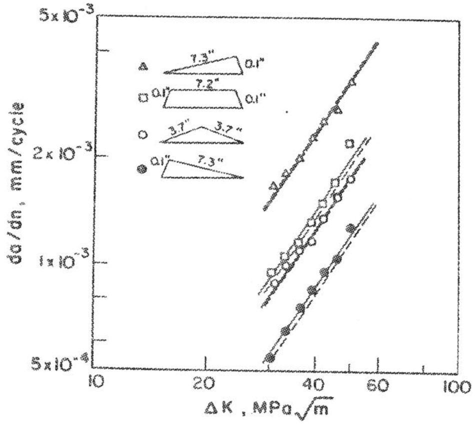

Fig. 2. Crack growth rate (da/dn) versus stress intensity factor range (ΔK) plot for different waveforms. Predicted crack growth rates according to equation (2) are shown by broken lines.

In the third group of tests, different tensile ramp times of 0.3, 1, and 14.6 secs were applied. The unloading time was kept constant at 0.1 sec. Although the waveform was similar, the frequency was different, i.e., 2.5 Hz, 0.91 Hz, and 0.068 Hz respectively. The log da/dn versus log ΔK plot is given in Fig. 3. It is again apparent that the slowest tensile loading time of 14.6 secs was the most damaging giving the highest crack propagation rate which was very similar to that of the specimen with a loading time of 7.3 secs. Scanning electron microscopy revealed that the fracture surface was intergranular.

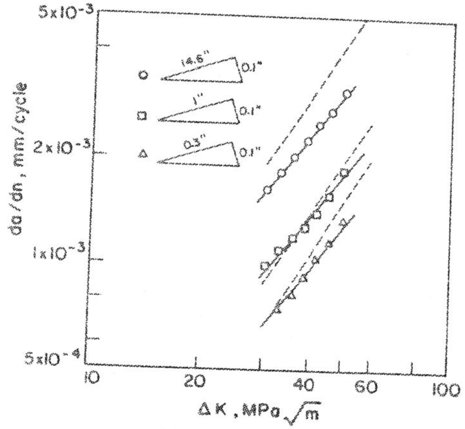

Fig. 3. Crack growth rate (da/dn) versus stress intensity factor range (Δk) plot for different tensile ramp times. Predicted values of crack growth rates using equation (2) are shown by broken lines.

DISCUSSION

The effect of decreasing frequency below 1 Hz has been shown to increase the crack propagation rate and at the same time allow time dependent intergranular fracture processes to develop. For a balanced wave-shape (i.e., equal-equal or fast-hold-fast) equation (1) effectively relates the crack growth rate with ΔK. However, for an unbalanced wave-shape (i.e., fast-slow or slow-fast) at the same frequency equation (1) must be modified to account for the faster crack propagation rate for the slow-fast waveform and the slower crack propagation rate for the fast-slow waveform when compared to the equal-equal waveform at the same frequency of 0.135 Hz. By substituting the term $1/2t_L$ (where t_L is the loading time) for the frequency, f, in equation (1), some allowance is made for the wave-shape. However, the predicted crack propagation rates for the longer loading times with an unbalanced waveform remain slightly lower than the observed rates. This is due to a synergistic effect of the fatigue and time dependent (i.e., creep-type) damage processes, hence an extra term should be introduced for complete description of viscoplastic behaviour. Guinemer and Plumtree [1] used a damage mechanics approach to illustrate that inclusion of a creep component to their model gave good correlation between the predicted and observed crack propagation rates in an austenitic stainless steel at high temperature. Using this as a basis, a similar approach is adopted here and the creep term takes a similar form (i.e., $da/dn = C_c \Delta K^{\nu} \delta^{x}$ where C_c, ν and x are material constants and δ = ratio of loading and unloading times). The terms may be identified by considering the first and second group of tests given in Figs. 1 and 2, and these are included in the full relationship:

$$da/dn = 3.54 \times 10^{-6} \Delta K^{1.53} (1/2t_L)^{-0.124} + 2.52 \times 10^{-7} \Delta K^{1.53} \delta^{0.604} \quad (2)$$

It is now possible to verify this model by considering the third group of tests with loading ramp times of 0.3, 1 and 14.6 sec. For these tests, the values of δ were 3, 10 and 146 respectively. Using equation (2) the crack propagation rates for the different tensile ramp rates may be predicted which are included in Fig. 3. It is seen that the predicted and observed crack growth rates are very similar indicating the applicability of equation (2). Obviously loading time is an important factor and has to be incorporated into any predictions, together with the creep term, allowing the loading (or strain) rate and the direction of loading to be considered. The highest crack propagation rate was recorded when a loading time of 14.6 secs was followed by an unloading time of 0.1 sec. During the relatively long loading sequence, time dependent internal damage developed at the grain boundaries, particularly within the plastic zone at the crack tip. Relaxation during the short unloading time was insignificant. In fact, during this rapid crack sharpening stage the main crack progressed rapidly by linking regions of intergranular damage. By contrast, for the group two specimen with the fast-slow waveform (i.e., $\delta = 0.014$), the time dependent damage was relatively small during the short loading period corresponding to a frequency of 5 Hz. Relaxation during the long unloading sequence was significant. No time dependent damage was allowed to accumulate and hence there was no grain boundary damage with which the fatigue loading sequence could interact. Supporting evidence came from microexamination which revealed that the fracture was completely transgranular. More grain boundary damage and side branch cracks were observed on the fracture surface of the specimens tested using a slow-fast waveform and high δ. When $\delta = 146$ ($t_L = 14.6$ sec) the fracture was intergranular.

CONCLUSIONS

1. The crack propagation rate (da/dn) of AISI type 304 stainless steel at 570°C was found to increase with decrease in frequency (f) below 1 Hz using a balanced waveform. For a constant frequency of 0.135 Hz, the crack propagation rate was influenced significantly by the type of waveform. A slow-fast waveform was the most damaging and a fast-slow waveform the least damaging, having a crack growth rate similar to that of the 5 Hz test. By substituting half the loading time for frequency and introducing a creep term which included the ratio of loading time/unloading time, the crack propagation rate could be expressed satisfactorily in terms of a model relating the stress intensity factor range, loading and unloading times.
2. Applying this model to crack growth of AISI type 304 stainless steel at 570°C subjected to different tensile ramp times (hence different t_L and δ values) good correlation between predicted and observed values was found.

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