Multiaxial High Strain Fatigue

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Synopsis

Little previous experimental work has been conducted on the effect of complex stress-strain fields on crack growth mode and direction. In the present work hollow cylinders have been subjected to a variety of multiaxial high strain conditions, and deformation and fatigue fracture have been studied. Fatigue crack growth is controlled by shear strain processes with crack orientation dependent on the position of planes of maximum shear strain and material anisotropy. The application of a tensile strain normal to the plane of maximum shear strain increases the rate of propagation and eventually permits Stage II crack growth to supersede Stage I growth.

Introduction

In an engineering component the growth of a fatigue crack is usually controlled by a complex stress-strain field. The rate, direction and mode of growth can not be predetermined and design engineers frequently have to formulate their predictions via empirical rules based on simple laboratory test data. In High Strain Fatigue research two kinds of test are commonly employed on cylindrical specimens. Firstly, the reversed torsion test in which the fatigue crack invariably grows along the plane of maximum shear stress; Stage I crack growth. Secondly, the push-pull test in which the majority of life is spent in Stage II growth i.e. crack propagation on a plane perpendicular to the maximum tensile stress. Little experimental work has been conducted on the effect of complex stress strain fields on crack growth mode and direction. The present work is concerned with the deformation and fracture behaviour of an anisotropic material subjected to multiaxial high strain fatigue.

The experiments

Cylindrical hollow specimens are subjected to push-pull, or reversed torsion, or combinations of these two loading modes. This system induces a triaxial state of strain which may be defined by λ where

$$\lambda = \frac{\text{TORSIONAL SHEAR STRAIN RANGE}}{\text{AXIAL STRAIN RANGE}} \quad (1)$$

Thus λ varies from zero in the case of a simple push-pull test to infinity in the case of a reversed torsion test. The same specimen geometry was used throughout and is illustrated in Fig. 1.

Extensometry was attached on the fillet radii, extremely close to the working length and at a diameter only 0.2 mm greater than the central zone diameter. In order to eliminate buckling and strain concentrations considerable rig and specimen development was necessary, details of which are given elsewhere (1). All tests were carried out at room temperature on rolled bar material of percentage composition as shown in Table 1.

Cr	Mo	V	Ni	C	Si	Mn	S	P
1.06	1.00	0.35	0.70	0.29	0.23	0.74	0.008	0.013

Table 1

The steel was heat treated for 2 hours at 975°C, then air cooled, followed by 20 hours at 700°C and furnace cooling. The research program involved 6 test series, i.e. λ values $0, \frac{1}{2}, 1, 2, 4$ and ∞. Each test was controlled between reversed total strain limits and at a constant shear strain rate.

Results

Deformation behaviour for all λ states may be expressed by the equation

$$\Delta\tau = k(\Delta\gamma_p)^n \qquad (2)$$

where $\Delta\tau$ = maximum shear stress range
$\Delta\gamma_p$ = maximum plastic shear strain range
n = cyclic shear-strain hardening exponent
k = constant

Fracture behaviour for all λ states may be expressed by the Manson-Coffin expression

$$(\Delta\gamma_p) N_f^{\alpha} = C \qquad (3)$$

where N_f = number of cycles to failure and α and C are constants.

Results for both deformation and fracture behaviour, exemplified by equations (2) and (3) are summarised below in Table 2.

λ	k/MNm^{-2}	n	α	C
0	896	0.114	0.608	1.14
0.5	1010	0.149	0.583	0.94
1.0	1010	0.149	0.561	1.06
2.0	1120	0.157	0.536	1.04
4.0	1110	0.173	0.576	1.50
∞	993	0.141	0.648	2.75

Table 2

The fatigue results are shown as linear functions in Fig.1; individual experimental points being omitted for clarity.

It is noted that λ effects both the slope α and constant C of equation (3) and that specimen endurance under pure shear conditions is approximately twice that under uniaxial push-pull conditions. This is in accord with the work of Benham (2) and Yokobori (3) who compared torsion and push-pull fatigue ($\lambda = 0$ and ∞ respectively). Similar results are reported by Parsons (4) who tested $\lambda = 0$ and $\lambda = \infty$ conditions on a cruciform specimen (5).

Variation in crack growth orientation for different λ states is shown in Fig. 2. The material rolling direction is the same as the specimen axis, i.e. $\theta = 0$. It should be noted that at small values of λ cracks tended to propagate from honing marks in the specimen bore. At high λ values an outside surface network of orthogonal cracks were frequently observed.

Discussion

To understand the processes controlling fatigue fracture in a multi-axial strain field, contours of equal life are constructed on a plot of maximum plastic shear strain $\Delta\gamma_p$ against the tensile strain range $\Delta\epsilon_n$ normal to the maximum shear strain plane; see Fig.3. Should fatigue life be shear strain controlled only, the life contours would be vertical lines. If tensile strain were the controlling parameter then the contours would be horizontal.

In general terms fatigue life can be seen to be a function of shear strain which is in agreement with the Tomkins model (6). Since plastic deformation, the precursor to fracture, is a consequence of dislocation movement along slip planes due to the application of shear forces, this result is understandable. At low plastic shear stresses the small normal tensile strains will have little effect on dislocation movement, or consequently life, in the range $\lambda > 2$. However at values $\lambda < 2$ the increased normal tensile strain does have an effect that increases with increasing $\Delta\epsilon_n$. At higher values of $\Delta\gamma_p$, and consequently lower endurance, all values of $\Delta\epsilon_n$ have an effect, as may be expected since dislocation cross-slip will be facilitated, thus permitting more decohesion at the crack tip.

At all values of $\lambda > 2$ the orientation of the crack plane is identical with the weakest plane of maximum shear strain, e.g. for $\lambda = \infty$ cracks grow along the rolling direction since this is the weakest plane in this anisotropic material. Thus in this regime crack growth is of the Stage I mode. Fig 2 shows that for $\lambda < 2$ the crack orientation changes rapidly and for $\lambda = 0$, the push-pull case, crack growth is by the Stage II mode. It is this change in mode of growth plus the anisotropy of the material that results in the limited but noticeable increase in crack propagation rates at decreasing shear strain values, (but constant $\Delta\epsilon_n$ values) in the very high strain fatigue regime. It should be noted that in Stage II crack growth the shear strain ears at the crack-tip (6) will be along planes that have identical mechanical properties and that crack growth is still a shear strain controlled process.

Finally in Stage I crack growth there is a restraining influence on crack propagation by the less-highly strained zone of the core material (7), whilst in Stage II the crack grows through a uniform through-thickness strain state. In the light of these findings results from past multi-axial strain fatigue programmes are now being reviewed (8) and further tests are being conducted at high temperatures.

Conclusions

1. Fatigue crack growth rate may be increased due to a tensile strain normal to the plane of maximum shear strain.

2. At low normal tensile strains the crack orientation follows a plane of maximum shear strain and is a function of the anisotropy of the material.

3. Stage II crack growth replaces Stage I crack growth when the tensile strain normal to the maximum shear strain plane exceeds a value that is a function of the shear strain range.

4. Deformation behaviour of materials subjected to multiaxial strain conditions may be described by a shear stress-strain relationship.

5. Fatigue crack growth is basically governed by shear-strain processes.

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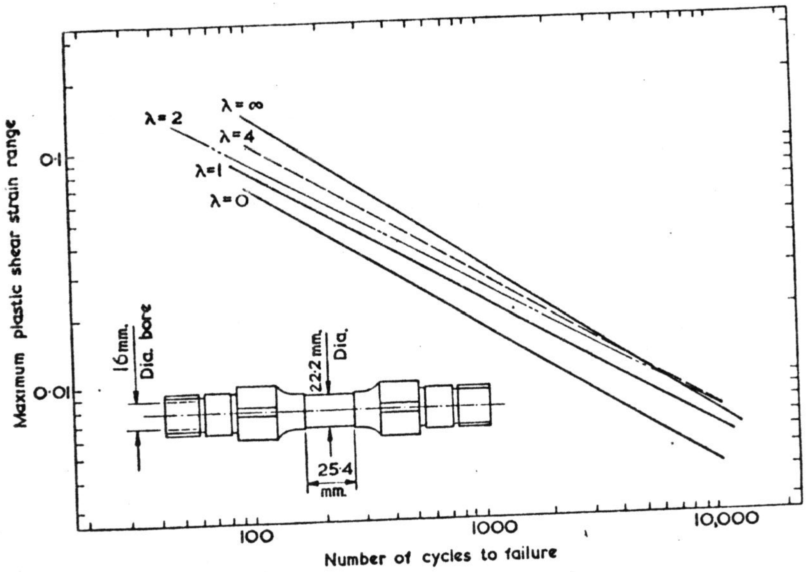

Fig.1 Multiaxial fatigue data and specimen geometry

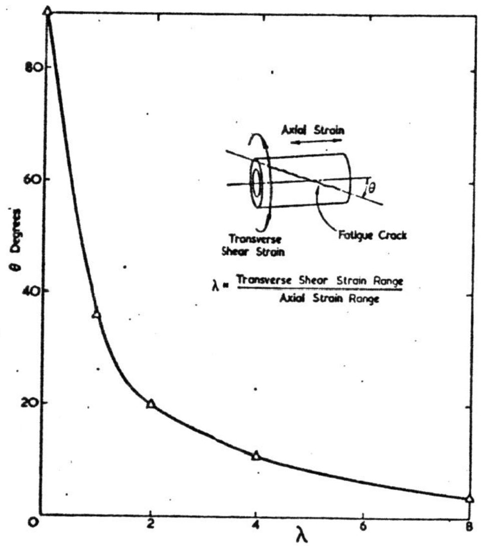

Fig.2 Effect of strain state on crack orientation

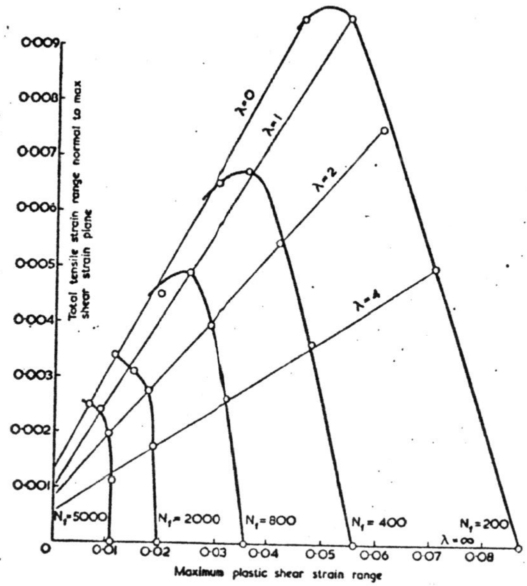

Fig.3 Fatigue life contours for various strain states.