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ΔK_{ol} level effects on fatigue crack propagation

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In order to determine the effects of ΔK_{ol} level on fatigue life, a single peak load was applied at distinct ΔK levels of 7.8×10.3 and 9.8×10^3 p.s.i. in$^{1/2}$. Here the ΔK_{ol} level was defined to be a ΔK level at which overload was applied. Three different overload ratios of 1.5, 2.0, and 2.5 were used to determine the overload ratio effect on the recovery factor. The result showed that the recovery factor, Z, was linearly related to ΔK as $Z = q\Delta K + Z_0$, where q was a function of overload ratio. The value of q decreased as the overload ratio increased in a given ΔK_{ol} level and seemed to be an important factor as well as retardation cycles in determining the fatigue life. For the same overload ratio, specimens that underwent overload at a smaller ΔK_{ol} level showed more improved fatigue life.

Nomenclature

a	Crack length
a^*	Overload affected zone size
B	Specimen thickness
$(da/dN)_{ca}$	Crack growth rate due to constant amplitude fatigue load
$(da/dN)_{ol}$	Crack growth rate after overload is applied
E	Young's modulus
K	Stress intensity factor
K_{min}	Minimum stress intensity factor
K_{max}	Maximum stress intensity factor
ΔK_{ol}	ΔK level at which overload is applied
N	Number of cycles
N_D	Number of delayed cycles
N_f	Number of cycles needed for a specimen to be completely fractured
r_p	Assumed plastic zone size
S	Load
σ_{ys}	Yield stress
W	Width
Z	Recovery factor

1. Introduction

Until it meets with catastrophic failure, a given structure is usually subject to both cyclic stresses and an aggressive environment. The cyclic stresses are variable in amplitude and generally random. It is important to predict the lifetime of a given structure in order for the structure to be used as an engineering structure. Although the prediction is meaningful when done under real conditions, it is almost impossible to reproduce the same conditions in the laboratory. These problems can only be approached by roughly simulating such loading conditions. Constant amplitude cyclic loading with a single peak loading is one example.

It is well known that the tensile overload decreases the fatigue crack growth rate and there are three prevailing theories to explain the causes of the retardation due to tensile overload. The first one is that retardation occurs due to crack blunting [1]; the second one is that residual compressive stress causes retardation [2, 3], and the third one is that retardation is caused by the crack closure due to plastic deformation [4, 5]. Accordingly, intensive research has been conducted to predict fatigue life when an overload is applied [6–8]. However, no model gives a fully satisfactory agreement between predicted and actual fatigue life.

In this work, fatigue tests with a single peak load were performed primarily for determining the effects of ΔK_{ol} level on fatigue life. Efforts were also made to find the recovery factor which relates a crack growth rate after overload, $(da/dN)_{ol}$, to a constant amplitude fatigue crack growth rate, $(da/dN)_{ca}$. In addition, three different overload ratios of 1.5, 2.0, and 2.5 were used in order to determine the overload ratio effect on the recovery factor.

2. Experimental procedure

Aluminium 2024-T3 was used for test material. Its mechanical properties are shown in Table I.

Single-edge notched (SEN) specimens were machined in the LT direction for fatigue testing. The configuration and dimensions are shown in Fig. 1. Loading was parallel to the longitudinal direction while crack growth was in the traverse direction. A constant amplitude load with single peak load fatigue tests were performed with an Instron machine. Sinusoidal loading wave shape and a loading frequency of 10 Hz were used for all constant amplitude load fatigue testing, except for a single peak load which was applied at a frequency of 0.1 Hz. All experiments were carried out at room temperature and the crack length was measured using a travelling microscope to an accuracy of 0.01 mm. Tests were performed in two groups. In the first test group, overload was applied when the ΔK level reached 7.8×10^3 p.s.i. in$^{1/2}$. In the second test group, overload was applied when the ΔK

TABLE I Mechanical properties

Alloy and heat treatment	Thickness (mm (in))	0.2% YS (MPa (10^3 p.s.i.))	UTS (MPa (10^3 p.s.i.))	Elongation (%)
2024-T3	1.6(0.063)	340(49.4)	415(60.23)	18.6

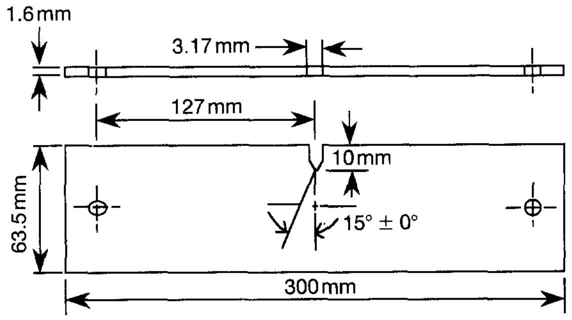

Figure 1 Configuration and dimensions of test sample.

level reached 9.8×10^3 p.s.i. $\text{in}^{1/2}$. A maximum load of 300 kg (666 lb) and an R ratio (minimum fatigue load to maximum fatigue load) of 0.1 were used for every fatigue crack growth test with the exception of application of a single peak load. The overload ratios applied were 1.5, 2.0 and 2.5, where the overload ratio was defined as the peak load to maximum fatigue load. The stress intensity factor of the single-edge notched specimen was calculated from the following equation [9]

$$K = (Sa^{1/2}/BW)[1.99 - 0.4124(a/W) + 18.7(a/W)^2 - 38.48(a/W)^3 + 53.85(a/W)^4] \quad (1)$$

where S is the load, B the thickness, W the width, and a the crack length.

3. Results and discussion

Delayed crack propagation was observed for each overload ratio in both test groups. The number of retardation cycles, N_D, was defined to be the period of zero crack growth [10] and was determined by extrapolating the stable crack growth curve to the zero crack growth line. As shown in Table II the N_D of overload ratio 1.5 is less than 4000 cycles for both groups. This observation is consistent with the tendency that an overload ratio less than 1.5 does not contribute to crack growth retardation severely. For an overload ratio of 2.0, the difference in retardation cycles between the first test group ($\Delta K_{ol} = 7.8 \times 10^3$ p.s.i. $\text{in}^{1/2}$) and the second test group ($\Delta K_{ol} = 9.8 \times 10^3$ p.s.i. $\text{in}^{1/2}$) is not as large as that of the overload ratio of 2.5. This seems to be due to the overload-affected zone size, a^*, where a^* of an overload ratio 2.0 is less than that of an overload ratio 2.5. a^* is defined to be the distance from the point of application of overload to that of resuming stable crack growth and it is equal to twice the assumed plastic zone size, r_p [11]. Therefore, it seems that the number of retardation cycles decreases as r_p decreases. However, considering that r_p is small and the crack growth rate is proportionally small at small ΔK_{ol}, one cannot definitely say that smaller r_p necessarily produces smaller N_D in all ΔK_{ol} ranges within which a crack initiates and fracture occurs.

TABLE II Influence of ΔK_{ol} level on a^*, N_D and N_f

Test group	Overload ratio	a^* (mm)	N_D (cycles)	N_f (cycles)
First	1.5	0.51	3 230	225 580
	2.0	1.03	21 250	377 640
	2.5	1.46	42 550	665 460
Second	1.5	0.63	3 750	185 470
	2.0	1.12	32 720	290 370
	2.5	1.91	71 530	498 800

In order to determine the recovery factor, $Z[(da/dN)_{ol}/(da/dN)_{ca}]$, $(da/dN)_{ol}$ was compared with $(da/dN)_{ca}$ when it resumed stable crack growth after overloading. Fig. 2 shows the fatigue crack growth rate measured under constant amplitude load conditions. The variations in the recovery factor with ΔK for each overload ratio are shown in Figs 3–5. The figures clearly show that a linear relationship exists between Z and ΔK. Therefore, Z can be expressed as

$$Z = q\Delta K + Z_0 \quad (2)$$

where q and Z_0 are constants. The value of q is of interest. As can be seen in Fig. 6, q decreases as the overload ratio increases for each test group. Thus, it can be assumed that q is a function of overload ratio. Because the value of q indicates the rate of recovery of a crack to the original crack growth rate, a large q

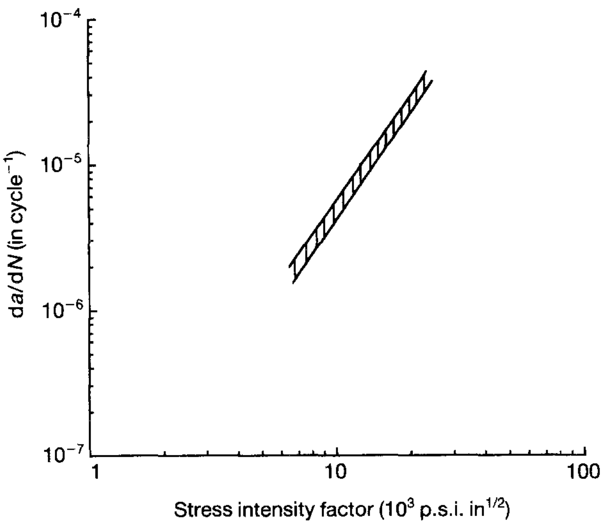

Figure 2 Constant fatigue crack propagation behaviour of aluminium 2024-T3.

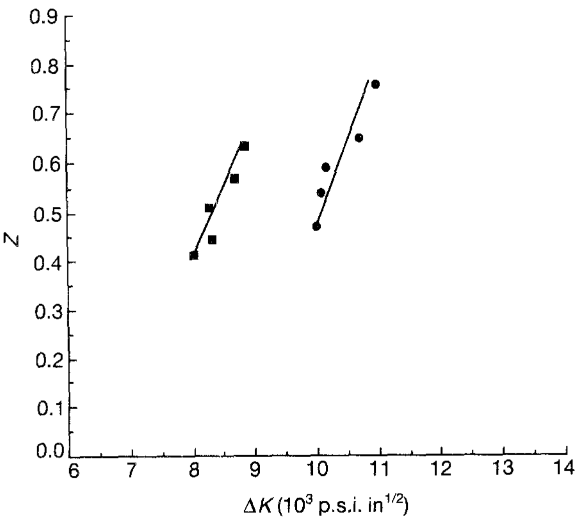

Figure 3 Variation of Z with ΔK for overload ratio 1.5: (■) first group, (●) second group.

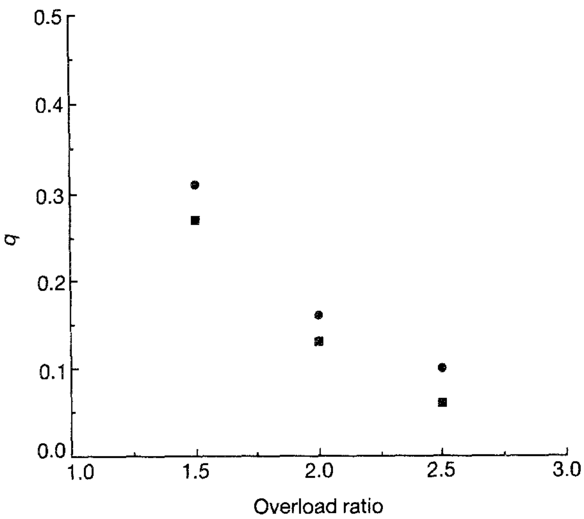

Figure 6 Variation of q value with overload ratio: (■) first group, (●) second group.

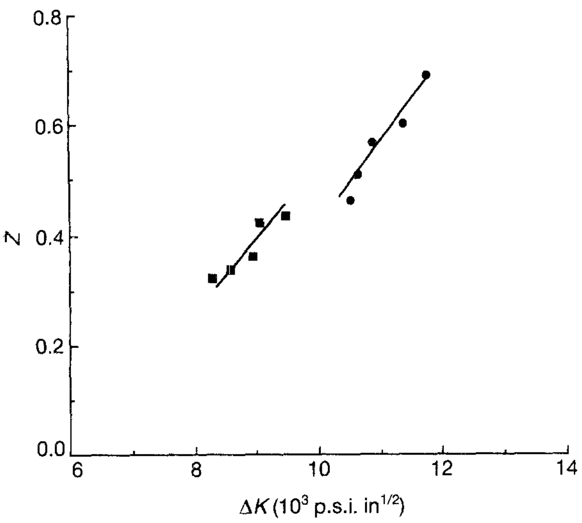

Figure 4 Variation of Z with ΔK for overload ratio 2.0: (■) first group, (●) second group.

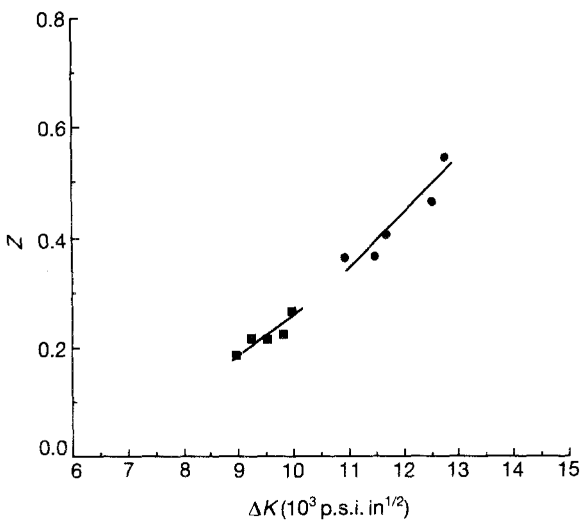

Figure 5 Variation of Z with ΔK for overloaded ratio 2.5: (■) first group, (●) second group.

value means that the crack growth rate after overload recovers quickly to the original crack growth rate. In fact, although N_D of the first group is less than that of the second group for a same overload ratio, the fatigue life of the first group is greater than that of the second. This is because q of first group is smaller than that of the second group. Therefore, crack growth of the first group recovers more slowly than that of the second group to the original crack growth, leading to a greater number of fatigue cycles for the crack to reach the complete fracture. In conclusion, the recovery factor is considered an important factor, as well as retardation cycles, in determining fatigue life. Also, the specimens which underwent overload at a smaller ΔK_{ol} level showed a more improved fatigue life.

4. Conclusions

Fatigue tests with a single peak load were performed to determine ΔK_{ol} level effects on delayed fatigue life and the recovery factor which relates $(da/dN)_{ol}$ to $(da/dN)_{ca}$. Three different overload ratios were used in order to determine the overload ratio effect on the recovery factor, and the following conclusions were obtained.

1. The recovery factor is linearly related to ΔK and can be represented by $Z = q\Delta K + Z_0$, where q is a function of the overload ratio and decreases as the overload ratio increases.

2. Specimens which had undergone overload at a smaller ΔK_{ol} level showed more improved fatigue lives, and the recovery factor should be considered in determining the fatigue life.

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