ON OVERLOADS AND THE RATE OF FATIGUE CRACK GROWTH IN A 9CR-1MO STEEL

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ABSTRACT

A previous investigation, carried out with aluminum and titanium alloys, on the response of the rate of the fatigue crack growth and the crack closure to the application of a single tensile overload has been extended to a medium strength steel, Mod. 9Cr-1Mo. The experimental results are found to be consistent with those obtained previously, despite the difference in chemical composition, microstructure and mechanical properties. The results further confirm the conclusion that the retardation in fatigue crack growth rate following a single overload is due to the excess closure in the plane stress, surface region, therefore can be eliminated by removing this

surface region. A calculation of the extent of the retardation based upon the concept of "equivalent average excess closure" agrees reasonably with the experimental results. It was also of interest to find that two opening events could be observed not only after the overload, but also under the constant amplitude testing conditions in a specimen of 3.4 mm thickness.

INTRODUCTION

In a recent study [1] a procedure was presented for the determination of the influence of overloads on the extent of retardation of the fatigue crack growth rates. It was concluded that the retardation following a single overload was due to the excess closure in the plane stress, surface regions when the fatigue crack penetrated the overload associated plastic zone, as evidenced by the fact that the machining away of the surface regions led to the virtual elimination of the retardation effect. Good agreement was obtained in a comparison between the predicted and experimental results for the aluminum alloy 6061-T6 as a function of thickness and ΔK level. The method also led to a reasonable correlation with experimental results for the titanium alloy IMI 829. In the present paper the method is extended to a steel of medium strength level, Mod. 9Cr-1Mo. One reason for the interest in the behavior of a steel stems from a desire to check on the generality of the experimental findings of Matsuoka and Tanaka [2] who found that in a medium strength, quenched and tempered steel the retardation effect persisted, and was in fact even more pronounced after removal of the surface layers.

EXPERIMENTAL

The material selected for this study was the tempered martensitic Modified 9Cr-1Mo steel, whose chemical composition and mechanical properties are given in Table 1&2. ASTM standard compact-type specimens of 6.35 mm thick, with an effective width of 57.15 mm and a height/width ratio of 1.2 were used in the fatigue crack growth studies. The fatigue crack growth tests were conducted at room temperature in air at load ratio R of 0.05 and frequency of 30 Hz, using an electro-servo-hydraulic testing system under stress intensity control with a sinusoidal cycling frequency of 30 Hz. The position of the crack tip was monitored optically to a resolution of about 10 μm.

Table 1. Nominal Chemical Compositions (Wt %) of Mod. 9Cr-1Mo Steel

C	Co	Cr	Cu	Mn	Mo	N
0.06	0.017	8.47	0.03	0.37	0.88	0.054
Nb	**Ni**	**Si**	**Ti**	**V**	**P**	**S**
0.07	0.09	0.19	0.001	0.21	0.021	0.002

Table 2. Mechanical Properties

Material	σ_y, (MPa)	σ_u, (MPa)	Elongation, %
M.9Cr-1Mo steel	531	668	26.0

Single tensile overloads of magnitude of 100% (percentage of overload is defined as $\frac{K_{OL} - K_{max}}{K_{max} - K_{min}} \times 100\%$) were applied manually, the constant amplitude ΔK baseline level was 15.0MPa$\sqrt{m}$. The rate of fatigue crack propagation was calculated by dividing the crack length increment by the number of cycles spent during this increment. The crack length and consequently the crack growth rate were determined at approximately 20 μm intervals during the post-overload transitional period, while under constant ΔK testing condition the crack length measurement was taken less frequently ($\sim 0.2mm$). In some cases, the specimen's surface was removed mechanically to investigate the effect of the surface plane stress region on the overload induced retardation in fatigue crack growth rate. In order to minimize the possible residual stress caused by the machining operation, the material taken off in each pass was less than 0.25 mm, and the new surface was then polished to a finish of 1 μm.

The crack closure measurements were made periodically throughout each fatigue and overload test, using the modified elastic compliance method [3]. In this technique, the crack opening displacement(COD) is monitored by a crack mouth mounted extensometer, and the COD signal is amplified to a level comparable in magnitude with the load signal from load cell. In the current test, the sensitivity of COD signal is about 5×10^{-5} mm/mV. In order to facilitate the determination of opening point, the load signal was then subtracted from COD signal. The resultant signal is denoted as the "offset displacement". When the crack is fully open, the compliance of the specimen does not vary with the load and this is reflected by a straight line on the load-offset displacement chart. Therefore, any deviation from the linear relation on this chart is an indication of crack closure.

RESULTS AND DISCUSSIONS

Constant Amplitude Test

The baseline ΔK level used in these tests was 15.0MPa$\sqrt{m}$. At this baseline level under steady state crack growth conditions the crack opening level prior to the application of the overload was approximately 5.5MPa$\sqrt{m}$. Prior work [4] with the Mod. 9Cr-1Mo steel has shown that at a ΔK level of 15.0 MPa$\sqrt{m}$, the plane strain opening level was 2.8 MPa$\sqrt{m}$ for the case of a fatigue crack grown under increasing ΔK conditions. In the present case where there is a longer crack wake associated with steady state growth, an opening load at a level of 2.8 MPa$\sqrt{m}$ was not detected. The higher opening level observed, 5.5 MPa$\sqrt{m}$, is interpreted to be the opening level associated with the surface, plane stress regions. To check on this interpretation a 6.35 mm thick Mod. 9Cr-1Mo steel specimen was tested under constant amplitude conditions at a ΔK level of 15.0 MPa$\sqrt{m}$. After steady state growth conditions had been established and an opening level of 5.7 MPa$\sqrt{m}$ determined, 1.5 mm of material was machined from each surface. Fig. 1 shows the influence of this machining operation on the crack closure behavior. It was found that the crack opening level was reduced to a value of 3.2 MPa$\sqrt{m}$ immediately after the machining, which is of the order of the previously determined plane strain level. It was also noted that upon further cycling of the specimen, now 3.35 mm in thickness after the surface removal operation, both a lower (3.2MPa$\sqrt{m}$) and an upper (6.0MPa$\sqrt{m}$) opening load were resolvable. The upper opening load became evident when the crack had advanced less than 0.12 mm. We conclude from these experiments that for the baseline crack growth conditions described the plane stress opening level is about 6.0 MPa$\sqrt{m}$ and the plane strain opening level is half of this value.

It was of interest to note that in this constant amplitude test, immediately after machining, but before the upper opening level was detected, the initial crack growth rate was 1.7×10^{-5} mm/cycle, which was slightly higher than the steady state rate of 1.3×10^{-5} mm/cycle before the machining, an indication that although the higher opening level at the surface, plane stress region does have an effect on the rate of fatigue crack growth, it is the plane strain closure that mainly controls the rate at which the crack advances under the constant amplitude conditions. It is, however, to be expected that

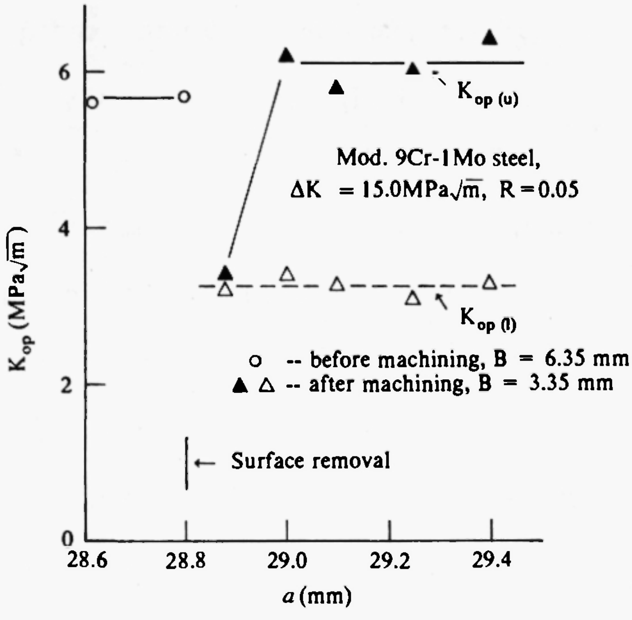

Figure 1. Effect of surface removal on the opening behavior of Mod. 9Cr-1Mo steel under constant amplitude testing condition.

the crack growth rate for a thinner specimen should be somewhat lower than for a thicker specimen due to the higher ratio of the depth of the plane stress plastic zone to the thickness of the specimen. This thickness effect is evidenced by the observation that the steady state growth rate of the machined specimen, 9×10^{-6} mm/cycle, is slightly lower than that of the full thickness specimen, 1.3×10^{-5} mm/cycle.

Single Overload Tests

a) Full thickness specimen: The response of fatigue crack to the application of a single tensile overload was analyzed in terms of the crack growth rate (da/dN) and the crack closure (K_{op}) level as a function of the crack length extension (Δa). The steady state crack growth rate at the baseline ΔK_b of 15.0 $MPa\sqrt{m}$ was 1.3×10^{-5} mm/cycle. The effect of the 100% overload ($K_{OL} = 30.8 MPa\sqrt{m}$) on the rate of fatigue crack propagation is shown in Fig. 2a. In the first specimen, the baseline ΔK_b testing was resumed after the overload and the test was run without interruption except for periodical closure measurements. The results of this test are represented by the circles in Figure 2a and 2b. It can be seen that after a brief initial acceleration, the crack growth rate rapidly decreased to about 10^{-6} mm/cycle and a period of retarded cyclic growth rate persisted over a distance of about 0.5 mm before the pre-overload crack growth rate was resumed.

The variation of the crack closure following the overload is shown in Fig. 2b also as a function of Δa. It is noted that the opening load was found to be changed by the overload event, from the pre-overload plane stress level of 5.0 MPa$\sqrt{m}$ in this specimen to the plane strain level of 3.0 MPa$\sqrt{m}$ in the very early stage of post-overload transient process. The corresponding

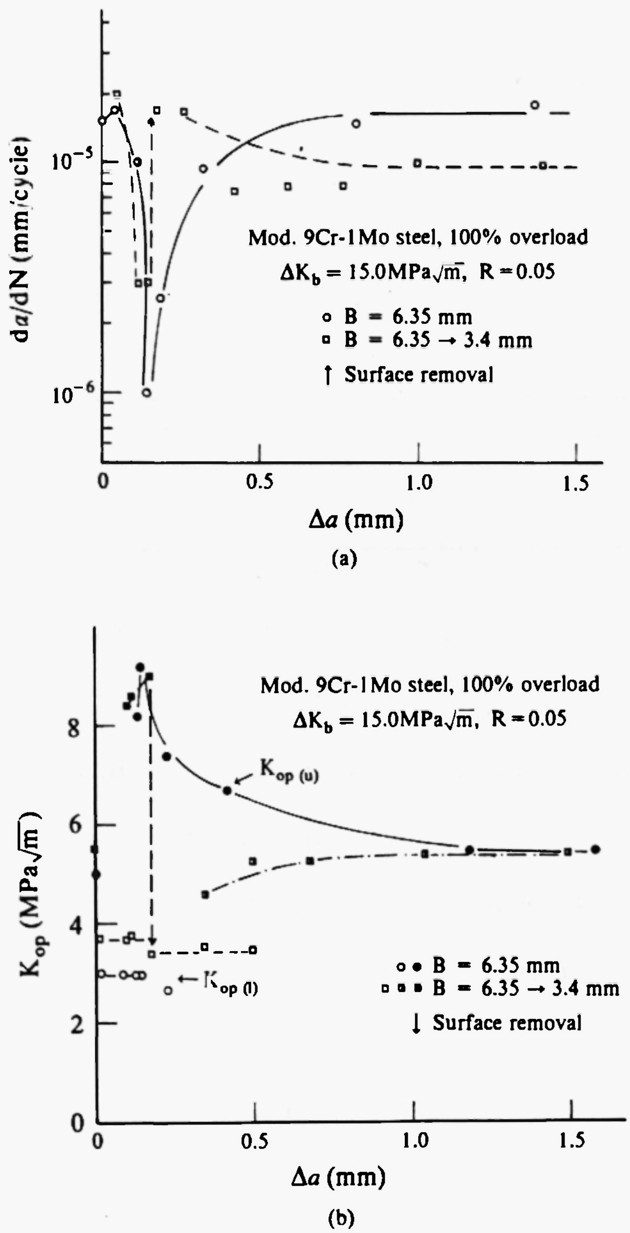

Figure 2. Response of crack growth rate and opening level to 100% overload for Mod. 9Cr-1Mo steel at ΔK_b of 15.0 MPa$\sqrt{m}$, R = 0.05. (a) da/dN vs. crack length increment Δa; (b) K_{op} vs. Δa.

micrographs of the crack profile showed that the overload led to a blunting of the crack tip accompanied by a well developed plastic zone ahead of the crack tip. As indicated previously, before the overload only the plane stress opening was observable, but due to the blunting of the crack tip, this plane stress opening level no longer existed. As a result the plane strain opening could be resolved at a level of 3.0 MPa$\sqrt{m}$. It was then found that as the crack tip penetrated the overload associated plastic zone, two opening levels instead of only one were detected. During the crack growth retardation process, the upper opening level quickly reached a peak of about 9.3 MPa$\sqrt{m}$ and then gradually decreased. In contrast to the variation in the level of the upper opening load, the lower opening load remained almost constant and then became non-resolvable after the crack tip traveled about half way of the overload induced surface plastic zone. When the crack had traversed the overload affected zone, the pre-overload growth rate was resumed, and the only resolvable opening event was determined at the level of 5.5MPa$\sqrt{m}$, which was close to the pre-overload plane stress value.

b) Machined specimen: In a second specimen, the same cyclic and overload conditions were applied, and the consequently similar crack growth and closure response was observed, as shown by the square symbols in Fig. 2 a&b. However, the test was interrupted when the crack growth rate had reduced to the minimum value, 3×10^{-6} mm/cycle. The surface removal operation was performed at this point. This machining process was designed to check the role of the plane stress, surface region in the post-overload retardation and to check the nature of the observed two opening level process. Fig. 3 shows some of the load-offset displacement charts of this specimen, which indicate the influence of the overload and machining operation on the closure behavior. Line A was taken just before the overload, where the pre-overload K_{op} was 5.5MPa$\sqrt{m}$. It is clear that the closure level (3.7MPa$\sqrt{m}$) was reduced by the overload, see line B, which represents the first loading cycle following the overload.

The depth of the plane stress plastic zone associated with the overload is estimated to be given by $\frac{K_{OL}^2}{2\pi\sigma_y^2}$. For a K_{OL} of 30.8 MPa$\sqrt{m}$ and σ_y of 530

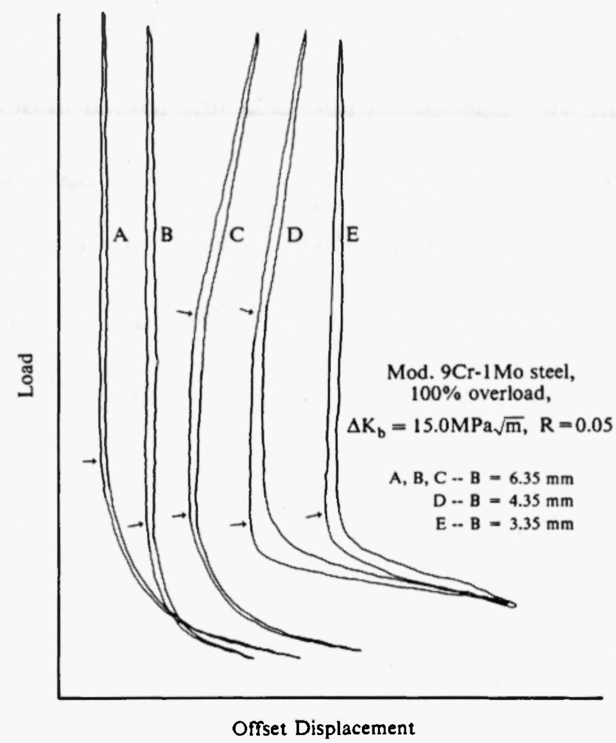

Figure 3. Crack opening behavior following a 100% single overload for Mod. 9Cr-1Mo steel(B = 6.35 mm). A--just before the overload; B--immediately after the overload; C and D--before and after the first surface removal; E--after the second machining. The arrows indicate the opening levels.

MPa, the depth of this overload zone for the Mod. 9Cr-1Mo steel was calculated to be 0.54 mm. In order to remove this zone, a layer of 1.0 mm was machined from each surface. However, the closure measurement taken immediately following the machining showed that the removal of this 1.0 mm was not enough to eliminate the upper opening level, but it did reduce the upper opening level from 9.0MPa$\sqrt{m}$ to 7.5 MPa$\sqrt{m}$, as shown by lines C and D of Figure 3. In order to determine if the removal of additional material would eliminate the upper opening event, an additional 0.5 mm was machined from each specimen surface. After this machining operation only the lower opening was evident, see line E of Fig. 3.

The specimen surfaces were then polished and the test was continued at the same ΔK level after this second machining. The crack growth data after this second machining are also shown in Fig. 2a by the square symbols. It is seen that the crack growth rate after machining increased from the retarded level of 3×10^{-6} mm/cycle to 1.7×10^{-5} mm/cycle, as indicated by the vertical arrow in Fig. 2a, which is about the steady state rate at the baseline ΔK. This immediate increase in the rate of crack growth indicated that the retardation effect due to the application of an overload was largely eliminated. The corresponding crack closure behavior after machining to a thickness of 3.4 mm is shown in Fig. 2b (square symbols). The downward arrow indicates the machining operation. It is clear that after this machining operation, the second, upper opening level disappeared and only the lower one ($\sim$ 3.3MPa$\sqrt{m}$) was evident. This indicates that, as with Al alloy 6061-T6, the two opening events for this Mod. 9Cr-1Mo steel are also plane stress-plane strain in nature, i.e., the upper opening being associated with the surface regions, and the lower one with the interior region.

As the crack grew further under the pre-overload baseline ΔK level following the machining, another upper opening load (shown in Fig. 2b by the half-solid square symbols) was detected in addition to the existing lower one. This upper opening load, represented by the half-solid square symbols in Fig. 2b, quickly reached its steady state value of 5.5 $MPa\sqrt{m}$, corres-dponding to the surface, plane stress opening, and became the only resolvable opening event.

It can been seen that when an overload was involved, the upper opening developed and reached its peak value in about 0.2 mm (Fig. 2b), but under constant amplitude cycling it took less than 0.1 mm of crack tip advance for the upper K_{op} to develop and reach its peak value(Fig. 1). This difference may be due to the blunting of the crack tip in the case of the overloaded specimen, and a consequently longer period of crack growth before this effect was overcome.

ANALYSIS

A semi-empirical analytical method has been developed in Reference 1 to estimate the extent of retardation following a single overload, in terms of the number of delay cycles. This method is based on the concept of "excess closure", i.e., the number of delay cycles can be calculated by dealing with an equivalent average excess closure, E.C., over the overload affected crack length, a_c. It will be used here to calculate the number of delay cycles, N_d, and the affected crack length, a_c, for the purpose of comparing with the experimental values. The experimental values are obtained from the plot of crack length extension, Δa, against the number of loading cycles, N, in Fig. 4. Again the circles represent the full thickness specimen.

Since the retardation in crack growth rate is mainly due to the extra closure brought about by the overload induced lateral contraction at specimen surfaces, it is reasonable that the E.C. is related to the plane-stress plastic zone associated with the overload, as well as the thickness, B, of the specimen. Therefore, it was assumed that [1]

$$E.C. = D(K_{OL} - K_{max})\{1 - \exp[-(\frac{K_{OL}^2}{2\pi\sigma_y^2 B})^m]\} \qquad (1)$$

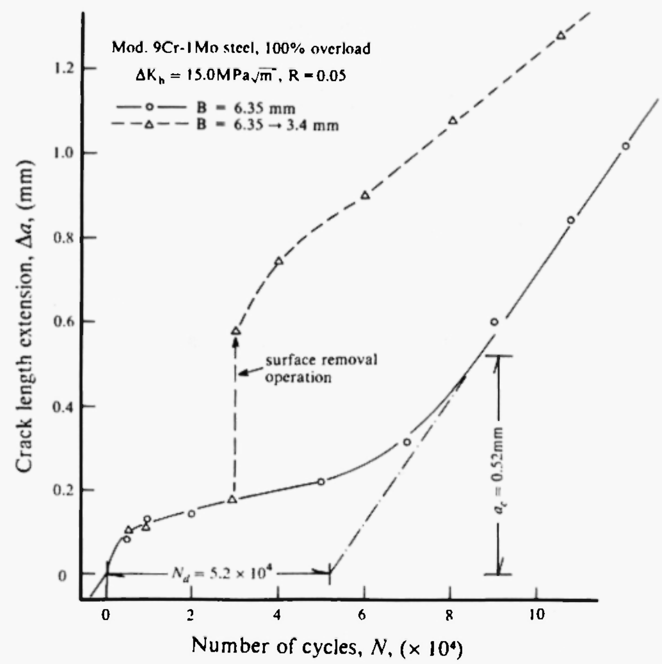

Figure 4. Variation of crack length increment with the number of loading cycles following 100% single overload for Mod. 9Cr-1Mo steel.

and where D and m are constants, which have been determined to be 1.25 and 0.5 respectively in the case of Al alloys. In this calculation, it will be assumed that these two constants for the Mod. 9Cr-1Mo steel are the same as for the aluminum alloys.

The expression generally used for the overload affected zone length, a_c, is given as [3] :

$$a_c = \frac{K_{OL}^2}{2\pi\sigma_y^2} \tag{2}$$

In order to calculate the effect of an overload on subsequent crack growth behavior, a constitutive relation is needed which correlates the crack growth rate with ΔK_{eff}. It has been found that, for both Al alloy 6061-T6 and 9Cr-2Mo steel, the fatigue crack growth rate can be related to the parameter $\Delta K_{eff} - \Delta K_{eff\,th}$ through the following equation:

$$\frac{da}{dN} = A\,(\Delta K_{eff} - \Delta K_{eff\,th})^2 \tag{3}$$

The fatigue crack growth rate for the 9Cr-2Mo steel as a function of the parameter $\Delta K_{eff} - \Delta K_{eff\,th}$ is plotted in Fig. 5, where the value of $\Delta K_{eff\,th}$ is 3.2 MPa$\sqrt{m}$, and ΔK_{eff} is the plane strain value. The straight line with a slope of 2 in this figure represents Eq. (3), and as shown the experimental results compare favorably with this equation. Since the fatigue crack growth behavior of Mod. 9Cr-1Mo is very similar to that of 9Cr-2Mo, it is assumed that this relation holds for this Mod. 9Cr-1Mo steel, and also that the value of A (2×10^{-10}, when crack growth rate is in unit of m/cycle) for 9Cr-2Mo can be used for the analysis of Mod. 9Cr-1Mo data. This assumption was supported by available experimental data from both constant amplitude tests and overload tests. For example, the measured maximum upper opening level is $9.3 MPa\sqrt{m}$ after the overload, and according to Eq. (3) this corresponds to a crack growth rate of about 2×10^{-6} mm/cycle, which is comparable to the observed minimum rate of 10^{-6} mm/cycle.

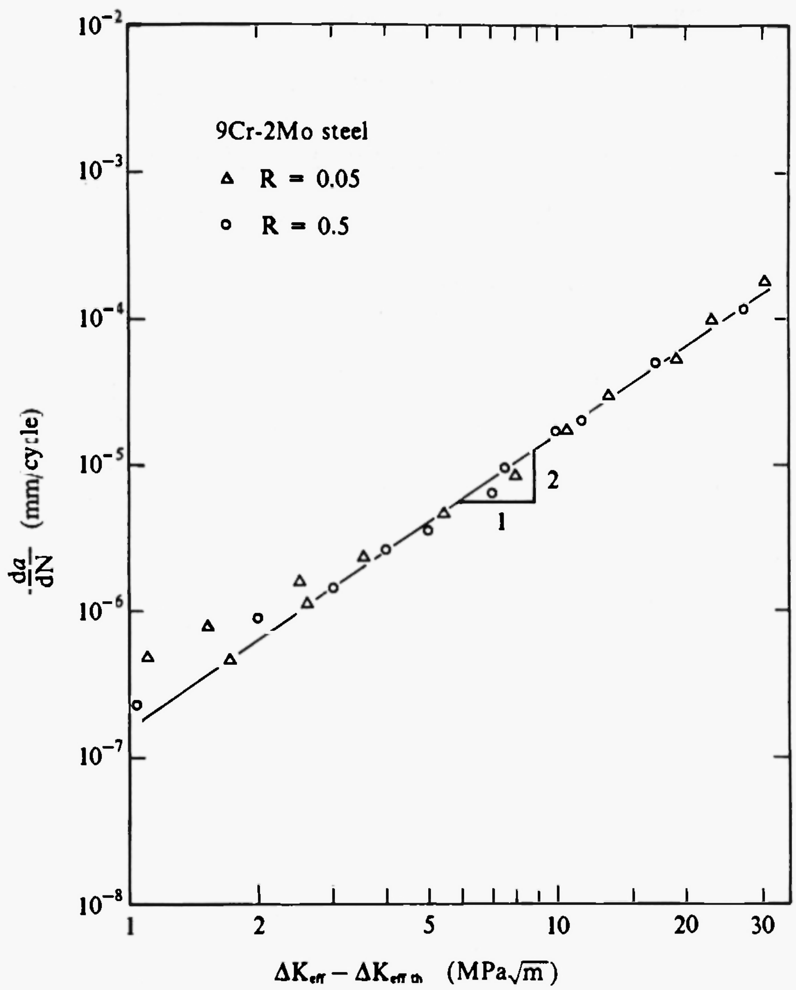

Figure 5. Correlation of fatigue crack growth rate of 9Cr-2Mo steel with the parameter $\Delta K_{eff} - \Delta K_{eff\,th}$ [3] . The straight line represents Eq. (3).

The number of delay cycles involved in traversing the overload affected zone is given by the total number of cycles required for the retarded crack to traverse the overload affected zone minus the number of cycles required the normal crack to traverse the same distance, is expressed as follows:

$$N_d = \frac{K_{OL}^2}{2\pi\sigma_y^2 A}\left\{\frac{1}{(\Delta K_{eff} - E.C. - \Delta K_{eff\,th})^2} - \frac{1}{(\Delta K_{eff} - \Delta K_{eff\,th})^2}\right\} \quad (4)$$

The calculated results are compared with the experimental values in Table 3, and it is seen that reasonably good agreement between the predicted and experimental values is obtained. It therefore appears that the response of this steel to an overload is similar to that of the aluminum and titanium alloys. However, the depth of the plane stress effect for the Mod. 9Cr-1Mo appears to be greater than for the aluminum alloy.

Table 3. Comparison of experimental and predicted values

	Experimental N_d	Predicted N_d	Experimental a_c	Predicted a_c
Mod. 9Cr-1Mo	5.2×10^4	5.6×10^4	0.52	0.54

CONCLUDING REMARKS

The fact that machining away of a sufficient amount of surface material from the Mod. 9Cr-1Mo steel specimens resulted in the elimination of the effect of the overload on the crack growth rate and opening load is generally quite similar to that observed with aluminum and titanium alloys. This observation confirms that the retardation effect is mainly controlled by the overload affected plane stress surface zone, and the removal of this surface leads to the virtual elimination of the retardation effect.

It is noted that the results presented herein are different from those reported by Matsuoka and Tanaka [2], who found that surface removal enhanced rather than eliminated the retardation effect. The cause for this difference is yet to be resolved.

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