FATIGUE STUDIES OF A HIGH STRENGTH AGE HARDENING WROUGHT Cu-Ni ALLOY

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ABSTRACT

As the first phase of a programme to study the conjoint action of stress corrosion and fatigue, fatigue crack growth studies have been performed on a high strength age hardening wrought Cu-Ni alloy.

KEYWORDS

Fatigue crack growth; grain size; microstructure; reversed plastic zone size; structure dominance; trans-granular and intergranular cracking; stress intensity factor.

INTRODUCTION

The conjoint action of stress corrosion and fatigue is of considerable importance in many situations, such as marine applications and aero-engines. This study represents the first phase of a programme to investigate the combined effect of stress corrosion and fatigue on a high strength age hardening wrought copper-nickel alloy, used in marine applications. As such, only fatigue is considered in an attempt to establish the fatigue crack growth mechanisms which operate at different stress intensity level. Future studies will investigate the influence of other parameters.

FATIGUE CRACK PROPAGATION

Linear elastic fracture mechanics (LEFM) has now gained almost universal acceptance as a powerful tool in assessing the fatigue integrity of components. The total life of a component will, in general, consist of the formation of an engineering crack; the subsequent fatigue crack growth; and finally failure by fracture or some other limiting criterion. These individual phases are discussed in the literature (Duggan, 1977, 1980; Duggan and Byrne, 1979; Duggan, Lowcock and Staples, 1979; Duggan and Proctor, 1979) and only limited considerations of fatigue crack growth (FCG) within LEFM conditions will be considered in the present paper.

Now if it is assumed that FCG is governed by the conditions at the crack tip, and that the crack tip conditions can be characterised by the stress intensity factor, then FCG as a function of stress intensity range ΔK can be determined. A graphical representation of FCG rates (da/dN) as a function of ΔK in general produces a sigmoidal shape curve which can be divided into three regions, namely

(i) slow crack growth and threshold conditions;

(ii) stable crack extension increasing with ΔK; and

(iii) unstable crack extension as K_{max} approaches K_{IC}.

It is generally supported by experimental observation that microstructure and other parameters have little or only secondary influence in the region corresponding to stable extension, i.e. outside the influence of threshold conditions and fast fracture. Within this region, which is often of most practical value, a linear relationship between (da/dN) and ΔK is often assumed on logarithmic co-ordinates. Thus, the well known Paris relationship is frequently used in the form

$$\frac{da}{dN} = C\ \Delta K^{n} \tag{1}$$

where C and n are experimentally determined constants. Since it has been demonstrated (Elber, 1970) that crack closure and stress ratio can significantly influence FCG rates, equation (1) is often modified to

$$\frac{da}{dN} = C'\ (\Delta K_{eff})^{n'} \tag{2}$$

where
$$\Delta K_{eff} = K_{max} - K_{op} = U\Delta K \tag{3}$$

and
$$U = \frac{K_{max} - K_{op}}{\Delta K} \tag{4}$$

and K_{op} is the stress intensity level corresponding to the conditions where crack opening occurs.

In an attempt to overcome some of the criticisms associated with the Paris relationship, Duggan (1977) developed a model based upon the damage which accumulates at the crack tip as the result of the irreversible process associated with plasticity. For the special case within the Paris regime, it was demonstrated that

$$\frac{da}{dN} = \left(\frac{\pi}{32}\right)^{1/2\alpha} \frac{1}{\alpha} \left(\frac{2}{\varepsilon_f' E K_c}\right) \Delta K_{eff}^{2/\alpha} \tag{5}$$

where ε_f' represents the fatigue ductility coefficient, α the slope of the plastic strain range versus cycles when plotted on logarithmic co-ordinates; E is the elastic modulus; and K_c the fracture toughness.

More recently, Proctor and Duggan (1979) have attempted to combine a continuum mechanics approach with consideration of microstructure. This approach utilises the concept of a fatigue process zone ahead of the crack tip, but within the reversed plastic zone, and for LEFM conditions it is demonstrated that the fatigue crack growth rate is related to a combination of parameters. It is shown that the relationship may be expressed in terms of the effective stress intensity range, the mechanical and low cycle material properties, a microstructural parameter, and the fatigue process zone. In equation form

$$\frac{da}{dN} = (\ell-\lambda)\left[\frac{4\varepsilon_y}{\varepsilon_f'(1-R)}\right]^{-\frac{1}{\alpha}}\left[0.489\,\frac{\Delta K_{eff}}{S_p}\,\frac{(\ell+\lambda)^{\frac{1}{2}}-(2\lambda)^{\frac{1}{2}}}{\ell-\lambda} - 1\right]^{-\frac{1}{\alpha}} \quad (6)$$

where ℓ is the fatigue process zone; λ a microstructural parameter such as grain size; ε_y is the yield strain; and S_p the yield strength. For the special case when the fatigue process zone ℓ is equal to the microstructural parameter λ, the FCG rate is zero, and hence

$$\ell = \left(\frac{\Delta K_I}{\Delta K_{th}}\right)^2 \lambda \quad (7)$$

This suggests that the fatigue process zone is a function of microstructure and stress intensity range and any parameter which influences the stress intensity would consequently influence the fatigue process zone.

CRACK TIP PLASTIC ZONES

The application of LEFM to fatigue crack propagation studies is limited to those situations where stress rather than structure dominates. The occurrence of microstructural sensitive crack growth has been related to a grain size crack tip plasticity interaction. Specifically, the occurrence of both trans and intergranular facets have been shown to occur (Beevers, 1977) when the reversed plastic zone size is smaller than the grain size. For situations where LEFM conditions apply, an estimate of the monotonic (or forward) and reversed plastic zone sizes may be estimated in terms of the uniaxial yield strength, S_p. In general,

$$\frac{r_p}{I} = \left[A\left(\frac{K_{max}}{S_p}\right)^2\right]^q \quad (8)$$

and

$$\frac{r_r}{I} = \left[A\left(\frac{K_{max}}{2S_p}\right)^2\right]^p \quad (9)$$

where r_p and r_r represent the forward and reversed plastic zone sizes respectively; K_{max} and ΔK represent the maximum stress intensity and stress intensity range respectively; I represents the stress state, ie. $I = 1$ for plane stress and $I = 1/3$ for plane strain; q and p are material strain hardening characteristics; and A is a constant, various values of which are found in the literature. It has been demonstrated by Lal and Garg (1977) that the extent of the plastic zone depends upon the monotonic and cyclic strain hardening characteristics of the material. Using a von-Mises-Hencky criterion for a perfectly elastic perfectly plastic material.

$$\frac{r_p}{I} = 0.239\left(\frac{K_{max}}{S_p}\right)^2 \quad (10)$$

$$\frac{r_r}{I} = 0.239\left(\frac{\Delta K}{S_p}\right)^2 \quad (11)$$

enabling estimates of crack tip plastic zones to be obtained.

EXPERIMENTAL STUDIES

The material studied is a copper base alloy having the following mechanical properties

Tensile strength, S_u = 768 MPa

0.2% Proof strength, S_p = 480 MPa

% elongation, = 21.7

Young's modulus, E = 110 000 MPa

Crack propagation data was obtained using SEN beam test pieces, subjected to cantilever bending. Crack length was measured utilising the dc potential technique. Additionally strain gauges were positioned on the back face of the test pieces and COD gauges attached to knife edges positioned either side of the notch, were used to measure back face strain and crack opening displacement. These readings were made at discreet pre-determined intervals of crack length and enabled crack closure to be studied.

Although from a fundamental point of view it can be argued that a constant strain rate is desirable throughout the test, during fatigue crack propagation the bending moment decreases with cycles and the situation is complicated. Also, where time dependent processes are important, frequency rather than strain rate might be more significant. Consequently, each test was conducted at a constant frequency of 16.66 Hz (1000 vib/min) and a constant stress ratio of 0.1 was used thoughout the testing.

For the particular case of a SEN specimen loaded in cantilever bending it has been shown (Duggan, Proctor and Spence, 1979) that the stress intensity factor can be calculated from

$$K_I = \frac{6Ma^{\frac{1}{2}}}{BW^2} Y \qquad (12)$$

where a is the crack length; M the applied bending moment; B and W the specimen thickness and width respectively; and Y the compliance function calculated from

$$Y = 6.06-41.06\left(\frac{a}{W}\right)+160.57\left(\frac{a}{W}\right)^2 -271.8\left(\frac{a}{W}\right)^3 +190.0\left(\frac{a}{W}\right)^4 \qquad (13)$$

Obtaining the crack length and corresponding stress intensity range with good accuracy is straightforward, but this is not necessarily true for the determination of FCG rates. It is sometimes difficult to obtain a smooth steadily increasing curve for the (da/dN) graph, and different numerical treatments of the same experimental data have yielded significantly different solutions (Austen, 1978). In the present study a simple finite difference method was used, based on samples at equal intervals of crack length. Thus, dividing the a-N curve into equal increments of crack length Δa, the FCG rate is obtained from

$$\frac{da}{dN} = \frac{\Delta a}{N_{i+1} - N_{i-1}} \qquad (14)$$

where ΔK is calculated at a; and

$$a_i = \frac{a_{i+1} - a_{i-1}}{2} \quad (15)$$

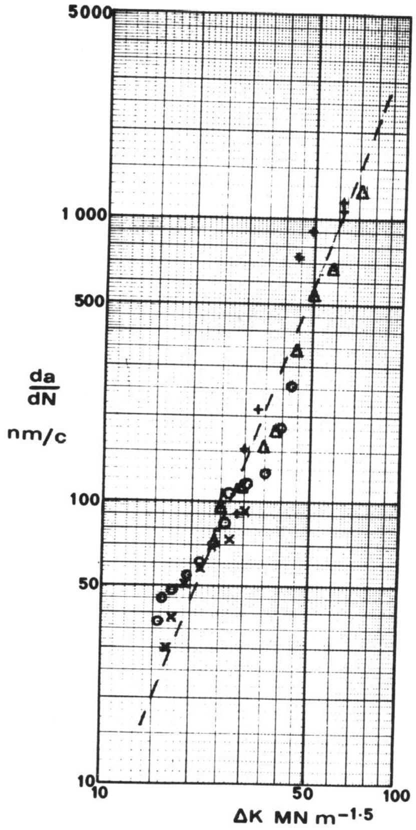

Fig. 1 Fatigue crack growth data

Figure 1 indicates the crack growth data obtained, and if a simple Paris relationship is used to describe the data, then a "visual best fit" gives

$$\frac{da}{dN} = 11.35 \times 10^{-3} \Delta K^{2.76} \quad (nm/c) \quad (16)$$

The application of equations (5) and (6) require low cycle fatigue data and threshold information, and testing is continuing in order to apply the models to this particular material.

FRACTOGRAPHIC STUDIES

Since the main objective of this study was to establish the fatigue crack growth mechanisms which operate at different stress intensity levels, fractographic studies have been carried out for various conditions, and Figs. 2 to 8 illustrate representative results.

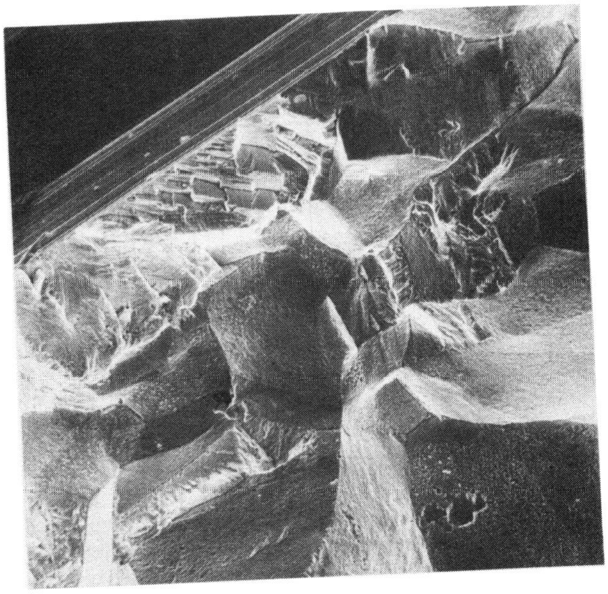

Fig. 2 Transgranular initiation (x 300)

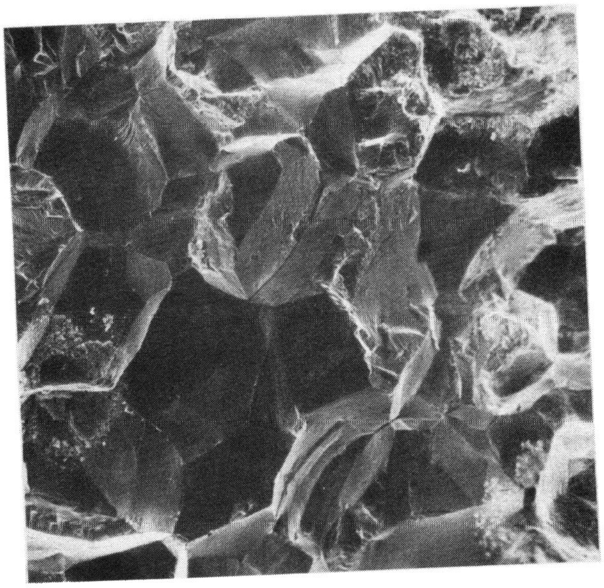

Fig. 3 Intergranular crack growth (x 150)

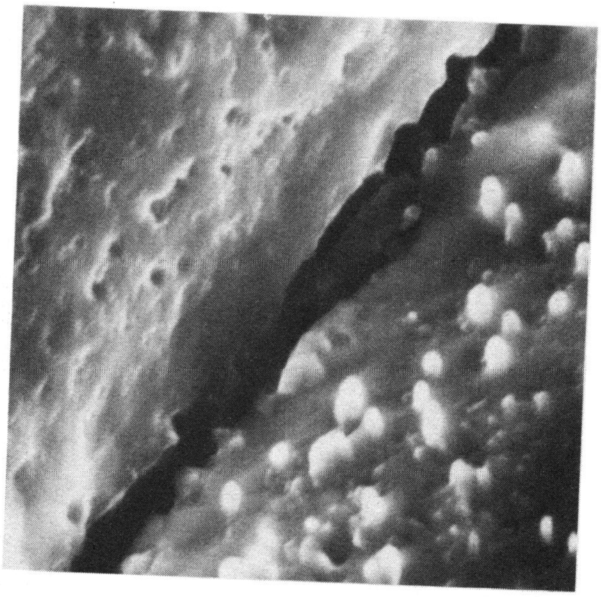

Fig. 4 Grain boundary Precipitates (x 7500)

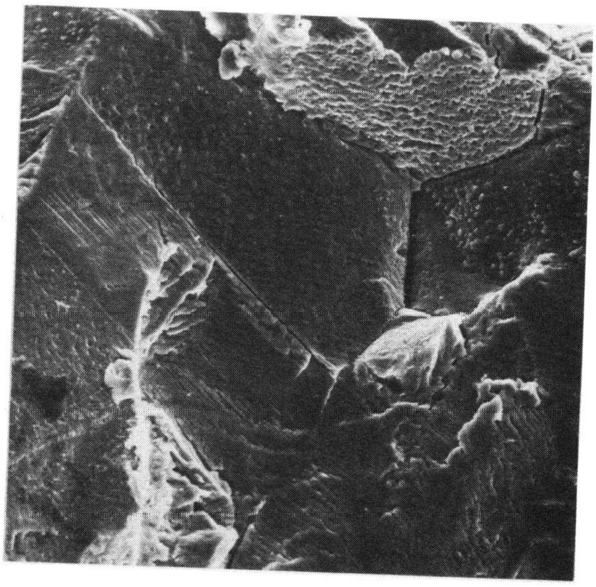

Fig. 5 Transition zone indicating intergranular cracking with some striation features (x 600)

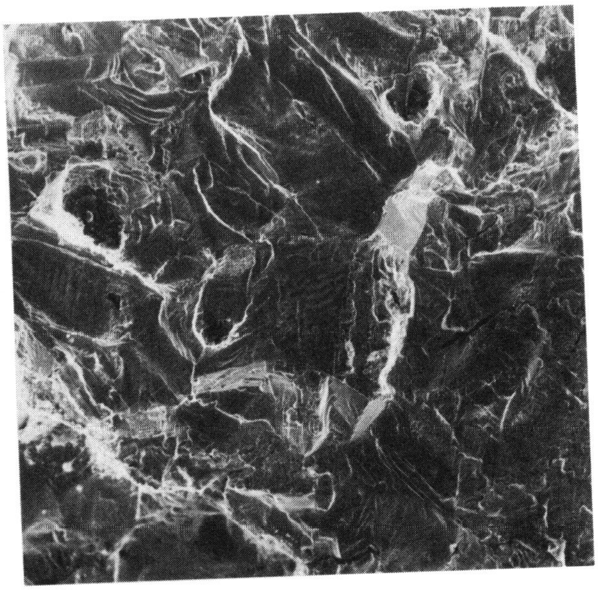

Fig. 6 Transgranular cracking with some striation features (x 150)

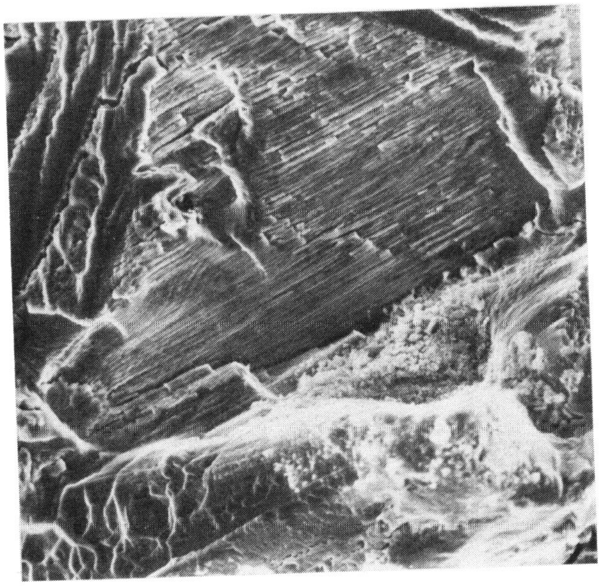

Fig. 7 Striation features with transgranular cracking (x 750)

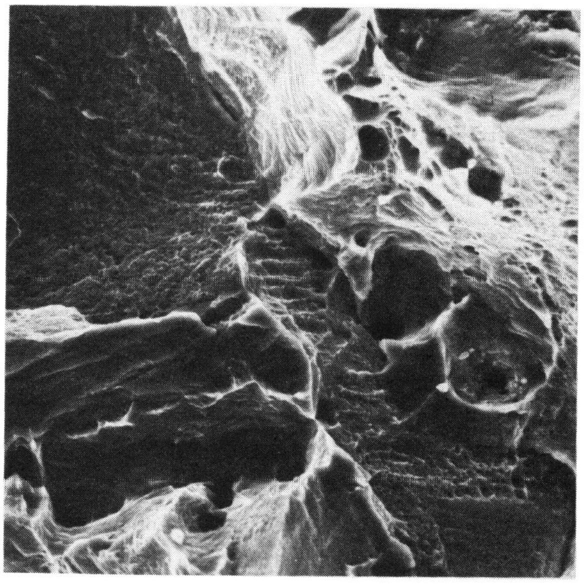

Fig. 8 Fracture surface produced by ductile overload (x 750)

It is observed that the fatigue crack growth mechanism appears to consist mainly of three phases, ie.

(i) transgranular initiation;

(ii) intergranular crack propagation; and

(iii) a region exhibiting striation features with mixed mode cracking.

Typical transgranular initiation at the root of the machined notch is shown in Fig. 2. This is followed by a region consisting exclusively of intergranular fatigue crack growth, Fig. 3, with grain boundary precipitates being evident, as shown in Fig. 4. A transition region then occurs indicating a combination of intergranular cracking with striation features, Fig. 5. The crack growth then changes to a mechanism which produces striated features on transgranular fracture surfaces, as indicated in Figs. 6 and 7. Finally, Fig. 8 indicates the fracture surface produced by a ductile overload, and is somewhat unusual in that it indicates some regions of flat fracture in addition to ductile dimples.

DISCUSSION OF RESULTS

It is of obvious interest to attempt to relate the changes in fatigue crack growth mechanisms to possible relationships between forward and reversed plastic zone sizes and microstructural features, such as average grain size.

Measurements were made to locate the length of fatigue crack corresponding to the transition from intergranular cracking to the region exhibiting striation features. Corresponding to this location in each test specimen, the stress intensity range and the corresponding plastic zone sizes have been calculated, and the results are indicated in Table 1. It is seen that the transition occurs at an approximately

TABLE 1 Conditions at Transition Region

Specimen No.	1	2	3	4
Crack length, (mm)	14.075	15.175	9.475	5.175
ΔK (MN m^{-312})	36.8	36.5	35.0	29.7
r_r (mm)	0.35	0.35	0.32	0.100
r_p (mm)	1.54	1.55	1.38	1.02

constant stress intensity range of about 36.5 $MNm^{-3/2}$, and this coincides roughly with a reversed plastic zone size of about twice the grain diameter. In the case of specimen number 4, the tip of the fatigue crack is still sufficiently close to the machined notch to be influenced by it, and since large notch strains are involved, the crack is likely to be controlled by notch plastic strain rather than by crack tip conditions (Hammouda, Smith and Miller, 1979). Since the length of the fatigue crack (excluding notch depth) for specimen number 4 is of the same order as the forward plastic zone size, LEFM conditions certainly break down.

Although it is evident that the transition from intergranular to a region involving striation features occurs at a constant ΔK (within the confines of LEFM conditions), no attempt is made at this stage to relate the condition specifically to microstructure. In fact, this transition could be due to an increasing amount of plasticity associated with the crack tip, and possibly an increasing shift from plane strain to plane stress conditions.

The mechanism of fatigue crack growth involving transgranular initiation is likely to be associated with the relationship between grain size and the reversed plastic zone size. In fact, assuming that notch plastic strain does not significantly affect the stress intensity range for specimen numbers 1 and 2, the reversed plastic zone size for these tests is less than the grain size, suggesting structure rather than stress dominance, and a change in mechanism would be expected.

CONCLUSIONS

1. Fractographic studies demonstrate the existence of different fatigue crack growth mechanisms at different stress intensity ranges.
2. Transgranular crack initiation occurs when the reversed plastic zone size is less than the average grain diameter.
3. A transition from intergranular to a region exhibiting striation features with transgranular cracking occurs at an approximately constant stress intensity range of about 36.5 $MNm^{-3/2}$. This corresponds to a reversed plastic zone size of about twice the average grain diameter.

REFERENCES

Austen, I.M. (1978). An assessment of the ability of various methods of fatigue crack growth rate determination. *British Steel Corporation Report No. PT/7422/8/78 B WG2/56.*

Beevers, C.J. (1977). Some aspects of fatigue crack growth in metals and alloys.

4th Int. Conference on Fracture, Waterloo, Canada.

Duggan, T.V. (1977). A theory for fatigue crack propagation. *Engrg. Fracture Mechs.* 9, 735-747.

Duggan, T.V. and Byrne, J. (1979). *Fatigue as a Design Criterion*, Macmillan, London.

Duggan, T.V., Lowcock, M.T. and Staples B. (1979). Predicting crack formation life. *J.Mech. Eng. Sc.* 21, 263-273.

Duggan, T.V., Proctor, M.W. and Spence, L.J. (1979). Intensity calibrations and compliance functions for fracture toughness and crack propagation test specimens. *Int. J. Fatigue*, 1, 27-46.

Duggan, T.V. (1980). Assessing fatigue integrity. *Trans. Indian Institute of Metals* (invited paper).

Elber, W. (1970). Fatigue crack closure under cyclic tension. *Engrg. Fracture Mechs.* 2, 37-45.

Hammouda, M.M., Smith, R.A. and Miller, K.J. (1979). Elastic-plastic fracture mechanics for initiation and propagation of notch fatigue cracks. *Fatigue of Engrg. Matls. and Structures*, 2, 139-154.

Lal, K.M. and Garg, S.B.L. (1977). On the evaluation of monotonic and cyclic plastic zones. *Engrg. Fracture Mechs.* 9, 433-442.

Proctor, M.W. and Duggan, T.V. (1979). A simple generalised model for fatigue crack propagation. In G.C. Sih and S.R. Valluri (Eds.), *Fracture Mechanics in Engineering Applications.* Sijthoff and Noordhoff, The Netherlands. pp. 227-239.