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CLOSURE: AN EXPLANATION FOR FATIGUE CRACK GROWTH RATE ACCELERATION/RETARDATION DUE TO OVERLOADS IN AUSTENITIC STAINLESS STEELS

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INTRODUCTION

Closure, as initially proposed by Elber [1], has been employed by a number of investigators to explain various phenomena associated with fatigue crack growth rate (da/dN), [2 - 10]. For example, the concept of closure has been used qualitatively and sometimes quantitatively to at least partially explain changes in da/dN due to changes in R ratio [2], environment [3 - 5], and overload [2, 4]. The concept of closure, however, is not universally accepted (as it should not be) as a rationale for all changes in da/dN created by changes external from the material [5, 10 - 12]. Most recently, investigations have cast serious doubt concerning the relevance of closure as applied to da/dN retardation following an overload [11]. The research reported here attempts to establish the applicability of closure concepts in a given instance to qualitatively and in some cases quantitatively, to explain da/dN phenomena associated with overloads.

Austenitic stainless steels, exhibit a full range of da/dN effects due to overloading, i.e., (1) accelerated da/dN upon an increase in load range (or stress intensity range ΔK), (2) short lived initial accelerated da/dN immediately subsequent to an overload, (3) retarded da/dN for some period after the application of an overload, and (4) increased da/dN after relaxation for a time interval at zero applied stress. Due to the sensitivity of da/dN in austenitic stainless steels to overloads, and because of the importance of this class of alloy as a structural material, Type 316 stainless steel was selected as the material in which to establish the importance of closure in predicting da/dN after multiple overload cycles.

MATERIALS AND EXPERIMENTAL PROCEDURES

A Type 316 austenitic stainless steel, in both the annealed and 19% cold worked conditions with room temperature yield strengths of $\sigma_y \approx 262$ MPa and $\sigma_y \approx 608$ MPa, respectively, was used for all tests. Fatigue crack growth rate tests were made in tension-tension with R ($\sigma_{min}/\sigma_{max}$) = 0.05 using compact tension specimens of the following dimensions; 1.27×10^{-2}m thick, 1.07×10^{-1}m height, and 1.11×10^{-1}m length. Overload conditions consisted of 20 cycles at some percentage above the previous maximum stress intensity. All experiments were conducted on an MTS electrohydraulic system at a cyclic rate of 10Hz, except during closure recordings when a rate of 0.1 Hz was used. Humidity averaged ~ 45% during test periods. After fracture, relevant regions of the fracture surface were examined by scanning electron microscopy (SEM) and a carbon replica technique to characterize fracture morphologies.

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The acoustic bulk wave device used for determining crack opening and closing loads has been described and illustrated elsewhere [14]. This procedure uses the location of a change in acoustic signal intensity with increasing load as an estimation of the opening load. At times opening and closing loads are not the same exhibiting a hysteresis during the loading and unloading portions of the cycle. When a hysteresis did occur opening load was measured. Also, a precise determination of this opening load is at times difficult due to the nonlinear variation of the acoustically measured crack depth with applied load. Using a technique established previously [2], extrapolation of the two segments of the experimental curves is used to define the opening load for the results presented in this work.

RESULTS AND DISCUSSION

Annealed Type 316 Stainless Steel

Fatigue crack growth rate in Type 316 stainless steel at 298K, uninterrupted by load excursions, is illustrated in Figure 1. Superimposed on this "normal" crack growth behaviour are da/dN results for identical test conditions with the addition of a 55% overload excursion applied for 20 cycles. Results are plotted as a function of applied stress intensity range (ΔK) and are presented semilogarithmically to magnify effects due to the overload. Two effects of the overload on da/dN are readily apparent from Figure 1. First, initial acceleration of da/dN is observed after fatigue cycling is resumed at the baseline stress intensity, and second, this acceleration is followed by crack retardation which occurs as a continuous decrease in da/dN to a minimum level after which da/dN increases at a faster rate than would be expected for the increase in ΔK. Not shown in Figure 1 is the observation that da/dN during the overload far exceeds what normally would be predicted for this overload stress intensity extrapolated from an uninterrupted da/dN versus ΔK plot, e.g., 3.7 vs. 0.45 μm/cycle. Adams [8] has adequately described this increased da/dN during an overload using closure concepts and as such it will not be discussed further here. The above observations were shown to be repeatable for a 55% overload and were also consistently observed for overload levels of 20 and 40%, with the periods of initial acceleration and retardation of da/dN decreasing with decreasing levels of overload.

Results presented in Figure 1 are presented again in Figure 2, however, this time da/dN is illustrated as a function of effective stress intensity range (ΔK_{eff}), where ΔK_{eff} is defined to be proportional to (P_{max}-P_o), and P_o is the opening load as determined by the procedure described in the previous section. Numbers written beside the data points in Figure 2 represent the chronological sequence of crack growth rate measurements. Immediately after the load excursion, the crack was shown to be fully open down to loads as low as 50 kg, whereas prior to the overload the opening load averaged ≈ 225 kg. This initial acceleration period (points 1 and 2) is followed by delayed retardation (points 3 through 8) which eventually yields to recovery (points 9 through 12). Each of these regions of da/dN after the overload is discussed below in relation to closure concepts.

Elber [7] qualitatively described the possibility of initial acceleration following an overload as follows: a high load excursion produces a residual displacement which is larger than the displacement at which the crack previously opened such that the crack cannot now close over the previous fracture surface. The result is a lower opening load which leads to a larger ΔK_{eff} and thus an increase in da/dN. Points 1 and 2 in Figure 2 illustrate this initial acceleration as a function of ΔK_{eff}. Remembering that on a semilog plot data that adheres to a Paris relationship [15] would exhibit a slight curvature as shown in Figure 1, it can be concluded that points 1 and 2 lie on an extrapolated curve drawn through the da/dN results prior to the overload.

In addition to opening load measurements and optical observations of crack lengths, Figure 3 illustrates fracture surface morphologies prior to, during, and after a 55% overload. Following the overload, striation spacings decreased in comparison to the cyclic crack advance during the overload, but increased, as compared to the striation spacing immediately prior to application of the overload cycles. Initial acceleration indicated in Figure 3 in comparison to pre-overload crack growth rates is seen to occur immediately after the overload and then decays as the crack progresses into the overload plastic zone. Crack growth rate measurements correlated well with striation spacings, but it should be pointed out that fractography in Figure 3 is not from the specimen yielding results for Figure 2.

The above crack opening load measurements, in concert with optical da/dN measurements and fractography, now provide a quantitative measure for the infrequently observed initial acceleration that occurs upon resumption of fatigue cycling at the lower baseline stress intensity. As pointed out by Chanani [16], this initial acceleration is not considered significant from a structural point of view because it is quite short lived. However, the importance of this initial acceleration is that it can be quantitatively accounted for by the change in opening load and thus helps to confirm the importance of closure concepts as applied to the prediction of da/dN in 316 stainless steel for multiple overloads.

Following the progress of the crack and continuing with the reasoning of Elber [7], delayed retardation (points 3 - 8, Figure 2) is explained by considering the behaviour of the plastic zone created by the load excursion ahead of the crack tip. The elastic material surrounding this plastic zone acts like a clamp on this zone, causing the compressive residual stresses. As long as this plastic zone is ahead of the crack tip, this clamping action does not influence the crack opening. As the crack propagates into the plastic zone, the clamping action will act on the new fracture surfaces. This clamping action, which builds up as the crack propagates into the plastic zone, requires a larger, externally applied stress to open the crack; hence the crack will propagate at a decreasing rate into this zone. Thus, the existence of delayed retardation would be indirect evidence that retardation is caused by plastic zone compressive stresses acting on residual deformations as the crack propagates into the plastic zone.

Figures 1 and 2 each illustrate different aspects of delayed retardation. Figure 1 illustrates the existence and extent of delayed retardation, whereas Figure 2 portrays the functional relationship of da/dN during this increasing delay period as a function of ΔK_{eff}. Of greatest importance is the relatively good correlation between ΔK_{eff} and da/dN during the delay period and da/dN prior to the overload, indicating again that da/dN may be described as a function of ΔK_{eff}. Also, the fact that a multi-overload excursion resulted in delayed retardation (and initial acceleration) is evidence that the crack must propagate some distance into the plastic zone before maximum compressive stresses and increased deformation move to the wake of the crack, creating high opening loads.

With regard to the recovery period, (points 9 - 12, Figure 2), qualitatively it can be explained by progression of the crack sufficiently beyond the overload plastic zone such that the influence of the increased residual deformation and the large compressive stresses associated with the overload plastic zone diminishes in importance. As illustrated in Figure 2, this zone of recovery can also be described quantitatively as a function of ΔK_{eff}.

The above results illustrate that a plot of da/dN versus ΔK_{eff} can be described by the unique relation $da/dN = A\ (\Delta K_{eff})^n$ which proves to be quantitatively relevant both before and after an overload. In other words, the effect of the overload is to create a condition at the crack tip wherein the crack now operates at a lower value of ΔK_{eff} after the overload, but otherwise follows the above da/dN versus ΔK_{eff} relation. This unique relation has previously been established on aluminum alloys [4]. Figure 2 does illustrate a slight hysteresis which is consistent in all our measurements and is probably due to the technique used in determining the closure load by extrapolation. However, the results do illustrate the applicability of closure concepts in quantitatively predicting initial acceleration, retardation, and recovery of da/dN in 316 stainless steel following an overload.

Cold Worked Type 316 Stainless Steel

To further substantiate the applicability of closure concepts following an overload, experiments described in the previous section were repeated for the same material cold worked 19%. Results are illustrated in Figures 4 and 5 as a function of ΔK and ΔK_{eff}, respectively. In each figure unnumbered data points correspond to results prior to an overload, whereas points 1 - 9 apply after the 55% overload and points 10 - 20 apply after a 130% overload. For this testing, initial acceleration was not conclusively observed due to crack branching, however, delayed retardation and recovery periods are well established.

As was true for the annealed material, da/dN after a multiple overload in 19% cold worked material can be quantitatively described by a unique function of ΔK_{eff} (Figure 5). A difference exists, however, in that the cold worked material exhibits much more rapid recovery than that observed for the annealed material, even for very large overloads (Figure 4). This can be explained by considering the effect of the plastic zone size on the magnitude of the opening load. The influence of the overload is limited to the period during which increased compressive stresses created by the overload influence material in the wake of the crack. When the crack progresses beyond the overload plastic zone, it would be expected that the opening load would again approximate that established prior to the overload and as such recovery would occur more rapidly the smaller the plastic zone size. For Type 316 stainless steel, 19% cold work increases the yield stress by approximately a factor of two, thus roughly decreasing the plane strain plastic zone size by a factor of four. It is not to be concluded, however, that a 1 to 1 correlation between plastic zone size and period of recovery is necessarily expected. Recovery is most likely a function of not only plastic zone size, but also the magnitude of residual deformation in the wake of the crack and the magnitude of the opening load during uninterrupted fatigue cycling. As will be seen below, the magnitude of the opening load is also influenced by cold work.

From a comparison of da/dN results for annealed and cold worked material (Figures 1 and 4), it can be concluded that for equivalent values of ΔK da/dN is substantially reduced due to the introduction of 19% cold work. However, when plotted against ΔK_{eff}, Figures 2 and 5 illustrate equivalent values of da/dN for annealed and cold worked materials. Essentially, the effect of cold work was to increase P_o resulting in a higher effective R value with an attendant decrease in stress intensity range. This increase in P_o is most likely due to increased compressive stresses in the plastic zone created by the higher elastic stresses possible in the higher yield strength cold worked material. Also, with a higher P_o it would be expected that recovery to a normal crack growth rate would occur faster after an overload as discussed above.

Closure concepts therefore again quantitatively describe da/dN behaviour after a multiple overload, this time for cold worked material, and also offer a quantitative explanation for the difference in da/dN for annealed versus cold worked material.

Relaxation Effects

It has been reported by other investigators [17] that relaxation at zero load following a high load excursion decreases delay in return to baseline da/dN. From results discussed above, it could be hypothesized that a decrease in delay would be accompanied by an attendant decrease in opening load. Indeed for annealed 316 stainless steel, after relaxation at zero stress for 48 hours, the opening load decreases from 4.67 MN to 3.43 MN. This phenomenon can conveniently be explained by considering relaxation of the elastic stresses that enclose the plastic zone, or by relaxation of the compressive stresses in the plastic zone itself. This would reduce the opening load (as measured above), and in turn increase da/dN and decrease the period of delay. Thus, closure concepts are consistent with relaxation theories and the opening load can be observed to decrease with time.

This relaxation explanation for annealed material does not however explain the effects of hold times at zero stress on cold worked 316 stainless steel. In Figure 4, data points 6 and 20 illustrate da/dN immediately after hold times at zero stress for times of 64 and 16 hours, respectively. It is apparent that hold times resulted in a decrease in da/dN. Concurrently, after each hold period the opening load was observed to increase. Similarly, Chanani [18] observed a significant increase in crack-closure after "relaxation" for 16 hours at zero stress in aluminum alloys. These results are a contradiction to those presented above for annealed material but as shown in Figure 5, when our results are plotted against ΔK_{eff}, they are quantitatively in agreement with closure concepts. Thus, it can be concluded that a consideration of opening load again results in a unique relationship between da/dN and ΔK_{eff}, this time to evaluate relaxation effects quantitatively in cold worked material.

SUMMARY

A considerable number of effects resulting from a multiple overload have been discussed in this paper. For example, it is observed that a multiple overload results in accelerated da/dN during the overload, an initial acceleration in da/dN upon resumption of the baseline stress intensity range, delayed retardation, recovery and a decrease or increase in opening load after hold times at zero stress. The magnitude and rate of these effects was often found to be dependent on the material condition, that is, annealed or cold worked. However, for all effects observed, consideration of the opening load, as defined by closure concepts, always resulted in a unique relationship between da/dN and ΔK_{eff} for Type 316 stainless steel.

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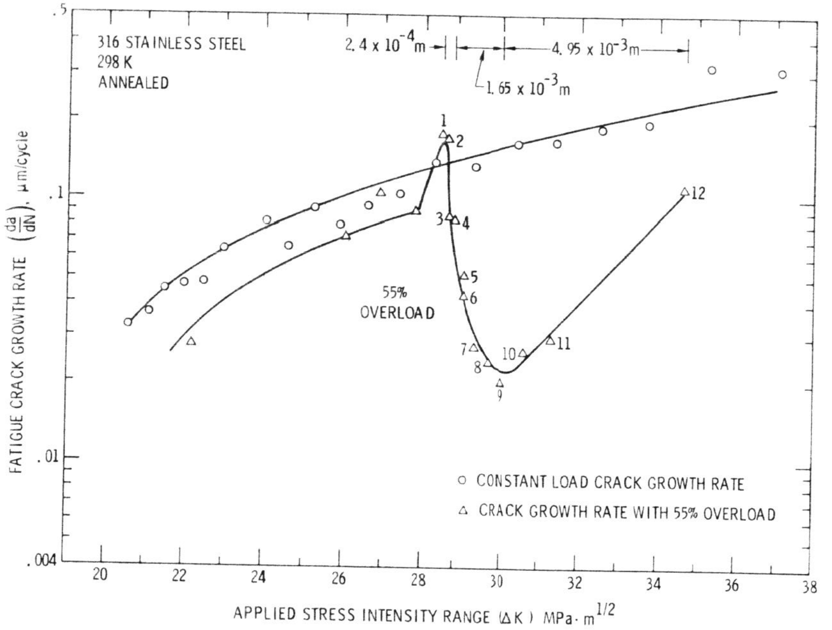

Figure 1 Fatigue Crack Growth Rate in Annealed 316 Stainless Steel With a 55% Multiple Overload Excursion as a Function of ΔK

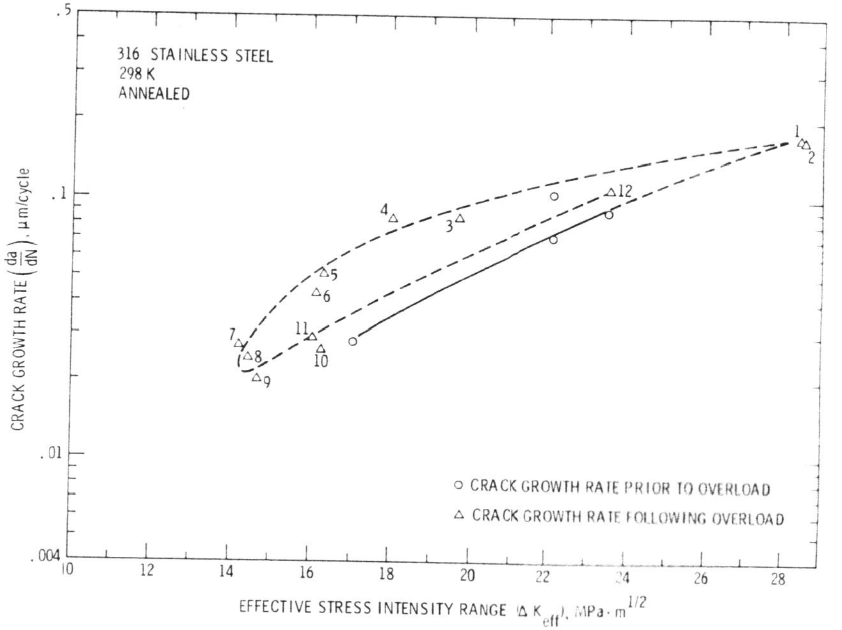

Figure 2 Fatigue Crack Growth Rate in Annealed 316 Stainless Steel With a 55% Multiple Overload Excursion as a Function of ΔK_{eff}.

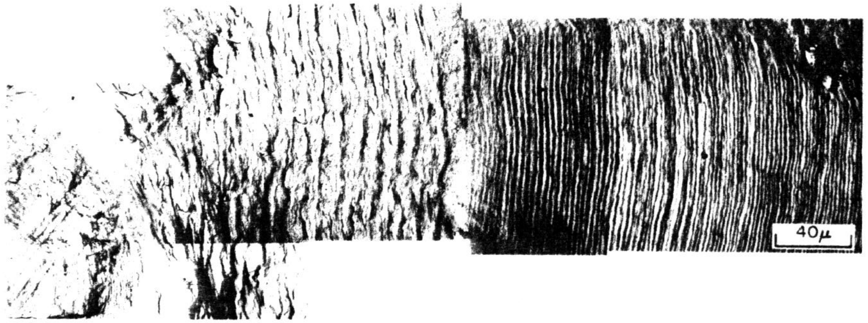

Figure 3 Fractography Illustrating Fatigue Crack Growth Rate Prior to, During, and After a 55% Multiple Overload Excursion in Annealed 316 Stainless Steel

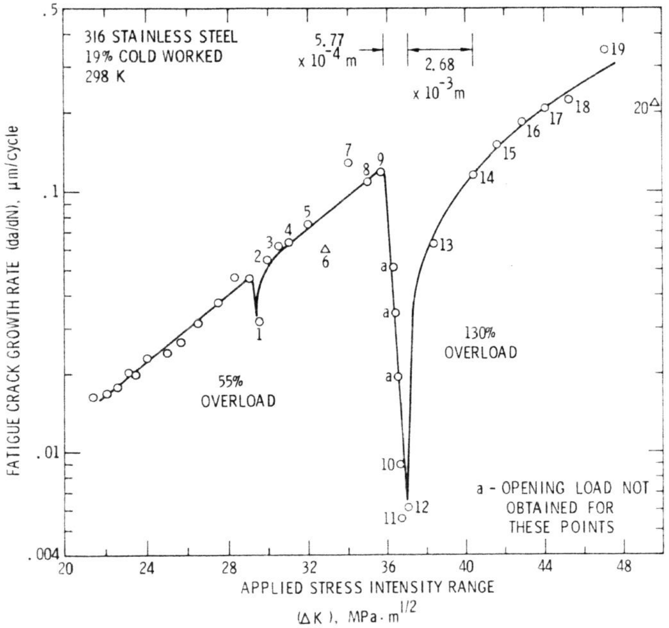

Figure 4 Fatigue Crack Growth Rate in 19% Cold Worked 316 Stainless Steel with 55 and 130% Multiple Overload Excursions as a Function of ΔK

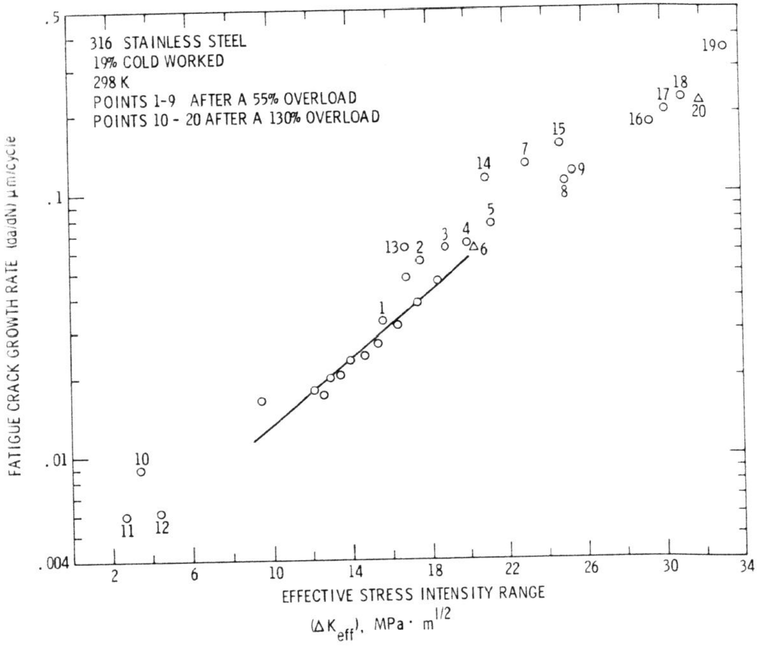

Figure 5 Fatigue Crack Growth Rate in 19% Cold Worked 316 Stainless Steel with 55 and 130% Multiple Overload Excursions as a Function of ΔK_{eff}