Effects of Overload-Affected Zone on Fatigue Crack Propagation Behavior after Applying a Single Overload under Negative Stress Ratio

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Abstract: *The fatigue crack growth rate actually accelerated after a tensile overload under a negative value of baseline stress ratio R. This type of crack propagation behavior was related to the tensile residual stress state distributed in the vicinity of the crack tip after an overload. In the present investigation, it was found that the extent of both the retardation and the acceleration of the crack propagation were associated with the overload-affected zone condition when the crack tip penetrated into this zone under baseline stress ratio R.*

Keywords: *Crack growth, Residual stress, Acceleration, Retardation, Overload-affected zone.*

1. Introduction

In service, loading conditions may involve variable amplitude rather than constant amplitude, which influences the fatigue life of a component. For example, a fatigue crack growth behavior will change after an overload. It is well known that the fatigue crack growth rate can be retarded following overloads [1-4]. The main cause of the retardation associated with the overload is compressive residual stress developing in front of the crack tip upon unloading to baseline [2-4]. However, under some loading conditions of negative stress ratio, the tensile residual stress generated in front of the crack tip following the overload is the major factor in the acceleration of the crack propagation rate [4-6].

After applying overload, in front of the crack tip, the static plastic zone and residual stress were created. Because the crack propagation behavior following the overload depends on the residual stress state as indicated by the fluctuation of the crack opening level, the extent of fluctuation of the crack opening stress level in the zone associated with the extent of retardation and acceleration of the crack growth was investigated under baseline stress ratio R of 0, -1.0 and -1.5. Also, the relationship between the plastic zone and the crack propagation behavior was investigated.

2. Material and testing conditions

The material used in the present study was 0.15 % carbon steel, and the chemical composition of the material was (wt, %): 0.15% C, 0.30% Si, 0.50% Mn, 0.013% P, 0.013% S, 0.05% Ni and bal. of Fe. The mechanical properties of that were 449 MPa. tensile strength, 283 MPa. lower yield strength and 69% reduction of area. The type of specimen employed was a center-cracked plate for which the width and thickness were 20 mm and 4 mm, respectively. A notch of 2.5 mm in length with a root radius of 0.1 mm was cut in the center of the flat section of the specimen by an electrical discharge machine. After being polished using an emery paper and a metal polisher, 0.5 mm of initial cracks were introduced from the notch roots by a push-pull hydraulic fatigue test machine. The crack length, $2a$, was defined as including the notch length. After annealing the specimen at 600^{O}C in a vacuum furnace for one hour, the fatigue crack propagation tests were carried out using a hydraulic fatigue testing machine with a loading frequency of 10 Hz in laboratory room conditions. The semicrack length, *a,* was measured by aid of a traveling microscope with accuracy to 10 µm on the flat surface of the specimen. When the semicrack length had reached 3 mm, the constant stress amplitude was interrupted, and a single overload was applied manually. Next, the constant stress amplitude was resumed.

Table 1 shows the testing conditions. The stress ratio R is defined as the ratio of the minimum cyclic stress S_{min} to the maximum cyclic stress S_{max}, where S_a is the stress amplitude, and S_{OL} is the overload stress. The percentage of overload is defined as follows [2, 3]:

$$\%Overload = \frac{K_{\max OL} - K_{\max b}}{K_{\max b} - K_{\min b}} x100\% \qquad (1)$$

where $K_{max\ OL}$ is the stress intensity factor at the overload point, and $K_{min\ b}$ and $K_{max\ b}$ are the stress intensity factors at the minimum and maximum of the baseline cyclic load, respectively. The crack opening point was measured by means of the subtracted displacement method [7] in the specimens.

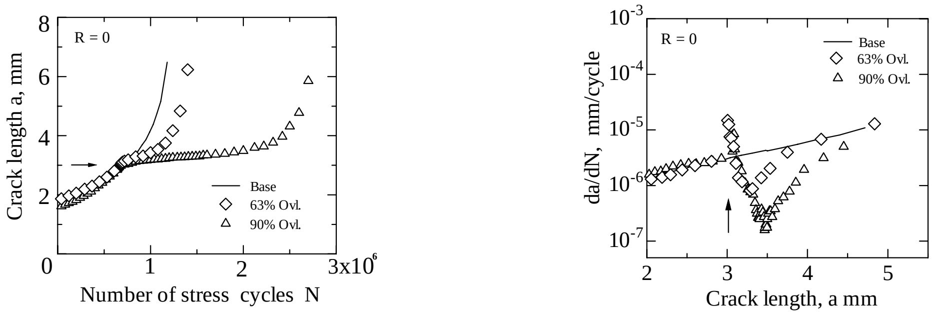
TABLE 1—Testing conditions

No.	R	S_a MPa	$S_{\max}$ MPa	S_{OL} MPa	% Overload
1	0	43	86	-	-
2	0	43	86	140	63
3	0	43	86	163	90
4	-1.0	67	67	-	-
5	-1.0	67	67	185	88
6	-1.0	67	67	210	107
7	-1.5	85	67	-	-
8	-1.5	85	67	135	40
9	-1.5	85	67	178	66

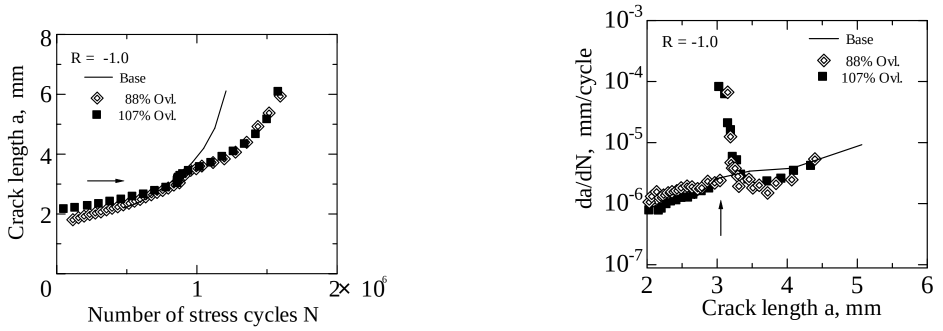
3. Results and discussion

3.1 Crack propagation behavior after overloading

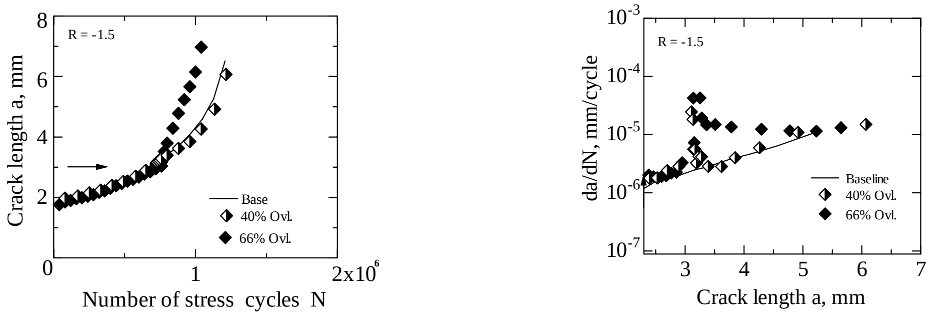
Figure 1 shows the crack length, *a*, function of the number of cycles, *N*, and the variation of the crack growth rate, *da/dN*, to the crack length, *a*. The arrow points to when the single overload was applied. In the case of stress ratio R = 0, the number of retardation cycles and the extent of the retardation period vary depending on the overload level as shown in the Fig. 1(a) and (b). The effect of the overload on the extent of the retardation and the deceleration period when R = -1.0 shows the same tendencies as in the case of R = 0, but the effect is less pronounced as shown in the Fig. 1(c) and (d). However, as shown in the Fig. 1(e) and (f), after being recycled on baseline stress ratio R = -1.5, the deceleration period was almost not observed as shown on the specimen with 40 % overload. The acceleration of the fatigue crack propagation was observed on specimen with 66 % overload, and in this case, the fatigue life became shorter than the baseline, and only the acceleration period was observed. Therefore, it is an indication that the fatigue crack propagation behavior is dependent on the loading history and overload level.



(a). Crack propagation curves for *R=0*. (b). *da/dN vs. a* for *R=0*



(c). Crack propagation curves for *R=-1.0.* (d). *da/dN vs. a* for *R=-1.0*



(e). Crack propagation curves for *R*=-1.5. (f). *da/dN vs. a* for *R=-1.5.*

Figure 1—The crack propagation curves and the crack propagation rate as a function of crack length (Ovl. = overload).

3.2. Effects of overload- affected zone on the crack propagation behavior

The residual stress state developing in the vicinity of the crack tip following overloading was indicated by the fluctuation of the crack opening stress level when the crack tip penetrated in the overload-affected zone. Figure 2 shows examples of variations of the crack opening stress level, which were obtained for *R* = 0, -1.0 and -1.5, respectively, as a function of the fatigue crack length, *a*, after application of an overload. When the crack opening stress level is higher than its base, it indicates that the compressive residual stress developed in the overload-affected zone as in the case of *R* = 0. However, when the crack penetrated in the zone under constant amplitude of *R* = -1.5, the crack opening levels were lower than its baseline and after emerging from the zone the crack opening level converged gradually to the baseline. This is an indication that tensile residual stress state developed in the overload-affected zone. In the specimens recycled under constant amplitude *R*=-1.0, not only the crack opening level being higher than baseline, but also lower than baseline, thus, in this case both compressive and tensile residual stress state developed in the zone.

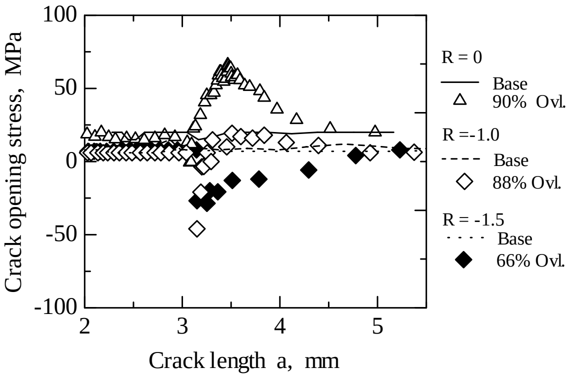
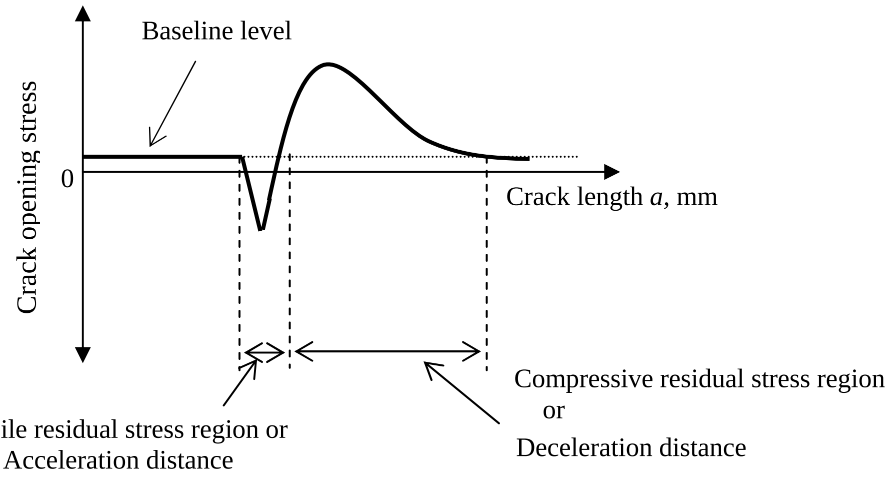
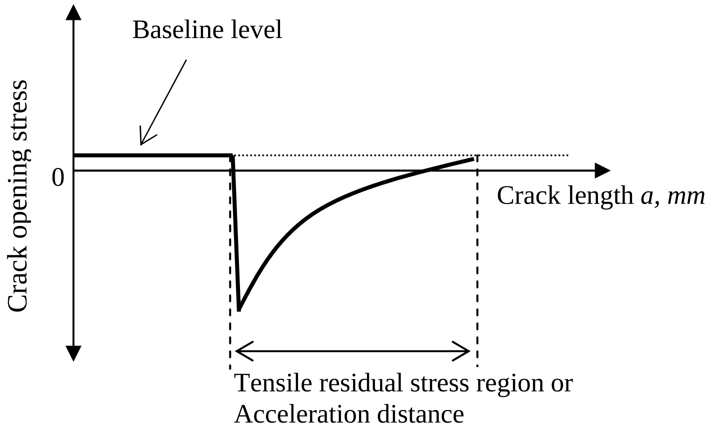


Figure 2—The variation of the crack opening stress level



(a) Deceleration case



(b) Acceleration case

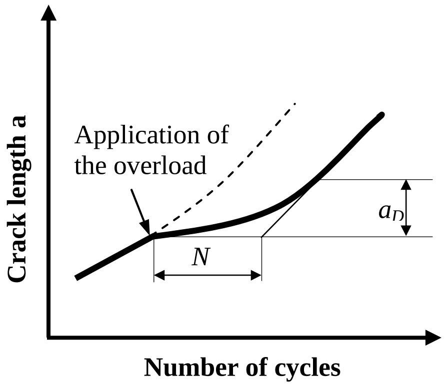
Figure 3—The schematic definition of the delay and acceleration distance associated with the variation of the crack opening stress level.

With reference to the variation of the crack opening stress level as shown in Fig. 2, Fig. 3 defines schematically the extent of retardation, a_D, and acceleration, a_C, associated with the variation of the crack opening stress level. The extent of deceleration is longer than the extent of acceleration when the crack growth is retarded after overloading as shown in Fig. 3(a). However, as shown in Fig. 3(b) the extent of deceleration may be completely eliminated, so that only the acceleration distance is shown. In these cases, the acceleration of the crack growth occurs, and the fatigue life becomes shorter than the baseline under some certain loading conditions of R = -1.5 (specimen No. 9).

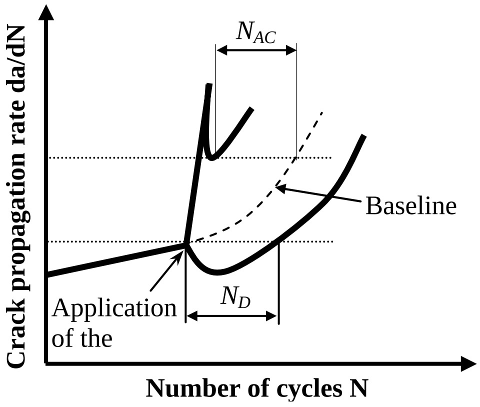
When a single overload is applied under stress ratio R = 0, the material in front of the crack tip region is plastically deformed because of the high stress concentration, and the material in that region is extended in the direction of the loading. Because the deformation is irreversible, upon unloading to zero load from the overload level, compressive residual stress is developed. The compressive residual stress causes an increase the crack opening level. As a result, the stress that effectively causes the crack growth is decreased. Therefore, the fatigue crack growth is arrested following the overload [2-4]. In the case of baseline negative stress ratio R, the effect of the overload on the retardation is less pronounced. Even under some loading conditions, the crack growth is accelerated following the overload, and the fatigue life becomes shorter than the baseline. In this case, the compressive residual stress changes to tensile residual stress. The development of tensile residual stress is explained as follows; upon unloading from an overload level to a minimum load of negative stress ratio, higher compressive stress than everywhere develops in front of the crack tip. If the compressive stress is high enough, the material in front of the crack tip will be yield, and the material will bulge. After unloading from the minimum load to zero load, tensile residual stress develops in the overload-affected zone [4-6].

3.3. Deceleration and acceleration of crack growth after overload

In the case of the retardation of the crack growth, the number of delay cycles, N_D, and the extent of delay length, a_D, associated with the overload application during a constant stress amplitude test are defined in the manner shown in Fig. 4(a) [4]. However, in the case of the acceleration of the crack associated with an overload, to define the number of acceleration cycles, N_{AC}, in the same manner as in the retardation case is difficult because the fatigue life becomes shorter than the baseline. So, the acceleration cycle, N_{AC}, is defined as the subtraction of the number of stress cycles of the overload test from that of the baseline at which the crack propagation rate, da/dN, reached minimum value after applying overload. Figure 4(b) shows a schematic representation of the relationship between N and da/dN and the definition of N_{AC} is shown. Also, the number of delay cycles, N_D, can be determined using this relation. N_D is defined as the number of cycles that are required to return to the base rate after deceleration from the point at which the overload was applied. Figure 5 shows an example of the da/dN and N relation, which represents cases of retardation and acceleration. The arrow points to when the overload was applied.



(a) The number of delay cycles



(b) The number of acceleration cycles

Figure 4—Definition of delay and acceleration cycles

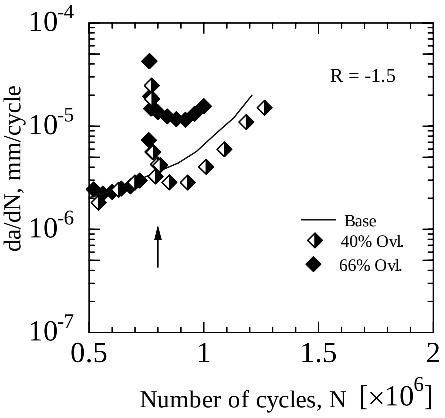


Figure 5—Example of relationships between crack propagation rate, *da/dN*, and the number of cycles, *N*.

4. Concluding remarks

As the results of the present study, it is concluded that:

- The crack growth behavior following an overload depends on the overload level and stress ratio *R*. In the case of *R* negative, the effect of the overload related to the retardation is less profound. Even under some loading conditions of R =-1.5, the crack growth is accelerated by overloading and the fatigue life is shortened.

- The deceleration and acceleration depend on the residual stress state developing in the overload-affected zone, and they depend on the compressive and tensile residual stress state, respectively.
- It was found that there are the delay extent, a_D, and the acceleration extent, a_C, within the overload-affected zone.

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