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THE DECELERATION AND ACCELERATION OF CRACK PROPAGATION FOLLOWING TENSILE OVERLOAD AND HOLD TIME

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Abstract

The effect of the hold time of a tensile overload on crack propagation behaviours following the overload was investigated. In the study, the crack propagation behaviour after the overload was observed under constant amplitude load with stress ratio zero and negative, respectively. The result of the study shows that the fatigue life, the deceleration and acceleration of the crack propagation depends on the magnitude, the hold time of the overload and the shape of the crack tip as well as the stress ratio of the constant amplitude load following the overload. The deceleration occurs if the compressive residual stress develops in the zone affected by the overload in front of the crack tip. Whereas, if the tensile residual stress develops in that zone, the crack is accelerated, and the fatigue life is shortened. In addition, the shape and the displacement of the crack tip affect the residual stress condition in front of the crack tip, and the crack can be advanced by the hold time of the overload, thus, it also enhances the acceleration of the crack propagation following the overload.

Keywords: Crack propagation, Overload, Hold time, Deceleration, Acceleration.

1. Introduction

It is well known that a fatigue life of a member of structure associated with a crack propagation relates to cyclic load conditions, and it is affected by environmental conditions also [1, 2]. If the environment interacts to a fatigue crack propagation, such as in corrosive environment, common fatigue life models are often not able to estimate the fatigue life. When the load conditions alone is considered to affect the crack propagation, the fatigue life may be well predicted with available the fatigue life models. The fatigue crack propagation model is used to evaluate the fatigue life of a member of structure containing the crack. In this model, a prediction of fatigue life of a member can be made by relating the crack propagation rate to stress intensity factor [1-3]. The crack propagation may decelerate or accelerate depending on the cyclic load condition [3-5]. Therefore, the prediction may be accurate if the expected crack propagation behaviour is well understood.

The deceleration of crack propagation takes place when the crack is cycled under variable amplitude loads leading to the development of compressive residual stress in front of the crack tip [6, 7]. The compressive residual stress develops when the subsequent amplitude load is lower than the previous amplitude, and the stress ratio of the subsequent amplitude load is greater than zero [6-8]. The compressive residual stress in front of the crack tip reduces effectively the stress advancing the crack. Even, it causes the retardation of the crack propagation. In this case, the behaviour of the crack propagation will not endanger the integrity of a member because the fatigue life is prolonged by the existence of compressive residual stress in front of the crack tip. However, the variable amplitude load may also develop the tensile residual stress instead of the compressive one in the front of the crack tip. This development of tensile residual stress is caused by the amplitude loads being lower than the previous amplitude loads with the negative stress ratio. The tensile residual stress increases the stress advancing effectively the crack. It leads to the acceleration of crack propagation, and the fatigue life is shortened, thus, this situation may endanger to a safety of a member [4, 5, 8].

In service, besides the variable amplitude load, it is possible that a cracked member is subjected in load conditions in which the load is maintained in a certain level for period of time. If so, because the stress is highly concentrated in the zone in front of the crack tip for period of times, the region will be deformed plastically, and the deformation will increase after elapsed time. The increasing plastic deformation relating to period of time is well known as creep, and in most cases, the creep occurs in the elevated temperature [9]. However, when the stress subjected to a member is high enough, the creep may take place although in room temperature condition [10-14]. Because the deceleration and acceleration crack propagation depend on the residual stress state developing in front of tip, and that development corresponds to the plastic deformation in the zone in front of the crack tip [3-8, 15], hence, a hold time of a cracked member in certain level of static load causes the increasing of plastic deformation in front of the crack tip. The increasing plastic deformation can enhance the residual stress. If the load is continued to cyclic loads, which have lower level load than the previous static load, the crack will be decelerated or accelerated depending on the stress ratio of the cyclic loads.

In the recent study [16], the effect of the hold time of a tensile overload on crack propagation behaviours emerging from the notch root was investigated. In that study the crack propagation behaviour was observed under constant amplitude load with stress ratio zero and negative, respectively after being overloaded in period of times, and the results of the study show that the crack propagation behaviour is affected by the hold time of the overload, and the holding time together with the overload increases the plastic deformation in the zone affected by the overload in front of the notch root. Because the shape of the notch root was maintained to not change, thus, the crack propagation behaviour emerging from the notch was only affected by the residual stress state relating to the plastic deformation. However, the crack propagation behaviours corresponding to variable amplitude loads, such as, an overload are not only affected by the residual stress developing in front of the crack tip, but also associating with the shape of the crack tip after the overload [8]. Because of those reasons, in the present investigation the crack propagation behaviour cycled under constant amplitude load with zero and negative stress ratio, respectively, was investigated after an application of a single tensile overload held in period of time.

2.Methods

To know the crack propagation behaviour following the single tensile overload combined with the hold time, in the present investigation, the commercially pure aluminium with 75 and 100 MPa, respectively, for the yield and tensile strength was selected, and the elongation of the material is 40 %. The single edge crack type of specimen was used, and the specimen dimension is 2.3, 40 and 200 mm, respectively, for thickness, width and length. To initiate the crack, the sharp notch with 5 mm in length and 0.3 mm of the notch root diameter was machined on the edge of mid-section of the specimen. The crack length, a, was defined as including the notch length. To observe the crack propagation behaviour before and after the overload, the travelling digital microscope with magnification up to 250x was used. In order to be observable, the surface of specimen on which the crack propagated was polished with an emery paper and a paste of metal polish to obtain mirror like surface.

The specimens were cycled under constant amplitude load before and after the overload. The stress ratio, R, was 0 or -1.5 subjected to the specimen, and it is defined as the ratio of minimum stress, $S_{min.}$, to maximum stress, S_{max}, of the constant amplitude load. The frequency of the constant amplitude load was 10 Hz. An example of the representation of cyclic load pattern is depicted schematically in Fig. 1 for R = -1.5. When the crack length had reached 8 mm, the constant amplitude load was interrupted, and then the overload, S_{ovl}, together with the hold time, H, was applied automatically. Afterward, the constant amplitude load was resumed as before the application of overload. The cyclic load was conducted in the laboratory at room temperature condition by a servo-hydraulic push-pull testing machine.

The testing conditions in the present investigation are shown in the Table. 1. The crack propagation on the specimen only subjected under constant amplitude load without the overload and the hold time for every stress ratio was observed also, and the data obtained from the specimen was defined as the baseline. Because the crack propagation behaviour relating to variable amplitude loads is affected by the residual stress state in front of the crack tip, and the residual stress corresponds to the stress opening level of crack, C_{op}, hence, the stress opening level was determined by aid of the subtracted displacement method [17] in conjunction with the displacement of the notch mouth, h. The extensometer with accuracy 1 μm was attached on the notch mouth to measure the displacement.

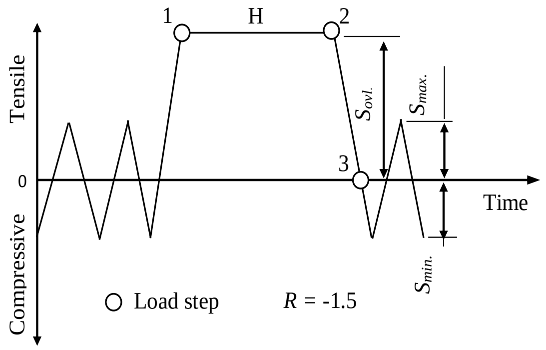


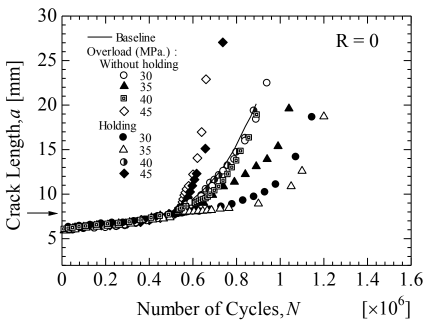
Fig. 1. An example of cyclic load pattern with *R* = -1.5.

Table 1. Testing conditions.

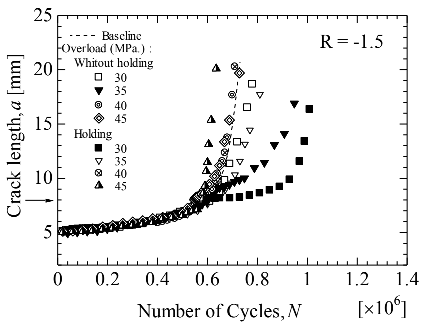
No.	*R*	$S_{max.}$ (MPa.)	$S_{ovl.}$ (MPa.)	*H* (minutes)
1	0	25	0	0
2			30	
3			35	
4			40	
5			45	
6			30	60
7			35	
8			40	
9			45	
10	-1.5	10	0	0
11			30	
12			35	
13			40	
14			45	
15			30	60
16			35	
17			40	
18			45	

3. Results

Figure 2 shows the relation of the crack length, *a*, and the number of cycles, *N*, indicating the fatigue life for stress ratio 0 and -1.5, respectively, in Figs. 2(a) and (b). The arrows in the figure point the crack length when the overload was applied. The similar crack propagation behavior after being overloaded is shown in the figure for both stress ratios if the overload alone was applied. The overload increased the fatigue life. However, when the magnitude of overload was as high as 40 MPa, the effect of overload was not profound and this was almost the same as when the magnitude of overload was 30 MPa for *R* = 0. In that magnitude the fatigue life was almost the same to the baseline for *R* = -1.5. The fatigue life was shorter than that of the baseline as the magnitude of overload was 45 MPa, and in the present investigation the such magnitude of overload shortened the fatigue life not only in -1.5 of stress ratio as presented in the previous study [5, 6, 9] but also in the stress ratio of 0. If the overload together with the hold time was applied, this affected more profoundly to the fatigue life than those without being combined to the hold time. Especially, when the overload was as high as 30 and 35 MPa, the fatigue life was longer than that of the baseline, even in comparison to the cases in which the overload alone was applied in the case of R = 0. When the subsequent stress ratio of the constant amplitude load was -1.5, after being overloaded as high as 35 MPa together with the hold time, the number of delay cycles was lower than that occurs in the 30 MPa of the application overload. The effect of the overload and hold time were almost to not change the fatigue life in comparison to the baseline when the magnitude of the overload was 40 MPa in the case of 0 of stress ratio. However, the fatigue life was not considerably different to the baseline when the following constant amplitude load after the overload was cycled under -1.5 of stress ratio. If the overload in conjunction with the hold period was 45 MPa, the fatigue life was considerably shorter to the baseline on both stress ratios.



(a) *R* = 0

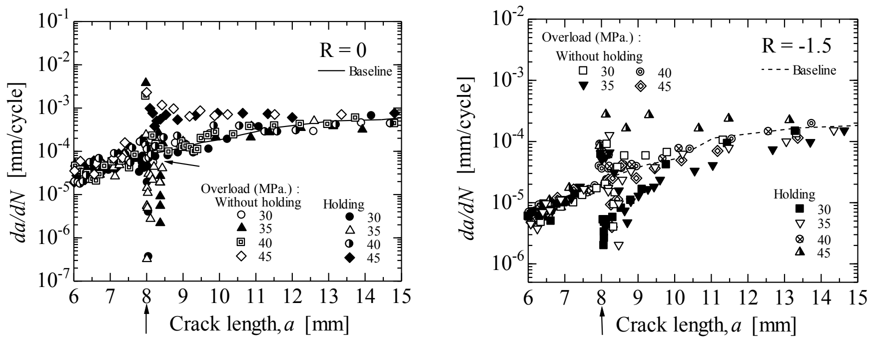


(b) *R* = -1.5

Fig. 2. The relation of the crack length, *a*, and the number of cycles, *N*.

In Fig. 3(a) shows when the R is 0 in which following the overload as indicated by the arrow the crack propagation rate, da/dN, fluctuates depending on the overload magnitude. In the case of the overload without the hold time, the deceleration occurred after being overloaded as high as 35 MPa. For 30 and 40 MPa of the overload as well as the 40 MPa of the overload with the hold time, the fluctuation of the crack propagation rate after the overload was not observed. If the overload was applied as high as 30 and 35 MPa, respectively, together with the hold time, the deceleration also occurred. However, their minimum value of the propagation rate was lower than that takes place in the case of 35 MPa of overload alone. Instead of the deceleration, if the magnitude of the overload was increased to the 45 MPa, the acceleration of the crack propagation rate was observed on both case of overload with and without the hold time. When the stress ratio of the constant amplitude load was -1.5 as shown in Fig. 3(b), the crack propagation rate was decelerated immediately by the overload alone of 30 MPa in very short period before converging to the baseline. When that magnitude of the overload together with the hold time was applied, the minimum value of the deceleration rate was lower than that took place in the 30 MPa of overload alone. When the magnitude of the overload was increased to 35 MPa, although the deceleration was observed, however, the minimum value of the crack propagation rate was higher in comparison to the case in which the magnitude of the overload was 30 MPa and combined with the hold time, thus, fatigue life was lower also.

The crack propagation rate just after the 35 MPa of the overload applied together with the hold time increased the crack propagation rate before immediately decreasing to the minimum rate, and then returning rapidly to the baseline rate. Because of that, the fatigue life was not so much different to that case of 30 MPa of the overload alone. When the magnitude of the overload was as high as 40 and 45 MPa, there was small fluctuation after the application of the overload in very short period in the cases with or without hold period, thus, the fatigue life was almost the same to the fatigue of the baseline. However, there was an exception in the case of 45 MPa of overload with the hold time. In this case, the crack propagation rate accelerated and the crack propagation rate was higher than that of the baseline as shown in the figure, and then the crack propagation rate returned and converged gradually to the baseline. The results of the study show that the hold time of the overload affects the subsequent crack propagation behaviours following the overload.



(a) *R* = 0 **(b) *R* = -1.5**

Fig. 3. The relation of the crack length, *a*, and the crack propagation rate, *da/dN*.

To know the effect of the overload and the hold time to the fatigue life, which is in most cases indicated by the number of cycles after the application of the overload [4-8, 18], in the present study because there are two kind of behaviours following to the overload, thus, Fig. 4 shows the relation of the number of cycles, *N*, and the crack propagation rate, *da/dN*, and the examples how to define schematically the number of delay cycles, N_d and the number of acceleration cycles N_{ac} as introduced in the previous study [4, 5]. With respect to the figure, 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, and N_{ac} is defined as the subtraction of the number of cycles of the overload test from that of the baseline at which the crack propagation rate reached minimum value after applying overload. The number of delay and acceleration cycles represent the fatigue life, which is longer and shorter, respectively, than that of the baseline.

With the same manner as defined in Fig. 4, the number of delay and acceleration cycles, respectively, in every test condition is summarized in Fig. 5. The continue line in the figure represents the expectation line for the application of the overload without the hold time whereas the expectation line for the overload with the hold time is represented by the dashed line. When the overload was applied without the hold time, the increasing of the magnitude of the overload increased the number of delay cycles, and if the magnitude was considerably high, it reduced the number of delay cycles in both cases of stress ratio 0 and -1.5. Even, when the overload alone was applied as high as 45 MPa with R = 0, the acceleration of crack propagation instead of the delay crack propagation occurred following the overload. Because of that, the number of acceleration cycles was used to quantify the number of cycles being lesser than that of the baseline, and it is marked with negative sign as shown in Fig. 5. The hold time of the overload affects the fatigue life. It may decelerate or accelerate the crack propagation depending on the magnitude of the overload.

When the stress ratio of constant amplitude load following the overload with the hold time was -1.5, and the overload level was 40 and 45 MPa, these caused to alter the number of delay cycles to the number of acceleration cycles, which means that the fatigue life becomes shorter than the baseline. The alteration of the number of delay cycles to acceleration cycles also took place in the case of $R = 0$ and 45 MPa of overload, and it was similar to that without the hold time. In contrast to the results of the previous studies that the acceleration of the crack propagation following the overload was observed only when the constant amplitude load after the overload was in negative stress ratio, and it occurred if the magnitude of the overload was high enough [4, 5, 8, 18]. Present study shows that the acceleration also occurs in the case of stress ratio zero. The result of both studies cannot be compared because there are differences relating to the testing conditions, type of materials and type of specimens. In addition, in the previous study the overload was carried manually without considering the effect of the time period during the application of the overload.

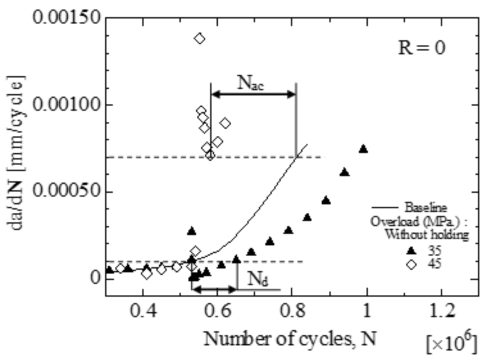
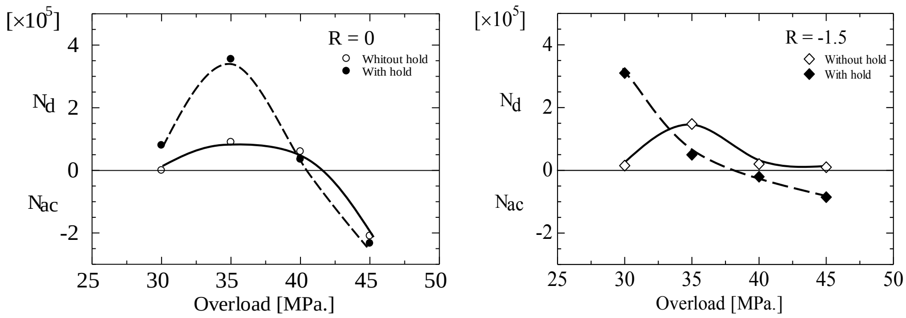


Fig. 4. The Definition of the number of delay and acceleration cycles.



(a) *R* = 0 **(b) *R* = -1.5**

Fig. 5. The effect of the overload and the hold time to number of delay and acceleration cycles.

4. Discussion

The crack propagation behaviours following the overload depend on the residual stress state developing in the zone in front of the crack tip affected by the overload [5-9]. Figure 6 shows an example of plots of subtracted displacement for the specimen with -1.5 of stress ratio and 45 MPa of overload with the hold time in which the crack opening level, C_{op}, and the residual stress state can be determined. The arrows in the figure point when the crack is open on every crack length. Before the crack length had reached to 8 mm in which the overload was carried out, the crack opening level was close to 0 MPa when the crack reached to 7.95 mm in length. However, after the overload and when the crack tip traversed in zone affected by the overload, the crack opening level was lowered by the overload and then returned gradually to the level as before the overload as represented by every arrow on crack length 9.3, 11.47 and 13.3 mm, respectively. The fluctuation of the crack opening level after the overload indicates that the tensile residual stress state developing in front of the crack tip [4-8].

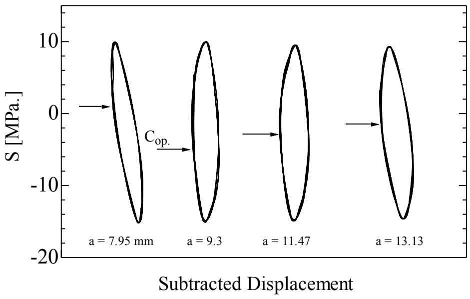
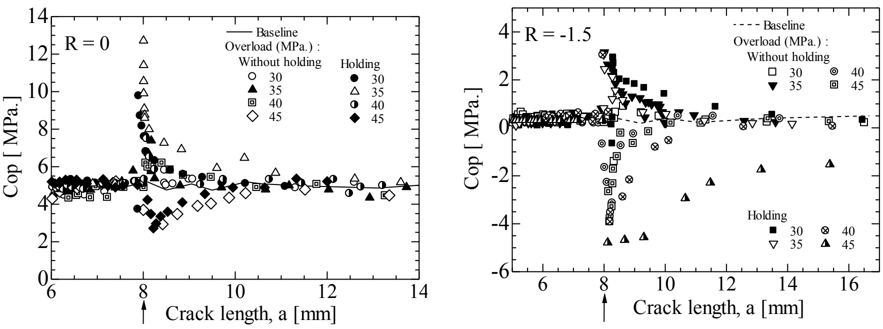


Fig. 6. An example of subtracted displacement method in the case of *R* = -1.5, overload 45 MPa with the hold time.

The variation of crack opening level obtained from the subtracted displacement method is summarized in Fig. 7, and the arrow points the crack length when the overload was conducted. When the stress ratio of the constant amplitude load is 0, the crack opening level of the 35 MPa of the overload with the hold time is higher than that of the baseline, and it is higher in comparison to that of the any other overload levels. The crack opening level gradually returns to the level of the baseline as the crack advances in the zone in which the effect of the overload is not profound anymore. The increasing of the crack opening level, which higher than the baseline indicates that the crack tip traversed in the affected overload zone having compressive residual stress [4-8]. Consequently, it reduces the effective stress advancing the crack, and the delay of the crack propagation takes place. Because of these, the fatigue life stated in the number of the delay cycles on specimen overloaded as high as 35 MPa together with the hold time is the longest.

The tensile residual stress developed in front of the crack tip after being overloaded as high as 45 MPa whether with the hold time or not as indicated by decreasing the crack opening level to be lower than that of the baseline when the crack propagated in the affected overload zone. Because of the tensile residual stress, the effective stress advancing the crack was increase, thus, the crack propagation was accelerated when it propagated in the zone and as the result, the fatigue life was shorter than the baseline. What occurred in the case of the R = 0, it occurred also in the case of R = -1.5. In addition, the crack propagation behaviours following to the overload in the both cases of stress ratio show that the hold time of the overload affects the level of the crack opening level, i.e., in the case of 30, 35 and 40 MPa of the overload, respectively, the hold time increased the level of the crack opening level when the crack tip traversed in the affected overload zone under constant amplitude load of R = 0.



(a) *R* = 0 **(b) *R* = -1.5**

Fig. 7. The variation of crack opening level.

In the previous work [16, 18], the investigation was focused on the crack propagation behaviours emerging from the notch root after being overloaded together with the hold time, and in this investigation the shape of the notch root was maintained to be not changed by the overload. Hence, the crack propagation behaviours emerging from the notch root was affected only by the residual stress conditions in front of the notch root after the overload. However, in the present work, because of the crack tip shape could be changed by the overload, thus, the relation of the crack tip conditions and the crack propagation behaviours after being overloaded was investigated.

The crack tip was observed to be not changed when the magnitude of the overload was as high as 30 MPa, even when the overload was carried out together with the hold time. In that case, the crack propagation behaviour following to the overload was merely affected by the residual stress state in front of the crack tip. Because of that, Fig. 8 shows that the shape of the crack tips, which have been changed by the overload only presented. The figure shows that the crack tip was blunted by the every overload magnitude, and the continue line on the lower and uppers side are the reference lines on the surfaces of the crack used to indicate the displacement of the crack surfaces at the overload or at load step 1 as shown in Fig. 1. The arrows indicate the point on the crack surface observed during the hold period, and the dashed line represents the displacement of the upper side of the crack surface due to the hold time of the overload. When the magnitude of the overload was 35 MPa, the crack tip was blunt at the time of the overload (load step 1), and after elapsing for 30 minutes, the upper side of the crack face displaced as shown by the dash line and arrow.

The displacement was remain unchanged when the hold time of the overload approached to 60 minutes or at load step 2. In this case, with respect to Fig. 7 the state of the residual stress developing in front of the crack tip was in compressive, thus, the residual stress was dominant to affect the crack propagation behaviour in front of that crack tip. Besides that, reinitiating of the crack from the blunted crack tip could increase the number of delay cycles. When the overload was increased to the 40 MPa the displacement increased continuously until to be close to 60 minute, and it was higher than that occurred in 35 MPa case. Although the compressive residual stress developed in front of the crack tip for $R = 0$, however, this was lower than that takes place in the case of 35 MPa of the overload as shown in Fig. 7(a), and it caused the number of delay cycles to be decrease as shown in Fig. 5. Whereas, when stress ratio of the constant amplitude load was -1.5, the displacement altered the residual stress state from compressive to tensile, and it led to the acceleration of the crack propagation following the 40 MPa of overload with the hold time.

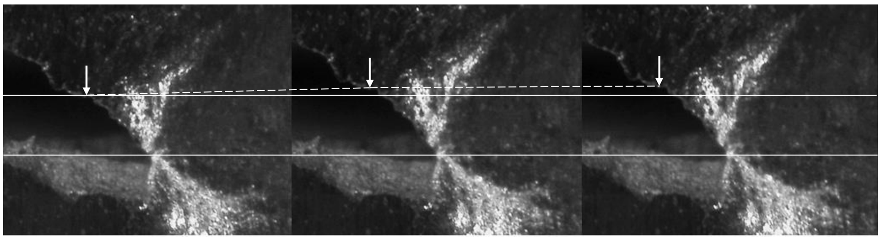
Besides, the upper side of the crack face displaced to be higher than those of previous levels of the overload, when the magnitude of the overload was 45 MPa, the crack advanced at the time of the overload (load step 1) as long as Δa, and the advancement became to be longer as the period of the hold time to be increase as shown in Fig. 8(c).

It is plausible that the Δa led to the tensile residual stress to develop in front of the crack tip after being recycled to the constant amplitude load following the overload as indicated in Fig. 7, and the emerging of the Δa is an indication that the element of the material in the zone affected by the overload could not sustain the stress concentrating in the zone. In addition, this indicates that the plastic deformation occurred in that zone was very high, and because of that upon being recycled to the constant amplitude load with $R = -1.5$, the tensile residual stress developed in that zone as reported in the previous works [8, 19], as the result the stress effectively advanced the crack to be increase, thus, this accelerated the crack propagation.

The acceleration also occurred in the case of 45 MPa of the overload with $R = 0$ whether with the hold time or not. It was caused by the maximum stress of the constant amplitude, S_{max}, which was higher than that with $R = -1.5$, and the tensile residual stress developing in front of the crack tip. Because the effective stress was determined by (S_{max} - C_{op}), thus, the effective stress in the case of $R = 0$ being higher than that occurred in the case of $R = -1.5$. Furthermore, the presence of Δa caused the acceleration of the crack immediately after the overload.

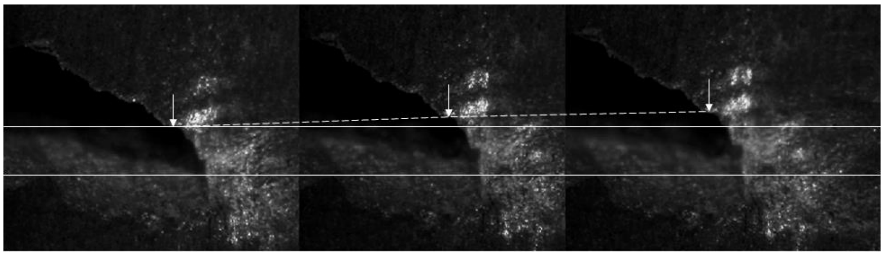
The displacement of the crack faces behind the crack tip corresponds to the plastic deformation taking place in front of the crack tip [8, 16]. It was difficult to measure the displacement of the crack surface behind the crack tip during the overload. To indicate that there was progressive displacement during the hold period in the overload level, the displacement of the notch mouth, *h*, was measured. This displacement was used to know the effect of the magnitude of the overload in conjunction with the hold period to the plastic deformation taking place a head of the crack tip as reported in previous effort [16]. The average of the displacement of the notch mouth is summarized in Fig. 9, and in the left hand side of the dashed line in the figure shows the effect of the hold time during the overload to the displacement for every magnitude of the overload. In the right hand side of the dashed line and as pointed by the arrow shows the displacement after being unloaded from the overload level to the zero load or at the load step 3 as shown in Fig. 1.

The hold time with 0 minutes is used to denote that the overload applied is without the hold time. Because the displacement of *h* corresponds to the plastic deformation in front of the crack tip, hence, the figure indicates that the hold time of the overload may increase the plastic deformation taking place in front of the crack tip, and because the displacement is irreversible as pointed by the arrow in the right hand side of the dashed line, the plastic deformation occurring in front of the crack tip relating to the hold time of the overload. The plastic deformation causes the development of the residual stress in front of the crack tip following the overload [4-8]. Consequently, the residual stress state in front of the crack tip on which the overload was carried out depending also to the hold time and the shape of the crack tip or the displacement of the crack face, besides the stress ratio condition of the constant amplitude load after the overload and the magnitude of the overload.



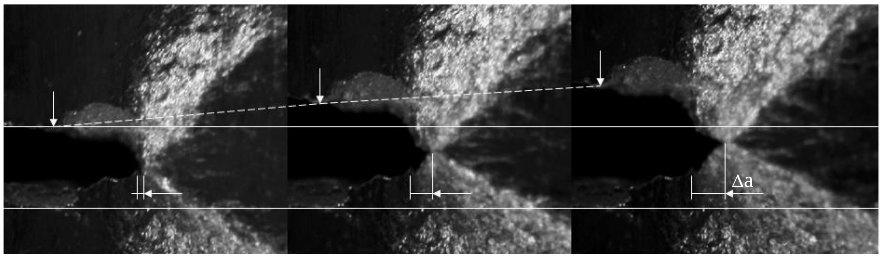
I II III 0.2 mm

(a). Overload 35 MPa, *R* =-1.5; I. Overload,
II. After 30 minutes, III. Approaching 60 minutes



I II III

(b). Overload 40 MPa, *R* =-1.5; I. Overload,
II. After 30 minutes, III. Approaching 60 minutes



I II III

**(c). Overload 45 MPa, *R* =-1.5; I. Overload,
II. After 30 minutes, III. Approaching 60 minutes**

Fig. 8. The examples of the crack tip shape during the overload.

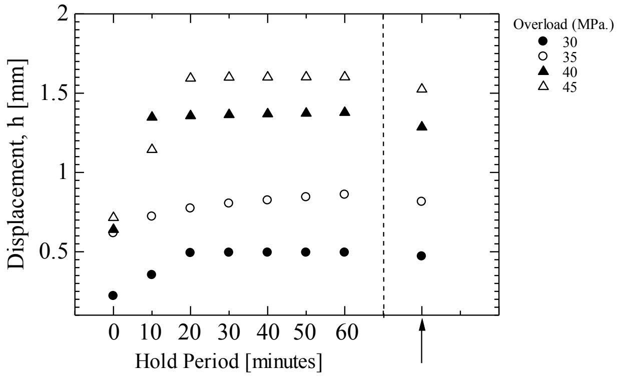


Fig. 9. The summary of the displacement of the notch mouth, *h*.

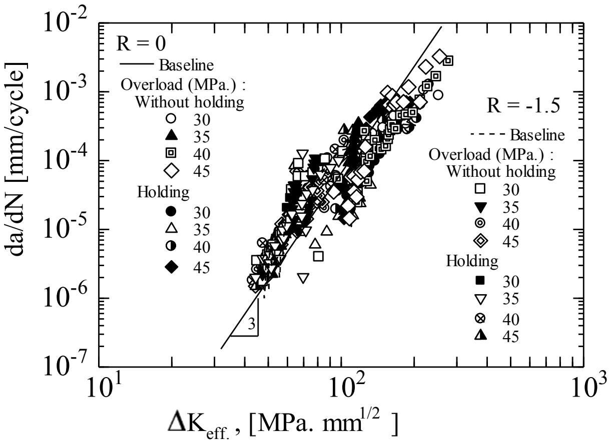


Fig. 10. The relation of the $\Delta K_{eff.}$ and *da/dN*.

It is well known that to evaluate the fatigue life associating with the crack propagation behaviour under variable amplitude load condition, the relation of crack propagation rate, *da/dN*, and the stress intensity factor effective range, ΔK_{eff}, plotted in log scale is used as shown in Fig. 10 [4-8]. The effective stress intensity factor range is the stress intensity factor advancing the crack effectively during the cyclic load, and it is determined by the reduction of the K_{max} by the K_{op}, in which the previous stress intensity factor is determined by the stress of the maximum constant amplitude load, S_{max}, and the former one is the stress intensity factor when the crack begin to open, C_{op}. With respect to the figure, it is found that the relation of the effective stress intensity factor and the crack propagation rate is independent to the kind of stress ratios and the magnitude of the overload as well as the holding time of the overload, and it almost coincides with the expected tendency as indicated by the continue line in the figure. The relation in Fig. 10 shows a good agreement to the previous works [4-8]. Therefore, the relation may be used to assess the fatigue life of members or structures associated with the crack propagation under variable amplitude loads whether there is involvement the hold time of the overload or not. In addition, if the expected line is stated in the Paris equation [20] associating with the crack growth rate in which the Paris constant and exponent, respectively, for all loading conditions is close to 10^{-9} mm/cycle and 3.

5. Conclusions

Some conclusions from the present study are given below.

- The number of delay and acceleration cycles, deceleration and acceleration of the crack propagation depends on the magnitude and the hold time of the overload as well as the stress ratio of the constant amplitude load following the overload.
- The hold time of the overload affects the residual stress state as indicated by the fluctuation of the crack opening level when the crack traversed in the zone affected by the overload in front of the crack tip.
- The propagation of the crack is delayed by the overload if the compressive residual stress develops in the zone affected by the overload in front of the crack tip.
- If the tensile residual stress develops in that zone, the crack is accelerated, and the fatigue life is shortened by the overload as indicated by the number of the acceleration cycles.
- The shape and the displacement of the crack tip affect the residual stress condition in front of the crack tip, and the crack can be advanced by the hold time of the overload, thus, it also enhances the acceleration of the crack propagation following the overload.

Nomenclatures

a	Crack length
C_{op}	Stress opening level of crack
da/dN	Crack propagation rate
H	Hold time, s
h	Displacement of the notch mouth
K_{max}	Maximum stress intensity factor
K_{op}	Stress intensity factor when crack begin to open
N	Number of cycles of constant amplitude load
N_{ac}	Number of acceleration cycles of constant amplitude load
N_d	Number of delay cycles of constant amplitude load
R	Stress ratio
S_{max}	Maximum stress of constant amplitude load
S_{min}	Minimum stress of constant amplitude load
S_{ovl}	Overload stress
Greek Symbols	
Δa	Advancing crack during overload
ΔK_{eff}	The effective stress intensity factor range

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