THE EFFECT OF FREQUENCY ON FATIGUE CRACK PROPAGATION RATE

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ABSTRACT

It has been observed that the fatigue crack propagation rate of a nickel-aluminium bronze alloy is sensitive to the cycling frequency in the range 0.1Hz-100Hz. This effect is shown to be due to a strain-rate sensitivity in the material. The magnitude of the effect can be predicted using dislocation dynamics theory. This has important consequences for the prediction of fatigue life on the basis of accelerated tests carried out at high frequency.

KEYWORDS

Fatigue crack propagation; nickel-aluminium bronze; frequency effect; strain-rate sensitivity; dislocation dynamics.

INTRODUCTION

It is customary when assessing the susceptibility to fatigue of components in service, to perform laboratory tests at relatively high frequency between 10 and 100Hz, even if the service application involves cyclic stresses at lower frequencies. Increasing frequency is a convenient way of accelerating the fatigue damage rate so as to allow assessments to be carried out in relatively short times. It is generally assumed that the change of frequency has no effect on fatigue properties such as number of cycles to failure or the crack propagation rate in mm/cycle.

There are, however, two situations in which fatigue properties are affected by frequency. The first is the case of fatigue enhanced by corrosion; it is well known that crack propagation per cycle is greater at lower frequencies if aqueous corrodants are involved (Atkinson and Lindley, 1977; Bamford, 1977; Barson, 1971). This effect, though still poorly understood, has been extensively documented.

The present paper is concerned with an effect which has received much less attention up to now; this is a frequency effect caused by strain-rate sensitivity. The mechanical properties of all metals are to some degree sensitive to the strain rate used in the testing; at high strain rates the yield strength tends to be higher and the amount of plastic strain at a given stress tends to be lower, than at low strain rates. These effects have been measured for many different alloys (e.g. Wulf, 1974; Tanaka and Najima, 1979; Kawata and others, 1977). In many cases significant effects are only observed at very high strain rates, such as those associated with ballistic problems. However, several alloys, including some in common use, show strain-rate effects even at strain rates which correspond to relatively low-frequency fatigue cycling, such as 0.1Hz.

EXPERIMENTAL DETAILS

The material used was a sand cast aluminium bronze, specification BS1400AB2. Further details can be found in (Macken and Smith, 1966; Taylor and Knott 1982; Taylor, 1981). Fatigue crack propagation tests were carried out using SEN specimens made from 20mm bar. Potential drop crack-length measuring equipment was used, and results displayed on a logarithmic plot of da/dN as a function of ΔK. Sine wave loading was used throughout, at frequencies of 0.1Hz, 1Hz, 10Hz and 100Hz.

RESULTS

Fig. 1 presents crack propagation results for a range of frequencies from 0.1Hz to 100Hz, at an R ratio of 0.28. It can be seen that the crack growth rate per cycle increases as the frequency decreases. Fig. 2 presents similar results at an R ratio of 0.5. Note that the lines representing the different frequencies are approximately parallel. Within the range of frequencies studied, a change in frequency by a factor of 10 can be seen to cause a change in da/dN by a factor of about 1.3.

Tests were also conducted using a pearlitic steel; the comparison of 100Hz and 1Hz cycling shown in Fig. 3 suggests that the frequency effect was not present in this material.

In order to rule out the possibility of a corrosion-fatigue effect, some tests were conducted on Aluminium Bronze in an inert gas atmosphere (argon). As Fig.4 shows, the frequency effect persisted, the growth rate at 1Hz being considerably higher than that at 100Hz. Further details of the corrosion fatigue behaviour of this material can be found in (Taylor and Knott, 1982; Macken and Smith, 1966).

PREDICTION OF THE FREQUENCY EFFECT - DISLOCATION DYNAMICS

It has been possible to predict the general form of the frequency effect working from the assumption that the crack growth rate at a given stress intensity range is proportional to the crack tip strain range. This is to say that, at a given stress intensity range, the amount of crack advance per cycle will depend on the amount of permanent plastic deformation that can be attained at the crack tip. Results suggest that in this material the amount of deformation is greater if the stressing is carried out more slowly, hence the existence of the frequency effect.

Yamada and co-workers (1975) have developed a theory to account for a frequency effect observed by them when carrying out S/N fatigue tests using pure copper. It was found by Yamada that the number of cycles to failure could be increased by testing at high frequencies, (see Fig. 5). Also included was a survey of similar work (Kikukowa 1965; Yamane, 1964; Taira and Emura, 1962; Harris, 1959; Eckel, 1951; Gucer, 1970) reported using other materials, testing at frequencies in the range 10^{-3} to 10^{5}Hz. It is likely that some of the frequency effects reported are in fact linked to

corrosion fatigue processes; for instance, the results obtained by Eckel (1951) using lead. However, the majority of the results presented, including the tests carried out by the authors themselves, seem to show genuine strain-rate sensitivity. No other work could be found in the literature showing an effect of frequency on propagation rate, apart from corrosion fatigue work.

Yamada et al made use of simple dislocation dynamics to deduce the plastic strain range, $\Delta\varepsilon_p$, for a given applied stress range. This strain range is dependent upon frequency because of the finite velocity of dislocations. The approach is, in essence, similar to that employed by Frost and Ashby in the derivation of deformation mechanism maps, but differs in some details of formulation

OUTLINE OF THE THEORY DEVELOPED BY YAMADA

The plastic strain rate $\dot{\varepsilon}_p$, can be expressed in terms of the dislocation velocity, v, and the density of mobile dislocations, ρ_m, thus :

$$\dot{\varepsilon}_p = gb\rho_m\bar{v} \qquad (1)$$

..... b being Burger's vector and g a geometric constant relating microscopic to macroscopic flow. The mean dislocation velocity, $\bar{v}$, can be expressed in the following way :

$$\bar{v} = v^*\exp(-D/\tau) \qquad (2)$$

..... τ being the applied stress and D a coefficient with dimensions of stress, which is referred to as the 'characteristic drag stress'.

Substitution for ρ_m in equation (1) is made more difficult by the phenomenon of strain hardening. To account for this, the following expression was developed :

$$\rho_m = (\rho_o + M\varepsilon_p)\exp(-H\varepsilon_p/\tau) \qquad (3)$$

The first bracketted term allows for the increase in dislocation density with increasing strain as more dislocations are created, ρ_o and M being material constants. The exponential term in equation (3) allows for the fact that a smaller proportion of the total number of dislocations are mobile at higher strain levels, H being a material constant.

Combining equations (1), (2) and (3) leads to a relationship between the plastic strain rate and the applied stress, including various material constants. Some of these constants, such as ρ_o and v*, can be found by reference to other work in this field. The constants D and H were deduced by Yamada et al from cyclic stress-strain data for their material. In doing this they found that strain hardening could be better represented by the expression :

$$\exp(-(H_1\varepsilon_p + H_2\varepsilon_p^{1/n})/\tau)$$

They also found that D is slightly sensitive to the frequency, F :

$$D = 3.3\ (\log f)^2 - 18\log f + 186.3\ \ \text{Kg/mm}^2 \qquad (4)$$

This leads to the equation :

$$\dot{\varepsilon}_p = gbv^*(\rho_o + M\varepsilon_p)\exp[-(H_1\varepsilon_p + H_2\varepsilon_p^{1/n} + D)/\tau] \qquad (5)$$

The values of the various constants used are listed in Table 1.

A complete analytical solutiom to this equation is difficult, if not impossible, but a number of interesting results can be derived from it using computer aided numerical methods. For instance it can be shown that if an instantaneous stress is applied, the variation of strain with time will take the form shown in Fig. 6. Note that even after quite long periods of time (e.g. 1 second) the strain is still rising at an appreciable rate.

The loading cycle corresponding to Fig. 6 can be equated to the first half-cycle of a square-wave fatigue-loading system. It is clear that the strain range achieved per cycle will depend markedly on the time period, and hence on the frequency.

Fig. 7 shows the effect of a sinusoidal loading pattern. Here the constant τ in equation (5) has been replaced by the expression

$$\tau = \sigma_o \sin(\omega t)$$

where σ_o = maximum amplitude
t = time
ω = angular frequency

So equation (5) can be used to estimate the cyclic strain range for a given stress range, waveform and frequency. At present this is only possible for copper because the various constants in equation (5) have not yet been determined for aluminium bronze. Also no account has been taken of cyclic hardening or of the Bauschinger effect. Despite these inadequacies, it has been possible to make a reasonably accurate prediction of the effect of frequency on crack propagation rate. Fig. 8 compares theoretical and experimental results it can be seen that there is fair agreement. As stated earlier, this prediction has been achieved by assuming that the fatigue crack propagation rate, da/dN, is proportional to the strain range in the crack-tip locale. It has further been assumed that the strain range deduced from Yamada's equation is proportional to the near-crack-tip strain range.

FURTHER WORK

It is encouraging to find that the frequency effect can be approximately predicted using simple theory, but it is clear that more sophisticated methods of prediction are needed. An understanding of frequency effects is essential for any method of fatigue life prediction which is based on the results of accelerated tests. This problem becomes particularly acute when dealing with very low growth rates, near the stress-intensity threshold for crack propagation. All the tests in the present work were carried out at crack growth rates above 10^{-5}mm/cycle. Testing at low growth rates (10^{-8} - 10^{-6}mm/ cycle) at low frequencies (less than 10Hz) is very difficult because the very long times involved put considerable demands on the stability of crack-length monitoring equipment. For this reason it is necessary to be able to predict the frequency effect, since reliable experimental data cannot be obtained.

It is hoped to continue this work in both theoretical and experimental directions. Experimental measurements of the monotonic and cyclic stress/strain behaviour of nickel-aluminium bronze will enable the various constants in the predictive equations to be redetermined. Modelling of fatigue stress/strain hysteresis curves should be included. Consideration must also be given to the relation between macroscopic and near-crack-tip properties. Propagation data should be collected for a wider variety of materials and over a greater range of growth rates.

CONCLUSIONS

1. Thefatigue crack propagation rate of nickel aluminium bronze is sensitive to the testing frequency. Tests carried out in the range 0.1Hz-100Hz showed an increase in propagation rate by a factor of about 1.3 for every factor of 10 decrease in frequency at the same stress intensity amplitude.

1. The magnitude of this effect could be predicted with some success using a simple theory based on dislocation dynamics.

3. It is important to be aware of, and to be able to predict, this effect if predictions of fatigue life in service are to be made using the results of laboratory tests accelerated by increasing frequency.

4. Further work is needed in this largely neglected area, to measure this effect in other materials, to separate this effect from corrosion-fatigue effects, and to refine the theoretical predictions.

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TABLE I: Values of the Constants used in Equation (5)

g	b	v*		M	H_1
1/3.06	2.55A	2270m/s	$10^{12}cm^2$	$5x10^{10}cm^2$	30,000 Kg/mm^2

H_2	n
$300Kg/mm^2$	8

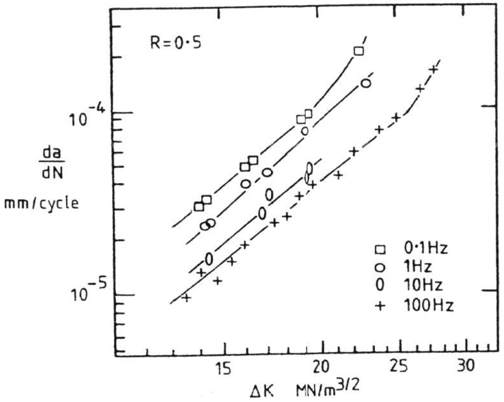

Fig.1 Results showing the Effect of Frequency, R=0.5

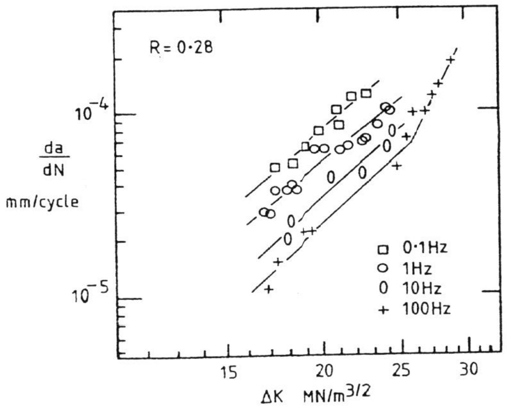

Fig.2 Results showing the effect of Frequency, R=0.28

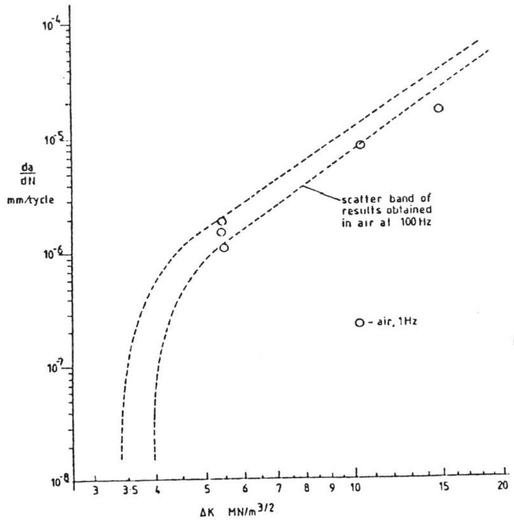

Fig.3 Results from Pearlitic Steel, in air at R=0.65 at 100Hz and 1Hz.

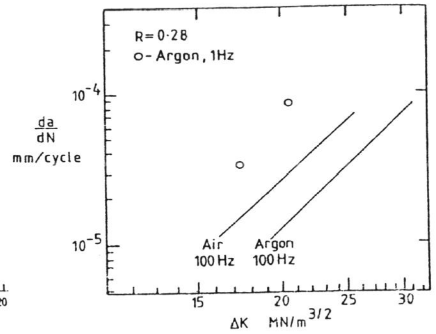

Fig.4 Results of tests in argon gas at 100Hz and 1Hz. Results in air at 100Hz included for comparison.

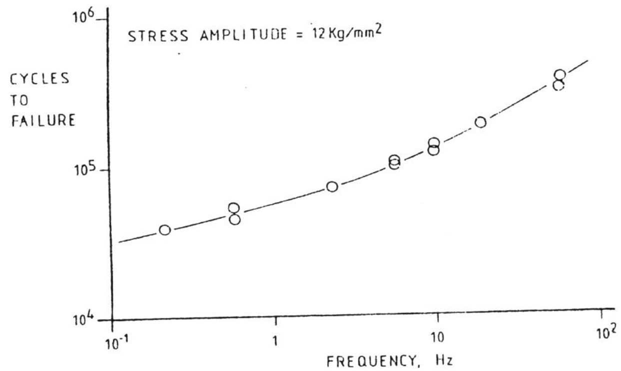

Fig.5 Results due to Yamada et al (10)

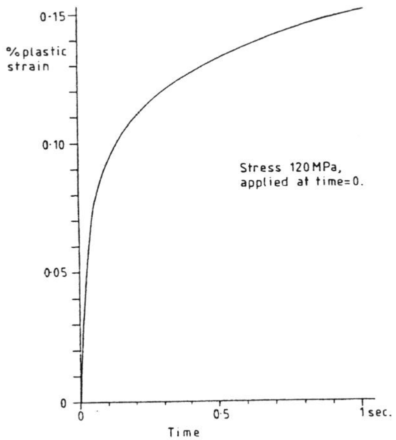

Fig.6 Modelling the response to an instantaneous applied stress.

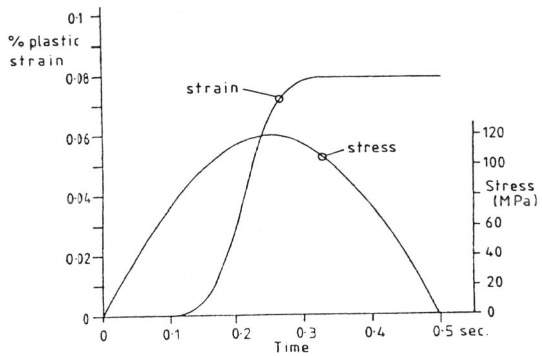

Fig.7 Modelling the response to a sinusoidal applied stress.

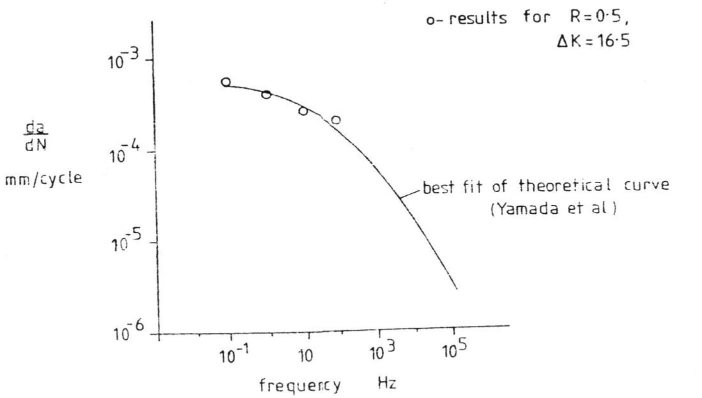

Fig.8 Comparison of theory and Experimental Results