The effects of loading variables on overload induced fatigue crack growth retardation parameters

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A growing fatigue crack is known to be retarded on application of an overload cycle. The retardation may be characterized by the total number of cycles involved during retardation, N_D and the retarded crack length, a_D. The loading variables play an important role to influence the retardation behaviour and thereby the retardation parameters N_D and a_D. The important loading variables are considered to be the stress intensity range, ΔK during constant amplitude loading, stress ratio, R and the ratio of the overload stress to the maximum stress in constant amplitude loading, OLR etc. The objective of the present investigation is to study the effect of different loading variables on the retardation parameters. The investigation has been conducted in a 2024-T3 Al-alloy with centre crack tension panels loaded using an Electromagnetic Resonance Machine. The crack extension and crack closure have been measured during cyclic loading under constant amplitude and under overloading situations. The results do indicate dependence of crack opening stress intensity factor, K_{OP} on loading variables such as ΔK, R and OLR. The delay cycle N_D is found to increase with loading variables ΔK, OLR and R. The functional dependence of retardation zone a_D on loading variables has also been identified.

Nomenclature

a	Crack length
Δa	Crack extension
a_D	Retarded crack length
N	Number of fatigue cycles
N_D	Number of delay cycles due to overload
K_{max}	Maximum stress intensity factor
K_{min}	Minimum stress intensity factor
ΔK	$K_{max} - K_{min}$ stress intensity range
K^{OL}	K corresponding to overload
K_{OP}	Crack opening stress intensity factor
K_{OP}^{OL}	Crack opening stress intensity factor after overload application
ΔK^{OL}	$(K^{OL} - K_{min})$ range of K for overloading cycle
R	Stress ratio (min to max stress in constant amplitude loading)
OLR	Overloading ratio (ratio of overload stress to max. stress in a constant amplitude loading cycle)
B	Thickness
U^{OL}	$(K^{OL} - K_{OP})/\Delta K$, dimensionless effective stress intensity range in overload condition
r_c^{OL}	Overload induced cyclic plastic zone radius

1. Introduction

Many engineering components and structures experience occasional overloads during service. Such overloads lead to retardation of a growing fatigue crack which may even culminate into crack arrest. Further, in fatigue critical structures, fatigue crack propagation under service conditions generally involves random or variable amplitude, rather than constant amplitude loading, such that the loading history i.e. interaction between loading cycles, can be a major factor determining the fatigue life. Single overload cycle is the primitive building block of the variable amplitude loading and represents the simplest situation involving retardation. Thus, the response of the material to single overload cycle should be understood for more versatile modeling of random load fatigue. The effect of overload has been experimentally observed by application of single overload cycle over a constant amplitude fatigue test [1, 2]. The overloading effect has been schematically represented in Fig. 1 in the form of crack length, a vs. number of cycle, N plot. The overload introduces a large plastic zone and hence residual compressive stresses in the vicinity of crack tip [3, 4]. The residual compressive stresses result in closure over a length longer than that during

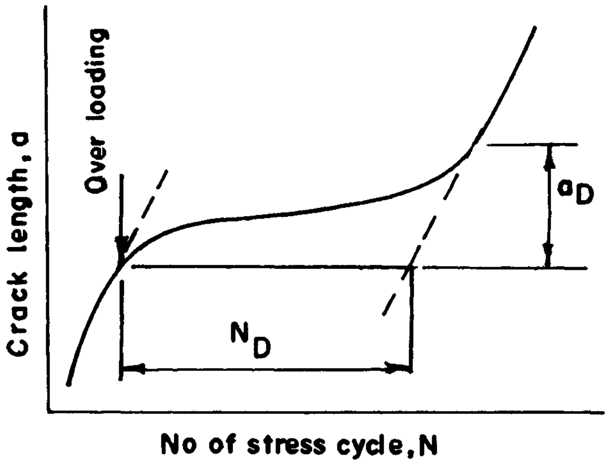

Figure 1 Schematic representation of the response of fatigue crack growth on overload application.

the constant amplitude condition [3, 5]. As a result a fatigue cycling can cause a growth only if the enhanced residual stresses are overcome to a degree that the crack tip is open again. This explains the low growth rate of the crack on tensile overload application. The effect of loading condition on crack closure and its role on the post overload retardation behaviour has been studied by several investigators [2, 5, 6]. However, except a few cases [2, 6], no quantitative correlation has been reported in literature connecting overload induced closure parameter with various loading variables (i.e. ΔK, K^{OL}, OLR etc).

The extent of retardation is usually expressed in terms of retarded crack length, a_D (see Fig. 1). It is observed by a few investigators that the overload affected crack length, a_D is commonly associated with the monotonic plastic zone at the crack tip [7, 8]. However, no systematic study has been reported correlating this retardation parameter with the applied loading variables.

The delay cycle, N_D as represented in Fig. 1 is the number of load cycles required to achieve the pre-overload crack growth rate. The N_D is considered to be an important parameter to characterize the crack growth retardation on overload application. Therefore an attempt has also been made to study the effect of basic stress intensity factor range, ΔK and OLR on delay cycle, N_D.

2. Experimental programme

The experimental study was conducted on a standard 2024-T3 Aluminium alloy of yield strength 377 MPa. The above material finds wide application in aircraft structures in the condition investigated. The material was available in sheet form of thickness 3.38 mm. The centre cracked tension (CCT) geometry with dimension of 220.00 × 85.00 × 3.18 mm were used for the fatigue tests. The fatigue tests were carried out in tension-tension mode under constant stress amplitude sinusoidal loading at stress ratios 0.17, 0.30 and 0.44 and at a frequency of 97 Hz, using an Electromagnetic Resonance Machine. The crack growth measurement was done using Electrical Potential Difference Technique. To measure the opening/closing load miniature clip gauge of 4.0 mm gauge length was mounted at a distance of 1 mm behind the crack tip and loading frequency for the purpose was maintained at 0.05 Hz. The specimens were subjected to overloading cycle at appropriate crack lengths. The level of overloading ratio, OLR ($= K_{overload}/K_{max}$) applied to the specimens were 1.5, 1.7, 1.9 and 2.1. The crack opening and closing loads were measured at various crack lengths for both the constant amplitude and overload conditions of specimens.

3. Results and discussion

The effect of introducing an overload spike over a constant amplitude cyclic loading are presented in the form of crack extension Δa vs. N plot in Fig. 2. It is observed that the application of an overload cycle results in crack growth retardation and the magnitude of retardation increases with increasing overloading ratio, OLR.

3.1. Effect of ΔK on crack closure

The variation of overload induced crack closure stress intensity factor (SIF), K_{OP}^{OL}, a retardation parameter with applied stress intensity range, ΔK has been presented in Fig. 3 on semi-log scale. The plot shows that K_{OP}^{OL} increases with increase in ΔK and OLR level for the investigated range of ΔK (7–13 MPa $\sqrt{m}$). Superimposed on the diagram are the K_{OP} values obtained under constant amplitude loading condition. Linear relationship may be noticed between K_{OP}^{OL} and ΔK at constant values of OLR and R which conform to the following equations,

$$\log K_{OP}^{OL} = (6.3\,\Delta K + 26.8)10^{-2} \quad R = 0.17 \text{ and OLR} = 1.9 \tag{1}$$

$$\log K_{OP}^{OL} = (10.3\,\Delta K - 24.0)10^{-2} \quad R = 0.17 \text{ and OLR} = 1.0 \tag{2}$$

(constant amplitude loading condition)

$$\log K_{OP}^{OL} = (5.9\,\Delta K + 37.5)10^{-2} \quad R = 0.30 \quad \text{and} \quad \text{OLR} = 1.9 \tag{3}$$

A comparison of Equation 1 with 2 does reveal that the ΔK dependence of K_{OP}^{OL} diminishes with application of

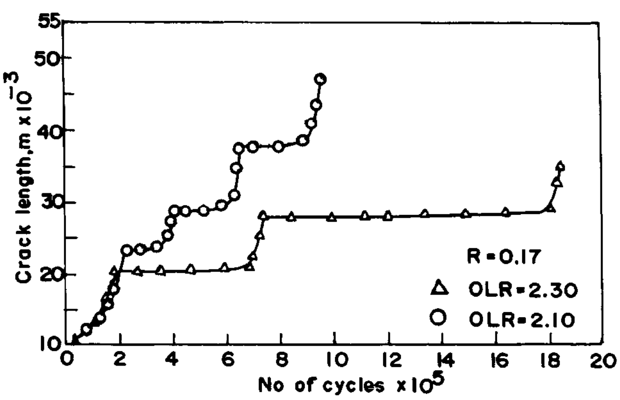

Figure 2 Typical overload cycle modified crack extension vs. no. of stress cycles.

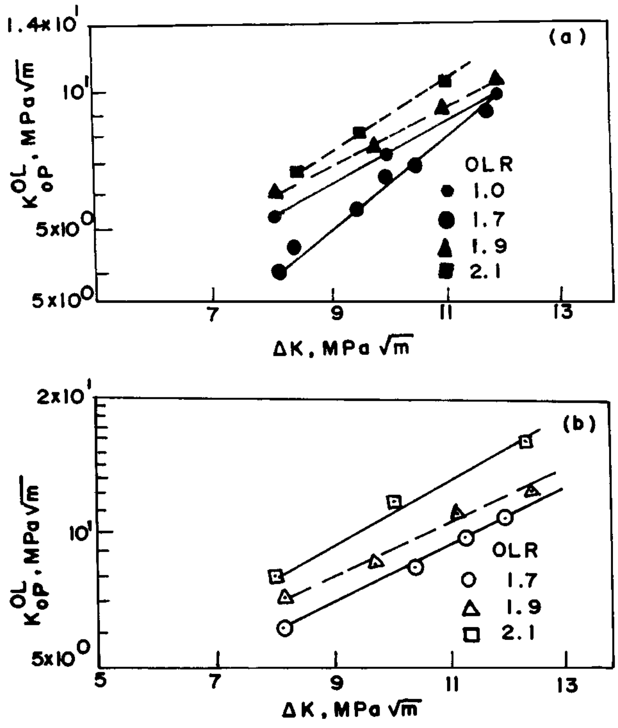

Figure 3 Variation of $K_{\text{OP}}^{\text{OL}}$ as a function of applied stress intensity range, ΔK and OLR at stress ratio, (a) $R = 0.17$ and (b) $R = 0.30$.

overload, as compared to the constant amplitude loading situation. However, the intercept level in the above equations is highest for the case of overloading indicating that the higher value of $K_{\text{OP}}^{\text{OL}}$ (as compared to K_{OP}, under constant amplitude loading condition) at a given ΔK is mainly attributed to this intercept effect. The higher 'intercept effect' is apparently caused due to higher K^{OL} level in the overloading cycle. The effect of increasing R also leads to a decreasing dependence on ΔK and an enhanced intercept effect.

3.2. $K_{\text{OP}}^{\text{OL}}$ as a function of K^{OL}

An increase in R or ΔK at a given overloading ratio causes an enhancement in K^{OL} level. Similarly with increasing OLR, the K^{OL} increases. Therefore, it appears that the rising trend of $K_{\text{OP}}^{\text{OL}}$ with OLR, ΔK or R could be a result of increase in K^{OL} and corresponding intensification of residual compressive stresses in the plastic zone [9]. Therefore an attempt is made to correlate $K_{\text{OP}}^{\text{OL}}$ with K^{OL} in Fig. 4. It is interesting to note that a unique relationship is obtained between $K_{\text{OP}}^{\text{OL}}$ and K^{OL} irrespective of R, OLR and ΔK level in the range of their values investigated. The $K_{\text{OP}}^{\text{OL}}$ vs. K^{OL} relation may be expressed by following equation,

$$\log K_{\text{OP}}^{\text{OL}} = (3.2\,K^{\text{OL}} + 15.4)10^{-2} \tag{4}$$

Above observation indicates K^{OL} as a prime variable to control overload induced crack closure level.

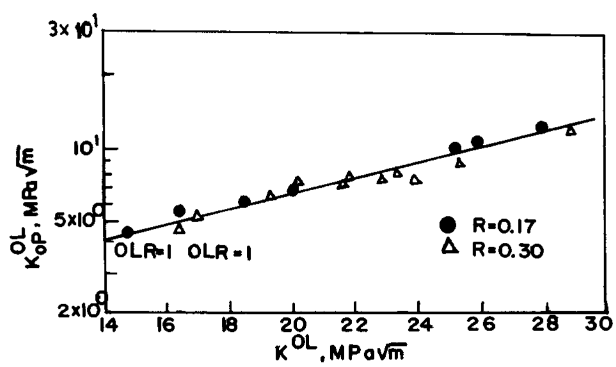

Figure 4 Effect of overloading stress intensity factor on overload induced crack closure parameter, $K_{\text{OP}}^{\text{OL}}$.

3.3. $U_{\text{min}}^{\text{OL}}$ as a function of ΔK and R

The crack closure due to overloading cycle modifies the effective stress intensity range available for crack growth. The dimensionless effective stress intensity range is given in terms of U^{OL} which is defined as,

$$U^{\text{OL}} = \left(K_{\max} - K_{\text{OP}}^{\text{OL}}\right)/(K_{\max} - K_{\min}) \tag{5}$$

In the present work, U^{OL} is obtained corresponding to maximum $K_{\text{OP}}^{\text{OL}}$ and denoted as $U_{\text{min}}^{\text{OL}}$. The behaviour of $U_{\text{min}}^{\text{OL}}$ with ΔK is shown in Fig. 5 at two different values of R. A decreasing nature of $U_{\text{min}}^{\text{OL}}$ is noticed with increasing ΔK. Whereas $U_{\text{min}}^{\text{OL}}$ is found to increase with R at a given ΔK in this alloy, a decrease in $U_{\text{min}}^{\text{OL}}$ with increasing ΔK is expected as $K_{\text{OP}}^{\text{OL}}$ increases with ΔK contributing to a reduction in $U_{\text{min}}^{\text{OL}}$ value. An increase in $U_{\text{min}}^{\text{OL}}$ with R (at a fixed ΔK) is related to a dominating role of $K_{\max}$ over the K_{OP}. Though, the latter (i.e. K_{OP}) increases with R, the $K_{\max}$ also increases and the overall effect is an increase in term ($K_{\max} - K_{\text{OP}}$).

3.4. Dependence of a_{D} on ΔK and OLR

The variation of a_{D} with ΔK is shown in Fig. 6. At a constant R and OLR level, a_{D} is generally found to increase with ΔK. It may be noted that in the above diagram a_{D} is simultaneously under the influence of ΔK as well as K^{OL} as the latter also increases with ΔK. Therefore the intrinsic effect of ΔK on a_{D} is not realized from this diagram. Increase in a_{D} with basic stress intensity range has also been reported by the other investigators [8].

The effect of OLR on a_{D} is presented in Fig. 7. The a_{D} values are found to increase with OLR in the beginning and beyond a certain level of OLR, a_{D} tends to decrease. As R and ΔK are fixed for a given line,

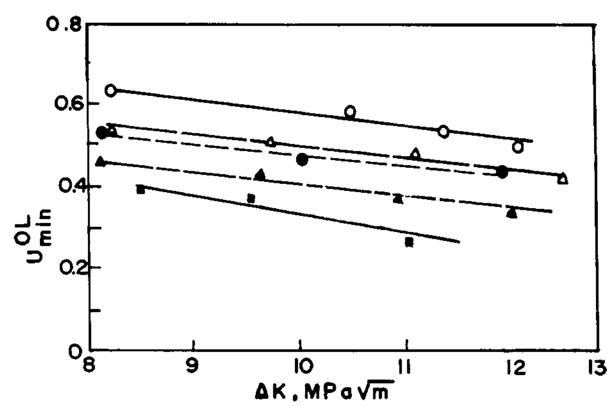

Figure 5 The crack closure parameter, $U_{\text{min}}^{\text{OL}}$ as a function of ΔK.

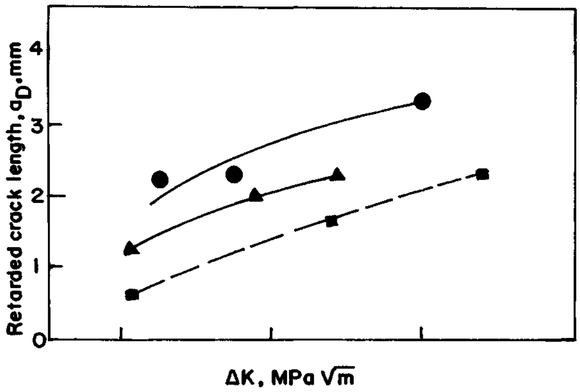

Figure 6 Variation of retarded crack length, a_D with ΔK at stress ratio, $R = 0.30$.

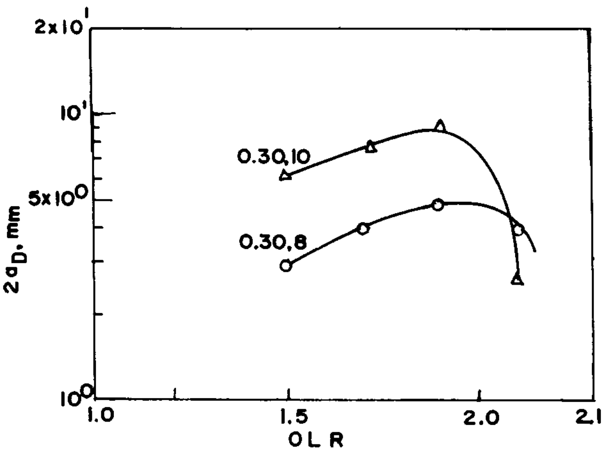

Figure 7 Effect of OLR on retarded crack length, a_D at stress ratio, $R = 0.30$.

increasing OLR has the effect of causing an enhancement in K^{OL} value. Thus, it is the K^{OL} which results in an increase or decrease of a_D while OLR is being raised. Analysis of data relating a_D and K^{OL} reveal that the drop/saturation in a_D value takes place at the level of $B/B_{p.strain} = 1.85$ where B is the specimen thickness and $B_{p.strain}$ is the plane strain thickness requirement for the cyclic plastic zone corresponding to ΔK^{OL}. Some data from literature [1, 10] on an Al alloy and steel have been analyzed and presented in Fig. 8 to ascertain the

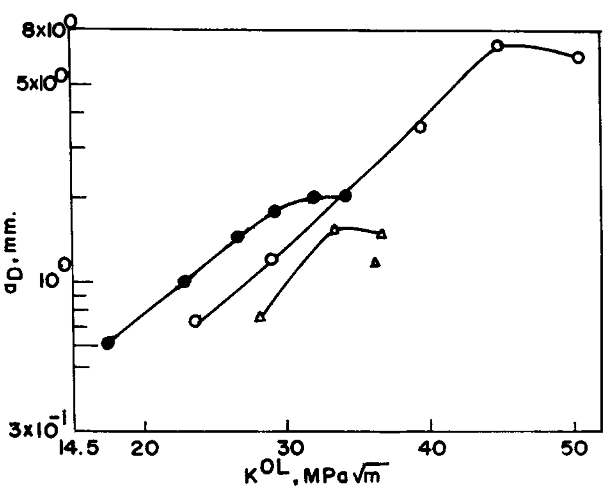

Figure 8 Effect of OLR on retarded crack length, a_D based on data from literature [1, 10].

dependence of a_D on OLR or K^{OL}. It is interesting to note that the transition in a_D vs. K^{OL} plots appeared at the level of $B/B_{p.strain}$ ratio of 1.85 in E-36 Steel, at 1.92 in Al-alloy (CT geometry) and 2.00 in Al-alloy (with CCT geometry). A value of 1.62 has been noted from the work of Mingda *et al.* [11] for aluminium alloy at the transition point. The residual compressive stress field remains confined in the cyclic plastic zone $2r_c^{OL}$ produced by ΔK^{OL}. Therefore it is likely that beyond a critical value of cyclic plastic zone a decreasing condition of crak-tip constraint sets-up. The above factor will affect retardation zone size, a_D leading to a decrease in a_D beyond a specific level of $B/B_{p.strain}$. It may be concluded from this analysis that the size of cyclic plastic zone as is produced by ΔK^{OL} i.e. r_c^{OL} vis a vis specimen stress state controls the behaviour of a_D significantly.

3.5. Variation of delay cycle with loading variables

The variation of N_D as function of ΔK is shown in Fig. 9. An increase in N_D is noted with ΔK at a fixed OLR. The effect of R on N_D may also be observed in this figure. It may further be noticed that at given OLR, a higher R (i.e. $R = 0.44$) exhibits enhanced value of N_D as compared to lower R (i.e. $R = 0.17$ and 0.30) level.

The increase in N_D with ΔK is supposed to be due to an increasing ratio of plane stress surface region to specimen thickness [12]. This observation is also in agreement with the effect of ΔK on K_{OP}^{OL} and retarded crack length.

The effect of overloading ratio on delay cycles, N_D is shown in Fig. 10. The N_D appears to be a sensitive function of OLR and increases significantly with OLR at a constant ΔK and R level in the range of OLR investigated. The relationship may be represented as follows,

$$\log N_D = 2.12\,(\text{OLR}) + 0.784 \qquad (6)$$
$$(\text{Al-alloy}, R = 0.17, \Delta K = 8.2\,\text{MPa}\sqrt{\text{m}})$$

The increasing OLR would increase the level of overload induced closure, K_{OP}^{OL} which in turn will result in an increase in N_D value. Almost similar observation has been reported by some other investigators [2, 11].

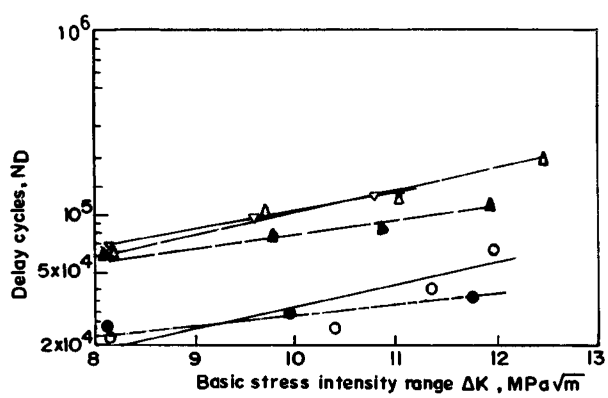

Figure 9 The variation of delay cycle N_D as a function of ΔK.

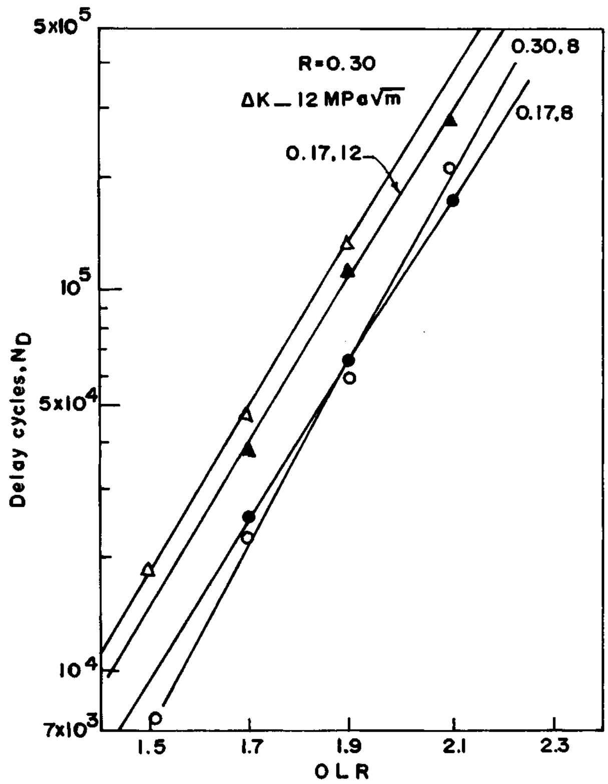

Figure 10 Effect of OLR on delay cycle, N_D.

From Fig. 10 the effects of ΔK and R may also be noticed at a given OLR level. At a given value of OLR, as ΔK increases N_D is found to increase. An increasing ΔK results in an increase in K^{OL} which may ultimately give rise to an enhancement in delay cycle, N_D analogous to increase in a_D.

4. Conclusions

The conclusions based on the present investigation are reported as follows:

1. The overload induced crack closure increases with applied ΔK and OLR. However ΔK dependence of K_{OP}^{OL} diminishes with increase in R as well as with level of overloading cycle.

2. The K_{OP}^{OL} varies linearly with applied overload level as follows,

$$\log K_{OP}^{OL} = (3.2\, K^{OL} + 15.4)10^{-2}$$

3. The crack closure level is mainly governed by the maximum SIF of the stress cycle.

4. Retarded crack length, a_D increases with K^{OL} till the thickness ratio $B/B_{p.strain}$ (corresponding to ΔK^{OL}) reaches nearly a value of 1.9, indicating the stress state with respect to cyclic plastic zone r_c^{OL} as the primary factor controlling the behaviour of a_D.

5. Delay cycle, N_D increases linearly on semi-log scale with loading variables ΔK, OLR and stress ratio R.

References

1. O. VARDAR, *Eng. Fract. Mech.* **30** (1988) 329.
2. R. KUMAR and S. B. L. GARG, *ibid.* **32** (1989) 833.
3. B. B. VERMA, "Effect of Overloading Cycle on Fatigue Crack Closure and Crack Growth Kinetics in Aluminium Alloy and Steel," PhD thesis, IIT New Delhi, India, 1993.
4. M. L. BUSCH and J. L. LEBRUN, "X-ray Diffraction Study of Stress Distributions Following a Single Tensile Overload Fatigue Crack Growth Under Variable Amplitude Loading" (Elsevier, 1988) p. 76.
5. R. KUMAR, *Eng. Fract. Mech.* **42** (1992) 151.
6. O. E. WHEELER, *J. Basic Eng., Trans. ASME* **D94**(1) (1972) 181.
7. R. K. PANDEY and B. B. VERMA, "Overload Induced Fatigue Crack Growth and Significance of Retardation Zone, advances in Fracture Research," Vol. 3 (ICF-9, Sydney, 1977) p. 1285.
8. N. RANGANATHAN, J. PETIT and J. DE FOUQUET, On the Influence of the Initial K Level on the Post Overload Crack Propagation Behaviour, Advances in Fracture Research, Conf. Proc. ICF-6 (1984) Vol. 3, p. 1767.
9. J. A. BANNANTINE, J. J. COMER and J. L. HANDROCK, "Fundamental of Metal Fatigue Analysis" (Prentice Hall, 1990).
10. C. ROBIN, M. LOUAH and G. PLUVINAGE, Fatigue of Eng. Mater. and Struct. **6** (1983) 1.
11. G. MINGDA, Z. YONGKUI and Y. MINGGAO, *ibid.* **5** (1982) 167.
12. G. H. BRAY, A. P. REYNOLDS and E. A. STARKE, Jr., *Met. Trans.* **23A** (1992) 3055.

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