A COMPARISON OF OVERLOAD AND MAXIMUM CYCLIC LOAD REDUCTION BEHAVIOUR

H. Taylor*, I.M. Kilpatrick** and G Jolley***

Maximum load reduction and overload behaviour in high strength steel (Q1(N)) have been studied. The resulting delays introduced in the fatigue crack growth rate are evaluated and related to the maximum stress-intensity. The differences found between the two regimes are attributed to crack closure effects.

INTRODUCTION

When steady state conditions are applied to a propagating fatigue crack the resulting crack growth rate can be determined and predicted with reasonable accuracy. Under the majority of conditions, however the load amplitude may change unpredictably causing changes in crack growth rate. Simplified load conditions allow such transient loading effects to be investigated and the results interpreted and applied to more complex behaviour.

The transient effects due to maximum load reductions (step-down) and those due to overloads are known to produce delays in the progress of the fatigue crack, but previous work has generally been restricted to one area. The delays introduced by either method must be measured if any sort of valid comparison is to be made, to accomplish this the delay must first be defined.

* National Nuclear Corporation, Risley, U.K.
** Admiralty Research Establishment, Rosyth, U.K.
*** Salford University, U.K.

THEORY

The evaluation of delay has been discussed by various investigators in terms of crack length and number of cycles. Obianyor (1) defined the delay in terms of the number of elapsed cycles over a fixed increment of crack growth from the point where the change in stress occurred. Others have defined the delay in terms of a resumption in what may be considered as the normal crack growth rate (2), giving delay as an affected crack length or number of cycles to the resumption of the baseline crack rate prior to the application of the overload. This concept is especially useful when conditions of constant stress-intensity are applied to the specimen through the use of empirical formulae, though not through maintenance of the crack growth rate. This method may also be employed when the effect of an overload is considered, as the delay can again be determined in terms of both elapsed cycles and affected crack growth increment. For conditions of constant load the point at which the behaviour returns to normal is more difficult to determine, as the nominal stress-intensity will increase with increasing crack length and in consequence so will the crack growth rate. When the load is reduced and retardation occurs an initial reduction is seen in the crack growth rate. The rate will subsequently increase until the conditions of normally increasing growth rate occur, associated with the unretarded behaviour. The typical behaviour is shown in figure 1, along with that for constant stress intensity after Druce et al (3) (figure 2). For constant stress intensity, a deviation in the nominally straight line behaviour produces a value for a*, the affected crack growth increment. By reference to the original curves of 'a' versus N, the value of N* can be found, (the number of elapsed delay cycles).

The extent of the retarded crack growth behaviour can be defined as being from the point of reduction in the block load to the return to a steadily increasing rate of change of crack growth. This has been shown (4) to be equal to the point where the stress-intensity equals that just prior to the reduction in cyclic load.

RESULTS

The data from fatigue tests conducted during the investigation (5) was available in the form of crack length versus number of cycles. The resulting plots of 'a' versus N are shown in figure 3, and clearly show that for lower block step-down ratios, significant delays are introduced.

Factors Affecting Delay

a. Stress Intensity Ratio

The use of the ratio of the maximum stress intensity factors to correlate the delay periods in terms of N* has been found by some workers (3,6) to be the main parameter controlling the delay. Variations in mean stress intensity amplitude have been shown to have no discernible effects on the extent of delay. Significant amounts of crack closure could account for this type of behaviour, as changes in maximum stress intensity would have a direct influence on the range of the effective stress intensity factor.

It can be shown (4) that as the step-down ratio is reduced, a threshold level is reached below which crack arrest occurs, as this lower level is approached the amount of scatter increases. Suresh (7,8,9) studied crack growth behaviour at near threshold stress intensities and concluded that in the presence of crack closure caused by plasticity, surface morphology or oxide formation can cause significant enhancements to the closure mechanism. This type of behaviour could easily explain the scatter found at lower step-down ratios, caused by changes in the relative humidity or crack kinking and branching. McDiarmid (10) also found a similar scatter effect at lower step-down ratios.

The behaviour of N* can be characterised as a function of the step-down ratio K2max/K1max thus for

$$0.56 < (K2max/K1max) < 1$$

$$N^* = 465000 - [(K2max/K1max)\ 502703]$$

having the general form of

$$N^* = NO - [(K2/max/K1max)\ nD]$$

for $(K2max/K1max) < 0.56$ arrest occurs.

b. Plastic Zone Size

Brog et al (11) studied the effect of tensile overloads on the subsequent crack growth behaviour of Inconel 600. They used a load shedding technique to control the value of stress-intensity to obtain a baseline value for crack growth rate. Following the application of a tensile overload the crack was grown until the original baseline crack growth rate was re-established. They found a linear relationship between the overload plastic zone size and the crack length increment at minimum crack growth rate, but the total effected crack length was considerably larger than the overload plastic zone size. Gan and Weertman (12) also found that the effect extended over a range several times larger than the overload plastic zone. Both conducted experiments under plane stress and used relationships for plastic zone size of the form

$$rp = (n/\pi)\ (Kmax/\sigma y)^2$$

based on the expression for stress, σy, along the x axis, $(\theta = 0)$

$$\text{ie. } s = K(2\pi r)^{-1/2}$$

The actual value for n used above were found to be Brog, 0.86 and

Gan, 1.0, though various values for n can be found the range 0.5 $< n < 1.24$ (13,14). In view of the relative uncertainty of the value for n, a crack was subjected to a 25KN tensile overload and the resulting surface was examined using a talysurf. The surface was initially prepared by lapping to obtain relative flatness to within 1 x 10-4mm/mm. The representation of the surface is shown in figure 4, the ordinances represent increments of 1.25 x 10-4mm. Superimposed on the surface representation is the value of rp for n = 0.5, indicating that the actual value of n is nearer 0.9, as found by Brog.

The previous discussion only applies to conditions of plane stress however, while the specimens examined revealed that plane strain conditions had prevailed. Irwin also proposed a plane strain correction to the estimate for rp such that n = .167 (15). The value assumed here is n = 0.1 for plane stress and this is also shown on the diagram.

As the plastic zone size is proportional to $Kmax^2$, it can be ignored in any direct relationship to the number of delay cycles eg. rp1/rp2. Though it might be considered that the difference in plastic zone sizes could be related to the affected crack length, the calculated values for rp differ from the retardation distances found by a factor of at least 10^{-3}. The foregoing discussion relates only to the monotonic plastic zone generated during increased loading. The reversed or cyclic plastic zone is formed during unloading and is theoretically one quarter the size of the monotonic plastic zone. Clearly if the cyclic plastic zone was used the difference encountered would be even greater.

Block Load Retardation Behaviour

The delay introduced due to a reduction in the cyclic stress intensity can be considered in terms of either an affected crack growth increment or the number of delay cycles.

a. Affected Crack Length

The previous comparison between the affected crack lengths and the plastic zone size shows a considerable discrepancy. All previous attempts in the literature to relate the two have concluded similarly, and clearly some other hypothesis must be responsible.

Considering crack tip closure to relate to the stress intensity at the point just prior to the reduction in cyclic stress intensity. The crack growth rate may now be affected until the closure previously determined is removed. Subsequent crack growth would then continue unaffected.

This condition might be expected to occur when the plastic deformations are of the same order as the maximum of those previously encountered (4). At this point the plastic zone formed at the crack tip would hold apart the previously closed crack faces. As the plastic zone size is directly related to K then the retarded behaviour would extend to the point where the maximum stress intensity value just equals that just prior to the reduction in block load.

Under conditions of normally increasing stress intensity each cycle would cause plastic deformations larger than those from previous cycles. This would alleviate any residual level of closure and would effectively limit closure to the cyclic crack tip.

Figure 5 shows a*, as determined by the method previously outlined, versus the crack length when K2max = K1max and shows a good correspondence between the two parameters.

b. Delay Cycles

The extent of the delay caused due to a reduction in block load is significant. The results indicates a considerable drop in crack growth rate immediately following the load reduction. This condition persists over a finite crack length in proportion to the reduction ratio.

<u>Overload Retardation Behaviour</u>

A similar retardation effect was experienced when a crack was subjected to a tensile overload, though the number of delay cycles were not as significant as those from a step-down test with similar ratios. The relative positions on the curve of 'a' versus N in figure 6 show the significantly reduced delay cycles resulting from the overload compared with that due to a block step-down of a similar ratio. The affected crack length (a*) however, is of a similar order to that for a block step reduction.

	Affected crack*		Delay cycles N*	
Load Ratio	0.65	0.5(.58)	0.65	0.5(.58)
Block Step	1.59mm	(4.14mm)	138800	(652200)
Overload	1.54mm	3.37mm	31500	236300

Table 1: Comparison of retardation for block and overloads

The 0.5 load ratio is not relevant to the block step behaviour, as crack arrest occurs at this level.

The significant variation in delay cycles due to step-down block loads and those due to tensile overloads are of the order of 4 to 1 respectively, again indicating some mechanism other than closure related to plastic zone size ratios is involved.

CONCLUSIONS

The ratio of the maximum stress-intensities is directly related to the extent of retardation found in both steady state load reductions and post overload behaviour.

In Q1(N) delay will be found for a steady state step-down ratio in the range 1 to 0.56. Below ratios of 0.56 crack arrest occurs.

Evaluation of the plastic zones formed suggest that the extent of the retardation is in no way related to either the sizes or changes in size of the plastic zones.

A crack closure model for the post transient behaviour would accommodate both steady state load reductions and overload behaviour.

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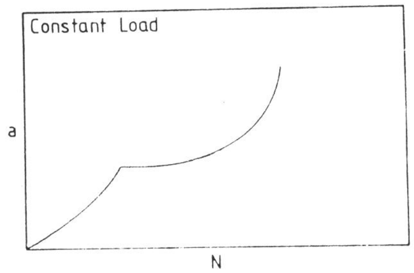

Fig.1: Constant load crack growth behaviour with overload.

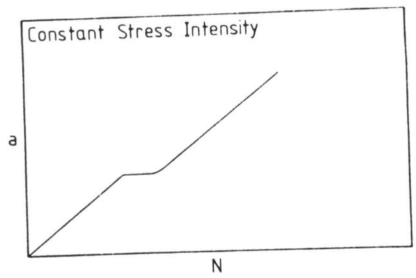

Fig.2: Constant stress intensity behaviour with overload

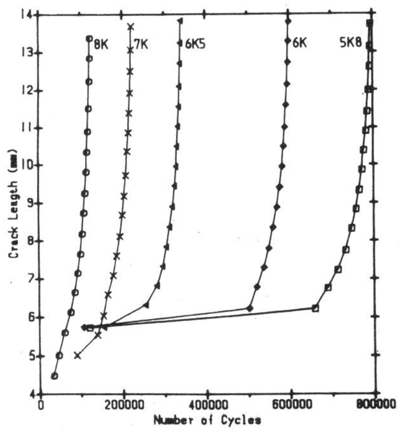

Fig.3: A versus N for various step down ratios

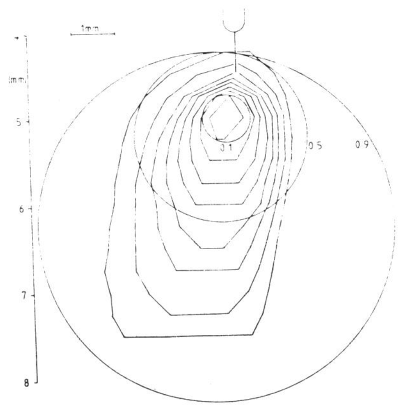

Fig.4: Surface contour of overloaded specimen.

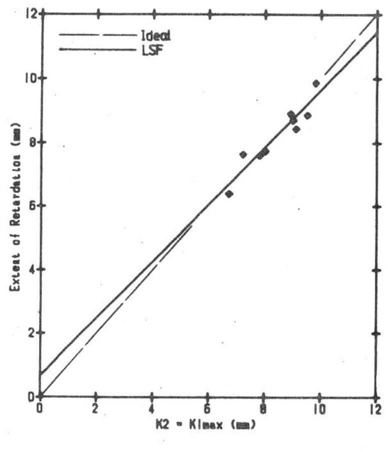

Fig.5: Correlation between a* and point were K2 = K1

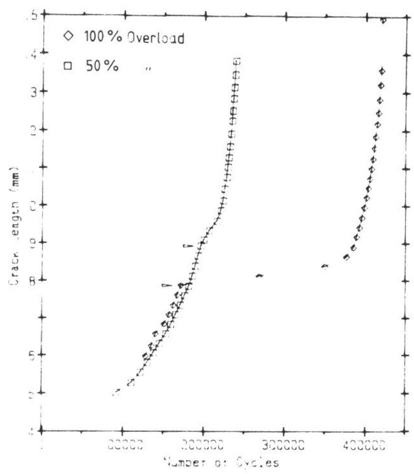

Fig.6: A versus N for various overloads