WAVEFORM AND FREQUENCY EFFECTS ON THE HIGH TEMPERATURE FATIGUE CRACK PROPAGATION RATE OF STAINLESS STEEL

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ABSTRACT

The influence of frequency, waveform, and tensile ramp time on the cyclic crack propagation rate of AISI type 304 stainless steel at 570°C in air has been studied. Using a balanced waveform, the crack propagation rate increased with decrease in frequency below 5 Hz. A slow-fast triangular waveform resulted in the fastest crack growth rate and the fracture surface was intergranular. On the other hand, the crack propagation rate associated with a fast-slow triangular waveform was less than that for a balanced triangular waveform of the same frequency. An empirical relationship is developed which expresses the cyclic crack propagation rate in terms of the frequency, ratio of loading/unloading times, and the stress intensity factor range.

KEYWORDS

Crack propagation rate; high temperature fatigue; frequency; waveform; AISI type 304 stainless steel.

INTRODUCTION

Austenitic stainless steels, used over a wide temperature range, are often employed in components which are loaded under severe conditions (strain cycling, hold time at a maximum load and thermal cycling). Microcracks can occur where stress concentrations exist at notches and welds. Growth and linkage of these microcracks result in the formation of a large crack whose propagation is influenced by such effects as the frequency and the load waveform. In order to predict component lives a thorough understanding is needed of the behaviour of material under fatigue and creep or environmental interaction (Coffin, 1969; Manson, 1972; Taira, 1962). 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 also is 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 provide a feedback signal for control of 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 of 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, after which the intended frequency and waveform were applied.

Several types of tests were performed. The first was a series using a triangular waveform having equal loading/unloading times and 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-up 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

Using a balanced triangular waveform, Fig. 1 shows the effect of varying frequency from 0.005 Hz to 5 Hz on the crack propagation rate. The crack growth rate is seen to increase with decrease in frequency and may be expressed by the following empirical relationship:

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

where ΔK is the stress intensity factor range (in the present case $\Delta K = K_{max}$ since K_{min} was zero), f is the frequency and C, α and β are material constants. This type of relationship has been observed by Guinemer and Plumtree (1982), James (1978), and Solomon and Coffin (1973), for elevated temperatures, and Yokobori and Sato (1976) at room temperature. Mukherjee and Burns (1971) used a statistical analysis to determine which testing variables, including frequency, were important in the prediction of fatigue crack propagation rate in PMMA. Their equation took the form

$$da/dn = C\Delta K^{\alpha} f^{-\beta} K_{mean}^{\nu} \qquad (2)$$

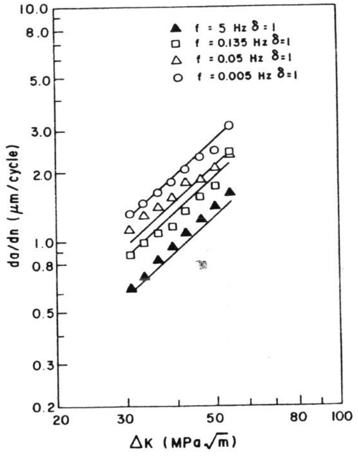

Fig. 1 Crack growth rate vs. stress intensity factor range at different frequencies. Solid lines are according to equation (6).

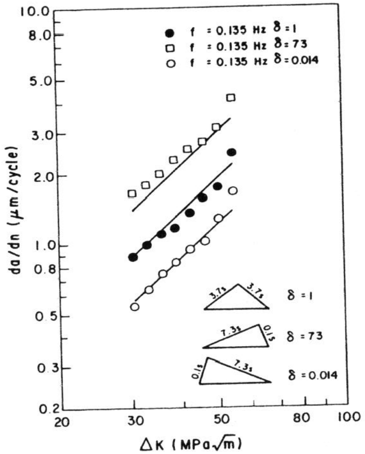

Fig. 2 Crack growth rate vs. stress intensity factor range for different waveforms. Solid lines are according to equation (6).

where K_{mean} is the mean stress intensity factor and ν is a constant. This equation reduces to equation (1) if tests are carried out at a single value of K_{mean}. Thus, equation (1) has been shown to be useful for the prediction of fatigue crack propagation rate in both polymers and metals.

In the present work, the effect of waveform was first studied 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 produced the lowest crack propagation rate of this group of tests, in fact, the growth rate was about the same as that for the 5 Hz frequency test carried out with a balanced triangular waveform. These results are in agreement with those of Yamaguchi and Kanazawa (1980) who performed a series of fatigue tests on AISI type 316 stainless steel at 600°C and 700°C.

Sidey and Coffin (1979) observed that even in vacuum, the life of AISI Type 304 stainless steel at 650°C was an order of magnitude lower in slow-fast tests than in equal-equal tests. Their results from other metals, including OFHC copper, also indicated slow-fast cycling to be the most damaging, resulting in the shortest fatigue lives.

Metallurgical examination of this group of specimens subjected to different waveforms revealed 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 surfaces of the specimens tested with a fast-slow waveform were completely covered with ductile striations and the main crack and branch cracks were transgranular.

In the third group of tests, different tensile ramp-up 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. Scanning electron microscopy revealed that the fracture surfaces were intergranular. Those associated with the faster ramp-up times were transgranular. These effects have been observed previously by Majumdar and Maiya (1978) and Sidey and Coffin (1979).

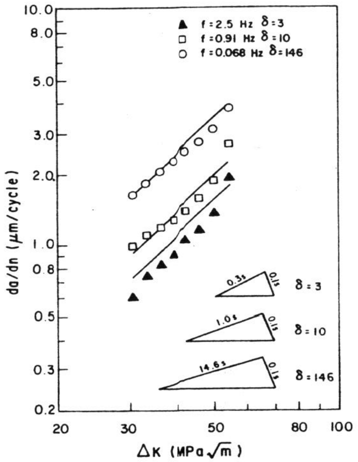

Fig. 3 Crack growth rate vs. stress intensity factor range. Solid lines are according to equation (6).

DISCUSSION

The influence of frequency on high temperature fatigue crack propagation rate has been attributed to a creep component or creep-fatigue interaction (Sadananda and Shahinian, 1980), whereas other studies have indicated that this effect is due to an environment-assisted cracking component (Coffin, 1969; James, 1978; Solomon and Coffin, 1973). Nevertheless, it has been hypothesized that time dependent or creep/environmental behaviour and time independent or fatigue behaviour could be accounted for separately using a linear superposition model (Guinemer and Plumtree, 1982; Saxena, 1981; Taira, 1962) such that

$$da/dn = F(\text{Creep/environment}) + G(\text{Fatigue}) \qquad (3)$$

Analysis of the present data using multiple linear regression techniques showed the second term to be negligible, indicating that the role played by pure fatigue was not significant.

As expected, these results have shown that for a balanced waveform decreasing the frequency below 5 Hz increases the crack propagation rate, allowing time dependent intergranular fracture processes to develop. Since the area under the load-time curve for the same frequency is not significant, equation (1) effectively relates the crack growth rate with ΔK for a balanced wave-shape (i.e., equal-equal or fast-hold-fast).

For the present work, this equation may be expressed explicitly:

$$da/dn = 3.74 \times 10^{-3} (\Delta K)^{1.54} f^{-0.11} \quad (\mu\text{m/cycle}) \qquad (4)$$

where values are obtained using the least squares method. However, for an unbalanced wave-shape (i.e., fast-slow or slow-fast) equation (4) 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. Figure 2 indicates that the loading rate is more important than the integrated load-time curve. Any additional term included in equations (1) and (4) must take this effect into account. By introducing the ratio of loading to unloading times (δ) an allowance is made for both wave asymmetry and loading direction. A value of $\delta = 1$ would indicate a completely balanced wave, $\delta < 1$ would indicate an asymmetric fast-slow wave and $\delta > 1$ an asymmetric slow-fast waveform. The highest crack propagation rates were recorded when loading times of 7.3 and 14.6 secs were followed by an unloading time of 0.1 sec. In these cases, the corresponding δ values were 73 and 146, respectively. During the long loading sequence, time dependent internal damage developed at the grain boundaries, particularly within the plastic zone at the crack tip. The short unloading time did not allow any significant relaxation to occur. During this rapid crack sharpening stage it is supposed that the main crack progressed rapidly by linking regions of intergranular damage. By contrast, for the group two specimens 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 rapid loading sequence could interact. Supporting evidence again 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 $\delta = 146$ the fracture was intergranular. These observations suggest that the fracture mode is more strongly influenced by the effects of the initiation and possible growth of grain boundary cavities during the long tensile loading sequence of the cycle than by the effects of shrinkage of cavities during the unloading time of the cycle. It has been shown that tensile hold periods favour grain boundary cavity initiation and growth, whereas compressive hold promotes cavity shrinkage (Baik and Raj, 1982; Majumdar and Maiya, 1978). Results obtained from asymmetrical hold time tests (Majumdar and Maiya, 1978) have indicated that longer tensile hold times followed in each instance by a short compressive hold were far less damaging than tensile hold alone. A specimen subjected to completely symmetrical hold times with the same period as the asymmetrical hold had an even longer life because of the more complete annealing out of cavities.

Equation (1) may now be presented to allow for δ as follows:

$$da/dn = C(\Delta K)^{\alpha} f^{-\beta} \delta^{\gamma} \tag{5}$$

where γ is a temperature and material constant.

Considering all the results from the three test groups, γ takes the value of 0.10. Hence equation (5) may be restated:

$$da/dn = 3.74 \times 10^{-3} (\Delta K)^{1.56} f^{-0.11} \delta^{0.10} (\mu m/\text{cycle}) \tag{6}$$

The crack propagation rates according to equation (6) are included as solid lines in Figs. 1, 2 and 3.

It is interesting to note that the exponents β and γ have similar absolute values in equation (6). Other research must be considered in order to define whether these exponents should be expected to have the same values. Okazaki and co-workers (1983) studied the effect of strain wave shape on low-cycle fatigue crack propagation of thin-wall cylindrical SUS 304 stainless steel samples at 600°C and 700°C. It was possible to express their data, allowing for frequency and waveform in the manner of equation (5) and, accordingly, it was found that the exponents δ and γ took different numerical values. For 600°C,

$$da/dn = 1.62 \times 10^{-2} (\Delta J)^{1.46} f^{-0.34} \delta^{0.14} \tag{7}$$

where ΔJ is the range of J integral and has the units of kN-m/m^2.

At present there is no theoretical support for the suggestion that the absolute values of β and γ should be similar. Considering the present experimental conditions and those of Okazaki and co-workers (1983), the variations in these exponents must be accounted for by the different specimen geometries.

CONCLUSIONS

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 5 Hz using a balanced waveform. The crack propagation rate was also 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 with a balanced waveform. By including the frequency and introducing the ratio of loading time to unloading time, the crack propagation rate could be expressed satisfactorily in terms of a modified Paris Law relating the stress intensity factor range and these terms.

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