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The effect of Hold Time of Overload on Crack Propagation Behavior Emerging from Notch Root

In the present study the crack propagation behavior under constant amplitude loads emerging from the notch root after being overloaded and held in a certain period of time was investigated. When the stress ratio of constant amplitude load is zero, the longer period of hold time of the overload increases the number of delay cycles and decelerates the crack propagation emerging from the notch root. However, the number of delay cycles is reduced by the increasing of the hold time period, and the acceleration of the crack propagation was observed immediately after emerging from the notch root when the stress ratio is -1.5. The magnitude and the period of the hold time of the overload as well as the stress ratio of the constant amplitude load condition following the overload are responsible for the residual stress state in front of the notch root affecting the crack propagation behavior.

Keywords: *hold time, overload, crack propagation, notch root, fatigue life.*

1. INTRODUCTION

In a structural design, generally, but not always, the existence of defects or flaws such as cracks or crack likes in a material is considered to determine whether a material can withstand load or not. The linear elastic fracture mechanics (LEFM) method is common to be used in that circumstance, and a residual strength of a material can be known. In addition, although the presence of crack in a component is not detected, with this method to improve a safety of structure integrity the presence of crack can be assumed [1]. Furthermore, by that method an estimation of life time of the components in the structures associating with the fatigue crack propagation can be determined. In the case of constant cyclic load, the life time estimation can be conducted by the aid of equation proposed by Paris and Gomes [2]. However, if the crack propagates under variable amplitude loads, the difficulties are often to be encountered because the crack propagates in an uncertain rate. It may decelerate or accelerate [3-8]. Hence, the accurate estimation of life time based on that equation cannot be obtained.

The deceleration or acceleration of fatigue crack propagation under variable amplitude loads is caused by mechanisms relating to the crack tip blunting, crack deflection, residual stress in front of the crack tip, plasticity-induced crack closure and roughness-induced crack closure [9-12]. However, among these mechanisms, the residual stress state ahead of the crack tip plays major role in the crack propagation behavior [4-7, 11, 12]. It has been well known that if the residual stress in front of the crack tip is in a compressive state, the crack propagation is retarded, and the crack propagation decelerates. This condition delays the life time of a cracked component under the cyclic load [3, 4, 12]. On the other hand, if the compressive residual stress in front of the crack tip alters to the tensile state, the crack propagation accelerates, and the fatigue life becomes shorter. This occurrence will endanger the safety of the structure [5-7].

The discontinuities in the components of the structures are not only cracks or crack likes, but also, they may be in form of other types, for example, holes, fillet, notch, etc., and these can concentrate stress in the vicinity of the edge of them. Hence, it leads to initiating a crack from those discontinuities. The crack propagation behavior emerging from the sharp notch root under variable amplitude load, such as overload had been confirmed, and it shows that the crack propagation behavior depends on the residual stress state in front of the notch root [13-15]. The compressive residual stress develops in front of the notch root after the notch was overloaded, and the residual stress reminds in a compressive state when it was cycled under constant amplitude loads with the stress ratio zero. If the stress ratio following the overload was in negative stress ratio, the tensile residual stress instead of compressive residual stress developed in front of the notch root, and as consequent the crack propagation accelerated rather than decelerated.

Since most components of structures are experienced in time-varying sequences of load fluctuations, it is important to know any type of crack propagation behaviors under that type of loads in order to obtain better estimation of the fatigue life. Many efforts have been conducted to understand the propagation behavior of crack under variable amplitude loads. However, most of them are associated with the crack propagation behavior after an overload or underload, as well as combination of them with varying sequences [5, 6, 13-15]. Besides the fluctuation of loads, it is possible that a component of structure is subjected

Received: March 2015, Accepted: October 2015
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doi:10.5937/fmet1601050P

to a certain level of load within some periods of time [16], and it may cause plastic deformation on the material of the component although the load is lower than the yield strength of the material. This phenomenon is well known as plastic deformation-time dependent or creep. If there are stress concentration sites, such as a notch, in the component of structure, those sites are potential to undergo creep. Although the creep occurs generally in a material subjected to high temperature environment [17], the phenomenon of creep may also be observed in the room temperature condition, even in a high strength material [18- 20].

The crack propagation behavior emerging from the notch root is affected by the residual stress state in front of the notch root in which the development of the residual stress relates to the material deforming plastically [13]. In the previous work, it has been found that a single tensile overload affects the behavior of crack propagation emerging from the notch root depending on the stress ratio of a constant amplitude load following the overload. In this work, the overload was applied manually before being cycled in constant amplitude load, and the periods of the overload were not taken into consideration [13]. The region in which stress concentration occurs such as in front of the notch root, may be vulnerable to be plastically deformed, and because the plastic deformation is also time-dependent, the plastic deformation may be enhanced by loads held in some periods of time. Therefore, in the present work, the effect of the hold time together with the magnitude of the overload to crack propagation behavior emerging from the sharp notch root will be confirmed under the room temperature condition.

2. EXPERIMENTAL METHOD

In the present work, the material selected was commercial aluminum. The mechanical properties of the material are 100 and 140 MPa. for yield strength and ultimate tensile strength, respectively, and the elongation is 15 %. Fig. 1 shows schematically the shape of a specimen, and its dimension is 220, 40 and 3 mm, respectively, for length, width and thickness. The single sharp notch with 0.3 mm of notch root diameter and 5 mm in length was cut on the edge of a mid-section of the specimen. The crack length, *a*, was defined as including the notch length. To observe the crack propagation behavior on the surface of a specimen, the traveling digital microscope with accuracy 10 μm was used. In order that the crack propagation be observable, the surface of specimen was polished with an emery paper and a paste of metal polish to obtain a mirror like surface.

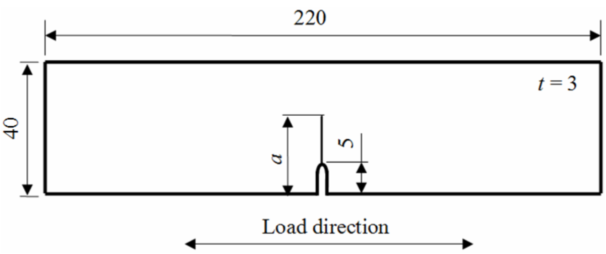

Figure 1. The shape of specimen

Figure 2 depicts schematically the representation of a cyclic load pattern when the stress ratio of the constant amplitude load, *R*, is -1.5. The stress ratio is defined as the ratio of minimum stress, $S_{min.}$, to maximum stress, $S_{max.}$, of constant amplitude load, and $S_{ovl.}$ is the overload stress. The specimens were cycled under constant amplitude load after being overloaded and held in some periods of time. The hold time period of the overload is denoted as *H*. The experiment was conducted in the laboratory at room temperature condition by a servo-hydraulic push–pull testing machine, and the frequency of the constant amplitude load was 10 Hz.

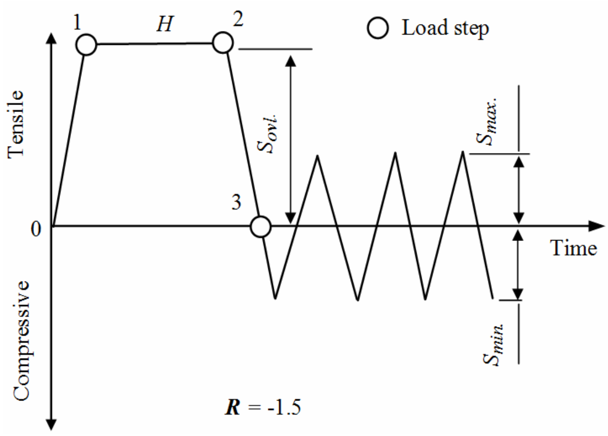

Figure 2. The representation of cycle's pattern with *R* = -1.5

Table 1 shows the testing conditions in the present study. The tests were also carried out on the specimens without the overload, and the data obtained from them in the experiment was defined as the base. Because the crack propagation behavior after overloading depends on the residual stress associated with the stress opening level of crack, Sop, hence, the stress opening level was determined by measuring the displacement of the notch mouth, V, in conjunction with the subtracted displacement method [21]. The displacement was measured by attaching an extensometer with accuracy 1 μm on the notch mouth.

Table 1. Testing conditions

No.	R	$S_{max.}$ (MPa.)	$S_{ovl.}$ (MPa.)	H (minute)
1	0	30	0	-
2			60	0
3				5
4				15
5				30
6			86	45
7	-1.5	25	0	-
8			60	0
9			86	0
10				15
11				45

3. RESULTS

Figure 3 shows that the magnitude of the overload and the hold time affect the crack propagation behavior emerging from the notch root when the stress ratio of the constant amplitude load is zero. The left hand side of the figure shows the relation of crack length, *a*, and the num-

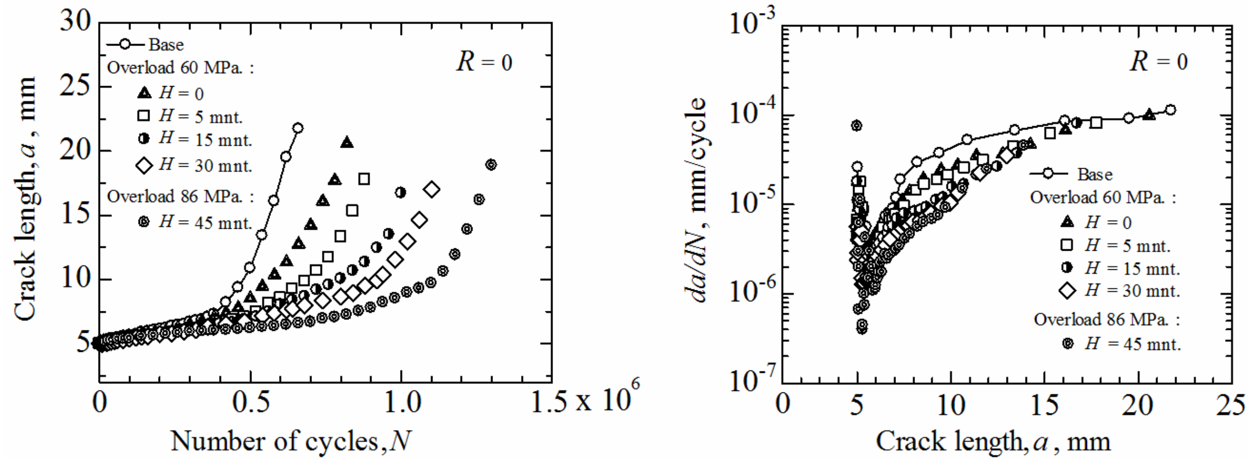

Figure 3. The crack propagation behavior under *R* = 0

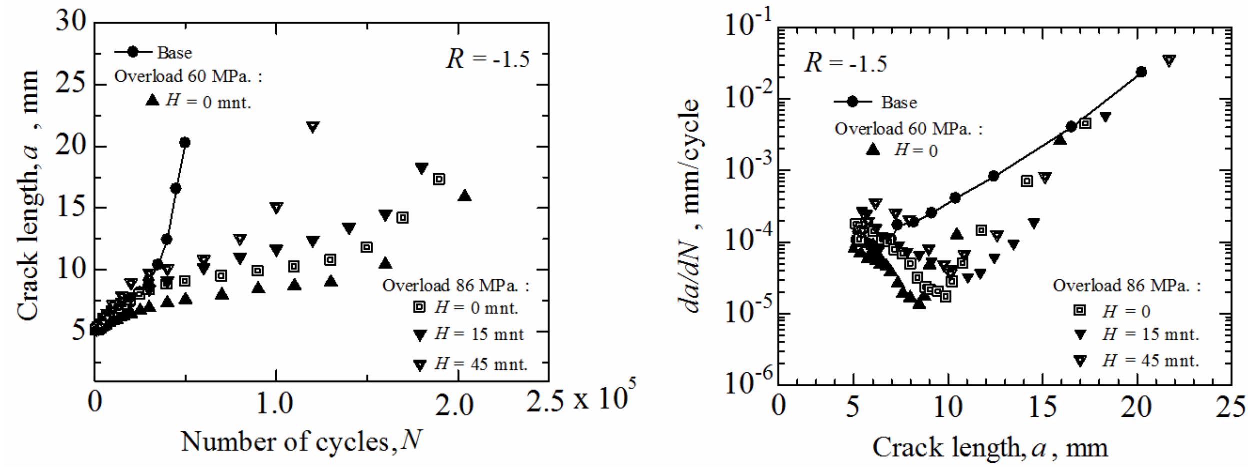

Figure 4. The crack propagation behavior under *R* = -1.5

ber of cycles, *N*. It can be seen that the common phenomenon of the retardation occurs as in previous study, and the fatigue life became longer than that of the base [3, 4, 11]. In addition, although the magnitude of the overload is the same, the fatigue life can be increased by holding the overload for a longer period of time, *H*. The retardation of the crack propagation emerging from the notch root relates to the rate of crack propagation, *da/dN* as shown on the right hand side of the Fig. 3. It can be seen in all specimens that just after emerging from the notch root, the crack propagation decelerates to its minimum rate, and then accelerates gradually after the crack propagates at some distances in front of the notch root. The lower minimum of crack propagation rate was observed in a higher magnitude of the overload, and the longer period of the hold time lowers the minimum rate of the crack propagation. On the specimen with the overload magnitude, it is as high as 86 MPa., and the period of the overload is 45 minutes. Although it is initiated by the acceleration of the crack propagation, the crack propagation decelerates immediately to its minimum rate, which is lowest in comparison to the other before gradually converges to the base rate, and this causes the fatigue life of the specimen to be the longest.

In the previous efforts [5-7, 13] when the subsequent constant amplitude load after overloading was cycled under the negative stress ratio, the effect of the overload reduced the retardation, and even it might accelerate the crack propagation emerging from the sharp notch root, it shortened the fatigue life. In the present work, the acceleration of the crack propagation causing fatigue life becomes shorter, but the base was not observed. This cannot be compared to the previous efforts because of the differences of the specimen type, material and load conditions. In spite of that, the same phenomenon occurs as in previous efforts, that is, the increasing of the overload magnitude reduces the number of cycles of retardation if the constant amplitude following the overload is in the negative stress ratio as shown on the left hand side of the Fig. 4 in which, in this case the stress ratio of constant amplitude load is -1.5. Besides that, the figure shows that the hold time period of the overload affects the fatigue life although the level of overload is the same, and the increasing of the hold time period leads to the reduction of the fatigue life. In addition, the right hand side of the figure shows that when the magnitude of the overload is 86 MPa, there is a period of the acceleration of the crack propagation immediately after emerging from the notch root. This period becomes longer if the overload is held for a longer period of time. Afterward, the crack decelerates to the minimum rate and then it increases gradually and converges to the base rate.

The number of delay cycles, ND, is often to be used to quantify the effect of overload to fatigue life [3-7, 13]. Fig. 5 shows the schematic representation of the method of determining ND. Because the present work shows that the hold time of the overload influences the fatigue life, hence Fig. 6 shows the relation of the number of delay cycles to the hold time of the overload. This indicates that the number of delay cycles is affected by the hold time period, H, the stress ratio, R, and the magnitude of the overload, Sovl. In the case of R = 0, the number of delay cycles is increased by the hold time period and the magnitude of the overload. On the other hand, in the case of R = -1.5 the number of delay cycles is lowered by the increasing of the hold time period of the overload. Due to this phenomenon, the hold time of the overload had to be also taken into consideration to estimate the fatigue life of components relating to the fatigue crack propagation behavior.

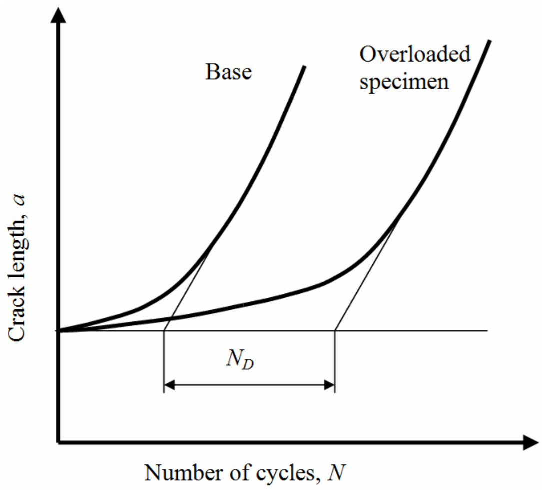

Figure 5. Definition of the number of delay cycle, N_D

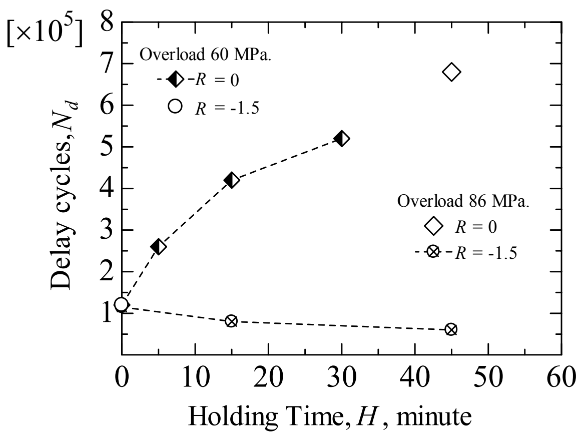

Figure 6. The number of delay cycles, N_D vs. The hold time of overload, *H*

Besides the magnitude of the overload, the result of this study demonstrates that the overload held for some period of time influences the following crack propagation behavior. Due to the fact that plastic deformation is time dependent, even at room temperature [16-20], it may enhance the plastic deformation in the overload-affected zone ahead of the notch root. If so, the hold time affects the residual stress state in that zone, and the crack opening level of the crack will vary depending on the residual stress state. Consequently, these lead to the crack propagation behavior to decelerate or accelerate. The relation between them will be discussed in detail in the following section.

4. DISCUSSIONS

Because the plastic deformation in the front of the notch root is time dependent, and it will affect the crack propagation, hence, the deformation in the vicinity of it was observed. Figure 7 shows an example of the result of observation on the specimen overloaded as high as 86 MPa. and held for 45 minutes. The plastic deformation is indicated by the displacement of the upper side of the notch surface, as shown between two white dash lines in the figure. The white arrow points the metal polish paste being left behind in the notch after the polishing process of the specimen surface. With respect to the load steps as depicted in the Fig. 2, the Fig. 7a shows the notch root condition before being overloaded. In the load step 1 the upper side of the notch surface is displaced by the overload as shown in the Fig. 7b. After being held for 45 minutes or in load step 2 the displacement increases, and the upper side of the notch almost coincides with the upper white dash line as shown in the Fig. 7c. In the load step 3 when the load is zero, the displacement of the upper notch surface returns to neither the position as before being overloaded nor as to the position of the load step 2. The displacement of notch surface is an indication that plastic deformation occurs after being overloaded and held in a certain period of time. In addition, the figure shows that the shape of the notch does not change after being overloaded, thus, the crack propagation behavior emerging from the overload is not affected by the notch shape condition, but only by the plastic deformation taking place in front of the notch root.

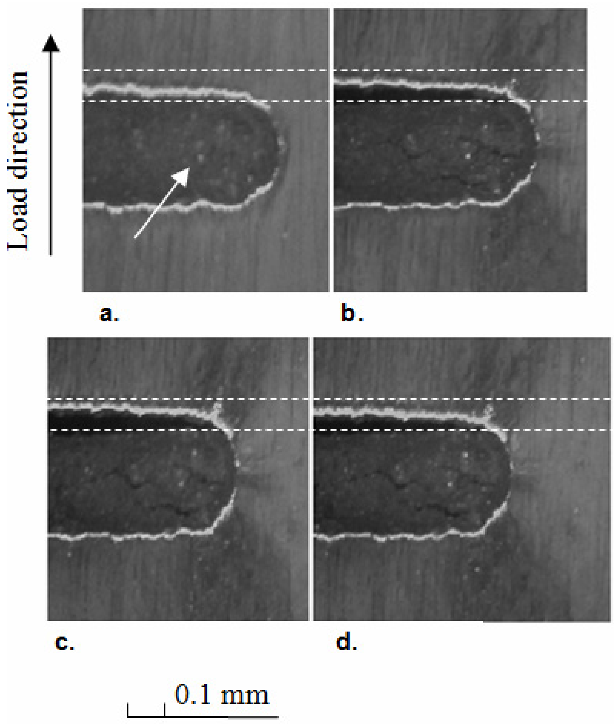

Figure 7. The development of displacement notch face on the specimen with overload 85 MPa., *H* = 45 minute, and *R* = -1.5: a. Before overloading, b. At the load step 1, c. At the load step 2, d. At the load step 3.

For convenience, instead of displacement measurement in the vicinity of the notch root, the measurement of the displacement was carried out based on the displacement of the notch mouth on the edge of the specimen to indicate deformation taking place in front of the notch root. Fig. 8 shows the relation of the displacement of the notch mouth to the hold time period of the overload. The solid plots indicate the averages of the displacement development when the specimens were overloaded as high as 60 MPa. and 86 MPa., respectively. It can be seen that the displacement is increased by the hold time period of the overload. After being unloaded to zero load or in load step 3, as shown in the Fig.2, the displacement is irreversible, and the upper surface of the notch remains displaced in the load direction to some fraction of millimeters, depending on the magnitude of the overload and the period of the hold time. The irreversible displacement is an indication that the element material in front of the notch root is plastically deformed, and it causes the development of the residual stress in front of the notch root. This will influence the crack propagation behavior emanating from the notch root.

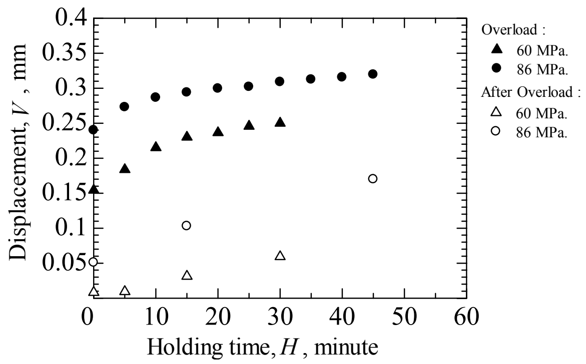

Figure 8. The development of crack mouth displacement

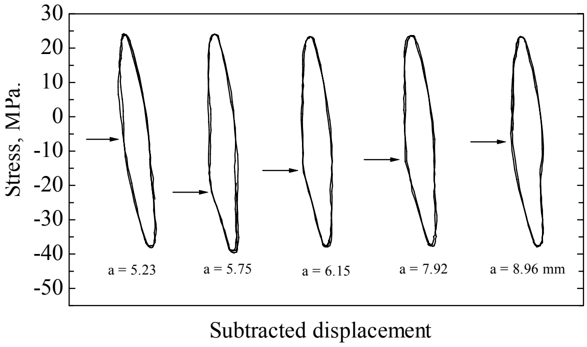

Figure 9. An example of subtracted displacement method in the case of *R* = -1.5, overload 86 MPa. and *H* = 45 minute

The presence of the residual stress in front of the notch root relates to the crack opening level, Sop, which may decelerate or accelerate the crack propagation [3-13]. The Fig. 9 represents an example plot of subtracted displacement method in which the crack opening level can be determined on the specimen with the stress ratio -1.5, the overload 86 MPa. and 45 minutes for the hold time. The arrows point when the crack is open. The figure shows that the crack opening fluctuates during the crack traversed in the plastically deformed zone in front of the notch root. The results of the subtracted displacement method are summarized for every test condition in the Fig.10.

The Fig.10 shows the variation of the crack opening level after the crack emerged from the notch root and being cycled under constant amplitude load with stress ratio 0 and –1.5, respectively. In the case of R = 0, the crack opening level increases for all cases when the crack just emerged from the notch root, and after reaching the peak level of the crack opening for every specimen, the crack opening level gradually decreased as the crack propagated in the zone in which the overload effect was less pronounced. However, the peak level of the base is the lowest, and the highest is on specimen overloaded as high as 86 MPa. and held for 45 minutes. In addition, when the overload is 60 MPa., the peak of the crack opening level is increased by the hold time period of the overload. In contrast to the former case, in the case of R = -1.5, only on the specimen overloaded as high as 60 MPa. the crack opening level is higher than the base after the crack emanated from the notch root. Because of that, the stress effectively advanced the crack reduction [3, 4], thus the crack underwent retardation and deceleration during the traverse of the affected-overload zone in front of the notch root. In other testing conditions, and those are when the constant amplitude load was initiated by 86 MPa of the overload, the crack opening level fluctuated, depending on the duration of the hold time. The figure shows that after crack emerged from the notch root, the level of the crack opening decreases to their minimum values before converging to the base, and after this the crack opening level increases to be higher than the base in short periods. The minimum value of the crack opening level is the lowest on the specimen overloaded and held for 45 minutes. Because the lower level of the crack opening increases the stress was effectively advancing the crack, thus, casuing acceleration to be observed when the crack emanating from the notch root, and the fatigue life was reduced. When the overload was conducted without the hold time, the fatigue life is longer than that with the hold time. It was caused by the contribution of fluctuation of the crack opening level being higher than the base just after crack emerged from the notch root in a short period.

The present study reveals that retardation of the crack propagation behavior associated with the variable amplitude load, such as overload, is induced not only by the magnitude of the overload and the stress ratio of the constant amplitude load condition following the overload as stated in the previous studies [3-13], but also by the hold time period of the overload. The hold time leads to enhancing the element material in front of the notch root to be plastically deformed, and upon unloading to zero loads from the overload the element material is not recovered, as shown in the Fig.7 & 8. The unrecovered material in front of the crack tip is indicated by the notch mouth displacement, which is neither recovered after being unloaded to zero loads. The plastically deformed element material in front of the notch root affects the residual stress state after being cycled in the constant amplitude load, thus the fatigue life associated with the crack propagation is affected, too. Figure 11 shows the relation of unrecovered displacement on the notch mouth, *Vp*, after being unloaded from the overloading and holding to the fatigue life stated in the number of delay cycles. The figure indicates that the number of delay cycles increases as the displacement increases when the stress ratio, *R*, is zero. On the other hand, if the stress ratio is -

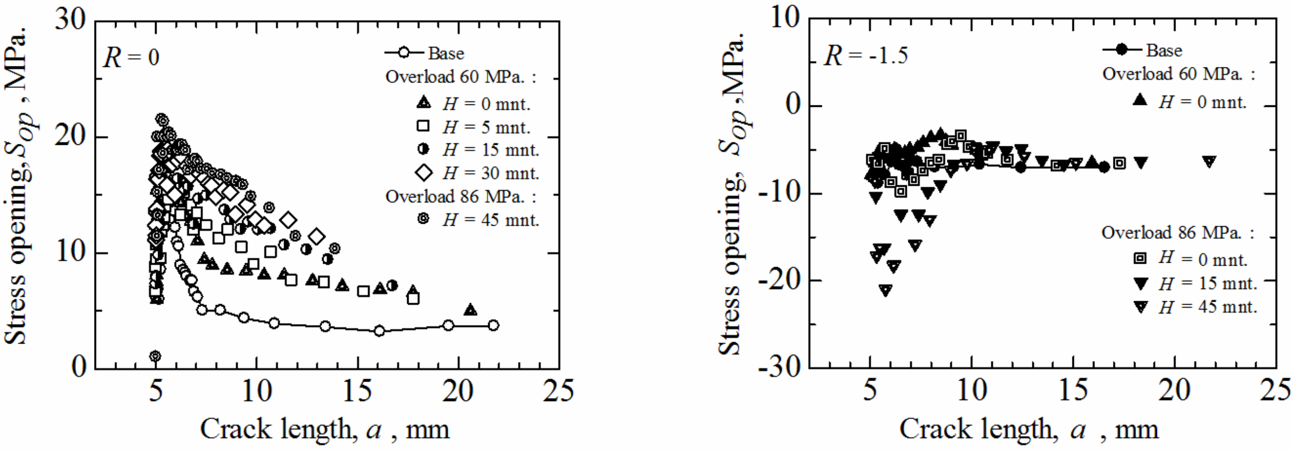

Figure 10. An example of subtracted displacement method in the case of R = -1.5, overload 86 MPa. and H = 45 minute

1.5, the number of delay cycles decreases as the displacement increases. Because the period of the hold times increases the displacement, it can be stated that the hold time causes two effects being contradictive, and those are the increasing and decreasing the number of delay cycles, respectively, when the stress ratio of constant amplitude is 0 and -1.5. Therefore, it is important to take into consideration the hold time period of the overload in estimation of fatigue life relating to the crack propagation because it may be responsible for integrity of a structure.

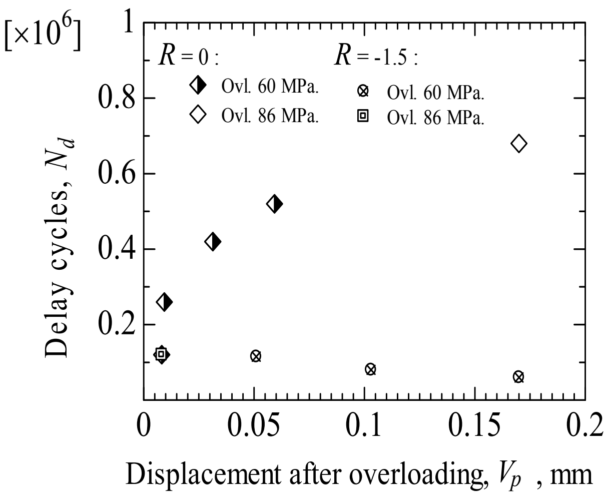

Figure 11. The displacement of crack mouth after overloading Vs. The number of delay cycles

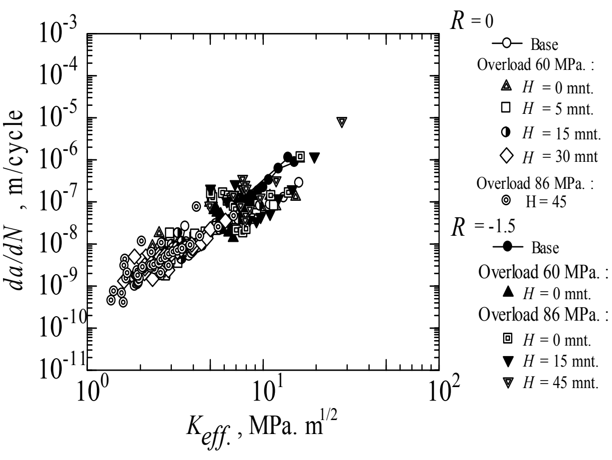

Figure 12. *da/dN* Vs. K_{eff}

The maximum stress intensity factor, $K_{max.}$, in conjunction with the rate of crack propagation is common to be used to assess a fatigue life as proposed by Paris, *et. al.*[2]. However, if it is used to assess the crack propagation cycle under variable amplitude load, the non-conservative result is obtained. The effective stress intensity factor, K_{eff}, instead of the maximum stress intensity factor, is used to improve the assessment of fatigue life [3-7, 9-13], and it is found that the relation of the effective stress intensity factor and the rate of crack propagation is independent of the variable amplitude load [3-7]. Figure 12 shows that the relation is not only independent to the kind of amplitude loads but also independent of the hold time of the overload. The value of $K_{eff.}$ is defined as $K_{max.}$ - $K_{op.}$, where $K_{op.}$ is the stress intensity factor at the crack opening level, $S_{op.}$. Therefore, the relation may be used to evaluate a fatigue life of a component associatied with the crack propagation.

5. CONCLUSION

The hold time and the magnitude of the overload together with the following constant amplitude load condition after overloading affect the crack propagation behavior emerging from the notch root. The plastic deformation in front of the notch root increase, as the hold time period and the magnitude of the overload increases, and the compressive residual stress develops upon unloading to zero load from the overload in front of the notch root.

The compressive residual stress is indicated by the variation of the stress crack opening levels being higher than the base as the crack tip traverses in the overload-affected zone under constant amplitude load with stress the ratio 0, and because the stress crack opening level increases, the stress advances effectively, the crack is reduced, and the crack propagation rate decelerates and the fatigue life becomes longer than the base.

When the stress ratio is -1.5, the compressive state of the residual stress is altered to the tensile state. In this case, the stress crack opening level is lower than the base at some distances in front of the notch root before gradually converging and being higher than the base. The lower crack opening level increases the effective stress, which is responsible for the acceleration of the crack propagation and the reduction of the number of delay cycles. In addition, the relation of the effective stress intensity factor and the rate of crack propagation is independent of the hold time period and the magnitude of the overload as well as to the stress ratio of constant amplitude load following the overload.

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УТИЦАЈ ВРЕМЕНА ЗАДРЖАВАЊА ПРЕОПТЕРЕЋЕНОСТИ НА ТОК ШИРЕЊА ПРСЛИНЕ НАСТАЛЕ УСЛЕД ЗАОБЉЕНОСТИ УРЕЗА

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Рад се бави истраживањем тока ширења прслине, у условима оптерећења константне амплитуде, настале код заобљености уреза после преоптерећења и његовог трајања у одређеном временском периоду. Када је интензитет напона при оптерећењу константне амплитуде једнак нули, дужи период трајања преоптерећења повећава број циклуса кашњења и успорава ширење прслине изазване заобљеношћу уреза. Међутим, број

циклуса кашњења се смањује са повећањем периода задржавања преоптерећења и брже ширење прслине се уочава одмах после настанка заобљености уреза при интензитету напона од –1,5. Интензитет и период задржавања преоптерећења, као и интензитет напона у условима оптерећења константне амплитуде праћеног преоптерећењем су узроци стања заосталог напона испред заобљеног уреза који има утицаја на ток ширења прслине.