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THE EFFECT OF THE HOLD PERIOD OF A SINGLE TENSILE OVERLOAD TO THE NUMBER OF DELAY CYCLES IN FRONT OF THE CRACK TIP

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ABSTRACT

The effect of a single tensile overload held in certain period was investigated on the crack propagation behaviour in front of the crack tip following the overload. The investigation was conducted by cycled the specimens under constant amplitude load with stress ratio to be zero, and after the crack had reached in certain length, the overload with and without combination of the hold period was subjected to specimens, respectively. The stress analysis in front of the crack tip was carried out by aid of software based on the finite element method. The result of the investigation shows that the hold period of the overload together with the magnitude of the overload affects the crack propagation behaviour following the overload. The compressive residual stress developing in front of the crack tip after the overload causes the retardation of the propagation of the crack, and then the number of delay cycles increases. The development of the residual stress associates with the plastic strain of the element material in front of the crack tip caused by the overload, and the strain is increased by the hold period of the overload. However, the increasing of the plastic strain may lead to the crack tip to be blunt, and it reduces the effect of the compressive residual stress to the crack propagation behaviour, thus, it decreases the number of delay cycles. In addition, because the hold period increases the plastic strain, upon unloading to zero load the plastic strain stretching to the overload direction is too high, and it reduces the magnitude of the compressive residual stress. Therefore, the hold period reduces the number of delay cycles after the overload.

Keywords: tensile overload, hold period, crack propagation, crack tip, delay cycles.

1. INTRODUCTION

It is well known that the fatigue life relating to the crack propagation of a member of a structure may be estimated by using linear elastic fracture mechanics (LEFM) method [1]. This method is only valid when the plastic zone size in front of the crack tip is considered to be small in comparison to the crack length [1], and the conservative result will be obtained when the crack propagates under constant amplitude load. However, in service, most of members of structures are often to be loaded in variable amplitude load [1], and it leads to the propagation of the crack to be uncertain because the plastic zone size developing in front to the crack tip to be varies also. There are two crack propagation behaviour causing the uncertainty, those are, the retardation or deceleration and the acceleration of the crack propagation. In the case of the retardation, the fatigue life becomes longer than that expected in which the estimation is made to base on the constant amplitude load. In contrast to the previous case, the acceleration of the crack propagation shortens the fatigue life [2-6]. This case may endanger the integrity of a structure due to the fatigue life to be shorter than the expectation.

There are several factors affecting the crack propagation behaviour, those are, crack tip blunting, crack branching, residual stress developing in front of the crack tip, plasticity-induced closure and roughness-induced closure. However, among the factors, the residual stress condition in front of the crack tip plays the mayor role in the behaviour of the crack propagation [2-7]. If the condition of residual stress in front of the crack tip is compressive, the crack propagation is retarded, hence, the fatigue life is increased [2, 3]. Instead of retardation, the crack propagation is accelerated when the crack tip traverses region in front of the crack tip in which the residual stress condition is tensile, and it lead to the fatigue life decreases [4-6].

The residual stress condition in front of the crack tip may be caused by the variable amplitude load. In this type of load, it is very possible that a cycle load is higher than the following load, thus, this causes the development of the residual stress in front of the crack tip, and the crack propagation will be affected by the residual stress condition [1-7]. The investigation crack propagation behaviour associating with the variable amplitude load has been conducted, and most of them are focused on the crack propagation behaviour following an overload [2-10]. The development of compressive residual stress in front of the crack tip causes the effective stress, which is responsible to advance the crack to be reduced, and this leads to the propagation of the crack to be retarded [2, 3, 7, 9, 10]. The compressive residual stress developing in front of the crack tip is caused by plastic strain taken place during overloading, and because the deformation is irreversible, hence, upon unloading to zero load the deformation is still in the overloading direction. This causes the compressive residual stress develops in the zone in front of the crack tip, and it is well known as the plastic zone [2, 3]. If after the overload, the cyclic load is continued under constant amplitude load with stress ratio being zero, the crack tip will traverse in the zone in front of the crack tip in which the condition of residual stress is compressive [2, 3]. However, if the subsequent constants amplitude after the overload is in negative stress ratio, the

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residual stress condition in front of the crack tip is altered to become tensile. The alteration occurs due to the residual compressive stress zone developing after the overload is in further compressive when the load is continued to the minimum load of the constant amplitude load with negative stress ratio. This lead to the compressive stress in the plastic zone is higher than elsewhere, and the element material in this zone become yielding. The yielding causes lateral contraction of the element material, as the result upon unloading to zero load from the minimum load of the negative stress ratio the tensile residual stress develops in the plastic zone [4-6, 8].

The plastic strain that develops in front of the crack tip is the key factor determining of the crack propagation behaviour. Hence, the any factors that cause the plastic strain in front of the crack tip will affect the behaviour of the crack propagation. The plastic strain is not only caused by an excessive load such as a single tensile overload, but also it may cause by relatively low load in certain period of time [11, 12], and the plastic deformation is dependent of time. The plastic deformation depending to the time is known as creep. In general creep occurs in metals exposed in the environment with elevated temperature [12]. However, the creep may take place in the room temperature on metal, even this phenomenon is observed in high strength metal [13- 15]. In the previous efforts [16, 17], the relation of the creep to the crack propagation behaviour was studied in the region in front of the notch root. It was found that the plastic deformation in that region increases as the hold period of the overload is longer. Because the plastic deformation is increase, the residual stress developing in front of the notch root is increase also, and as consequent this affects the crack propagation behaviour. In addition, the hold period of the overload prolongs the retardation cycles due to the increasing of the magnitude of the compressive residual in front of the notch root.

The crack propagation behaviour after overloading is influenced not only by the residual stress condition in front of the crack tip, but the shape of the crack tip determines also the crack propagation behaviour [5, 7, 10]. Therefore, in the present work, the effect of the hold period of the overload is studied in the region in front of the crack tip. It is important to know this effect because the crack tip shape may be changed by the increasing of the plastic strain caused by the overload.

2. METHOD OF STUDY

The type of the specimen, in the present study was single edge crack. To initiate the crack, a sharp notch with 5 mm in length and 0.3 mm of the notch root diameter was machined on the edge of a mid-section of the specimen. The shape of the specimen is shown in the Figure-1, and the specimen dimension is 200, 40 and 2.5 mm, respectively for length, wide and thickness. The commercial aluminium was used, and its mechanical properties were 110 and 150 MPa., respectively, for yield and ultimate tensile strength. The elongation of the material was 15%. To observe the crack propagation, the surface of the specimen was polished with an emery paper, and then it was polished by a metal paste in order to obtain a mirror like surface. The measurement of the crack length was conducted by aid of a travelling digital microscope with accuracy 10 μm put on the surface on which the crack was expected to propagate. The crack length, a, was defined as including the notch length.

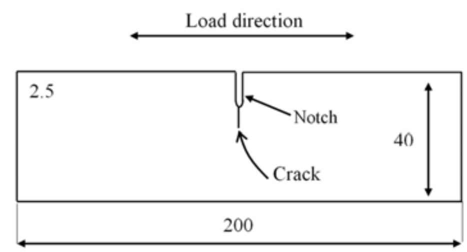

Figure-1. The shape of the specimen.

Table-1 shows the testing conditions in which the all tests were carried under constant amplitude load with stress ratio, R, to be zero. The stress ratio is defined as the ratio of minimum stress, S_{min}, to maximum stress, S_{max}, of the constant amplitude load. The overload, S_{ovl}, and the hold period of the overload, H, were carried when the crack, a, had reached 8 mm. A test was also carried out on a specimen without overloading and the hold period, and this is defined as the base. The environment condition of the test is in the room temperature of laboratory.

Table-1. Testing conditions.

No.	$S_{ovl.}$ (MPa.)	H (minutes)	R	$S_{max.}$ (MPa.)
1	0	-	0	12
2	30	-		
3		60		
4	35	-		
5		60		
6	40	-		
7		60		

Figure-2 shows schematically the representation of the cycles load pattern of the test. The cycles load was conducted by a servo-hydraulic push-pull fatigue testing machine. The frequency of the constant amplitude load was 10 Hz. The overload and the hold were applied after stopping the constant amplitude load, and after that the constant amplitude load was resumed.

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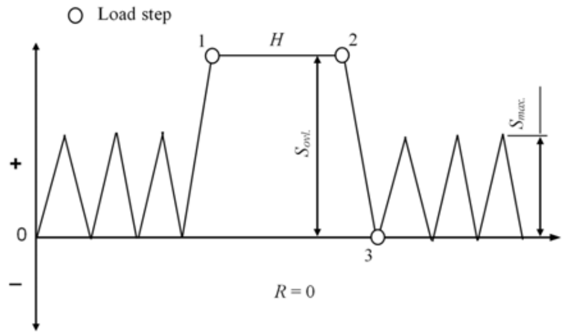

Figure-2. Representation diagram of cycles pattern.

Because the residual stress condition in front of the crack tip affects the crack propagation behaviour, hence, the stress analysis in front of the crack tip was carried out using software based on the finite element method, that is ANSYS, and the analysis referred to the software codes. The analysis was focused on the load steps as depicted in the Figure-2 since the residual stress developing ahead the crack tip depends on the stress upon overloading (load steps 1-2) and after of it (load step 3) [2-6]. In this analysis the semi model was made because of the symmetry shape of the specimen, and the model was meshed as that manner as shown in the Figure-3.

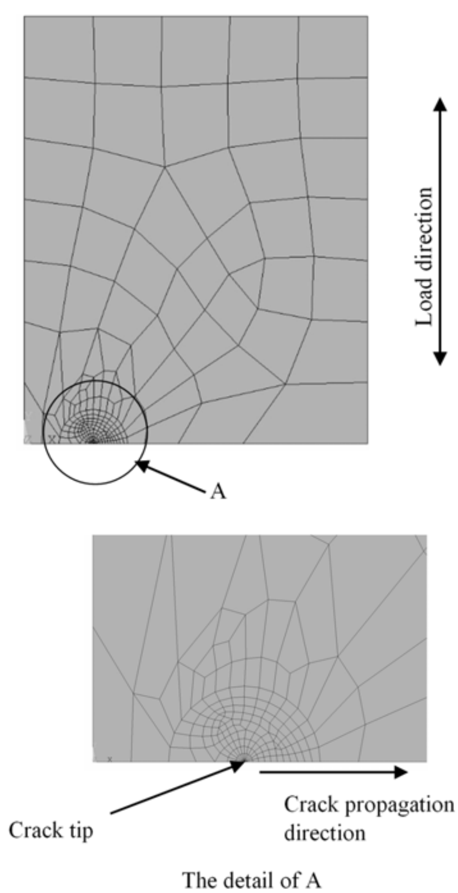

Figure-3. The model and meshing of the specimen.

3. RESULTS

Figure-4 shows the relation of the crack length, *a*, and the number of cycles, *N*. From the figure it can be seen that after the application of the overload as pointed by the arrow, there are two kinds of behaviours of the crack propagation. The first one is after the overload the crack propagation is retarded. In this case the fatigue life indicated by the number of cycles is longer than the fatigue life of the base, and the number of cycles is increased by the increasing of the magnitude of the overload. Secondly, when the magnitude of the overload is as high as 40 MPa. the retardation does not occur as indicated in the figure in which after the overload the crack propagation behaviour of that specimen is almost coincide with the base. In addition, the figure shows that the hold period of the overload reduces the retardation indicated by the number of cycles being shorter in comparison to those without holding period, but in exception this does not take place when the magnitude of the overload is 40 MPa. which is almost the same as the base.

The effect of the overload and the hold period to the deceleration or acceleration can be seen in the Fig.5. After being overloaded as high as 30 MPa., immediately the crack propagation accelerates, and the rate is higher than that of the base, then after reaching its maximum rate, the crack decelerates gradually to the minimum rate, which is lower than the base rate before gradually converging to the base rate as the crack advances beyond the zone affected by the overload. If such magnitude of the overload is held in the period as long as 60 minutes, there is small fluctuation that is higher than the base one in the very short range in front of the crack tip, and although the minimum rate is lower than that occurs in the case without holding period, the distance of the deceleration is shorter in comparison to that without holding period, thus, the fatigue life also shorter. Similarly, the acceleration and deceleration of the crack propagation following the overload takes place also in the case of magnitude to be as high as 35 MPa. However, the maximum rate of the acceleration and the minimum rate of deceleration are respectively higher and lower in comparison to the previous case of which the overload applied without holding period, and as the result the fatigue life become longer. The effect of the hold period of the overload that take place in this magnitude of the overload is also the same as shown in the former specimen case reducing the effect of the overload to the retardation of the crack propagation. In the case of the magnitude of the overload is 40 MPa., the effect of the overload alone to the crack propagation was not observed, and it also took place when the overload was combined with the hold period as indicated in the figure in which the subsequent rate of the crack propagation after being overloaded is almost to be coincide with the base rate, thus the fatigue life is not too far different.

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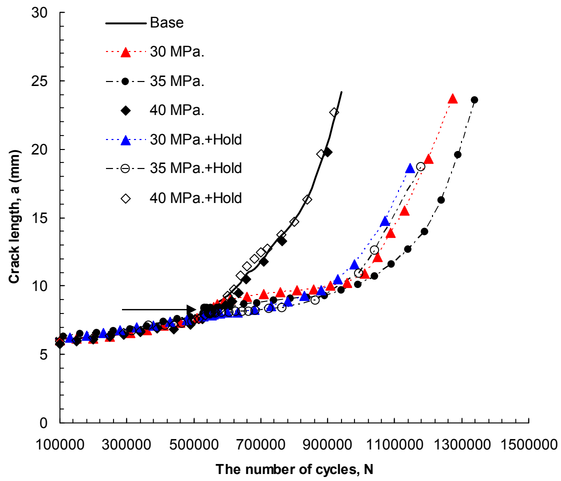

Figure-4. The crack length vs. the number of cycles.

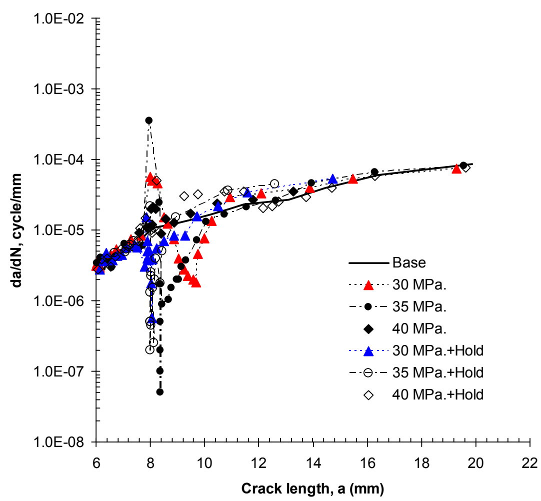

Figure 5. The crack length vs. the propagation rate.

To know the effect of the overload together with the hold period to the retardation, the number of cycles during the crack undergoes the retardation is often to be defined as the number of delay cycles, N_d, as depicted in the Figure-6 [2-6] in which the figure shows an example how to determine the number of delay cycles when the 30 MPa. of the overload alone was applied. Using this method the number of delay cycles in every test condition in the present study is summarized in the Figure-7.

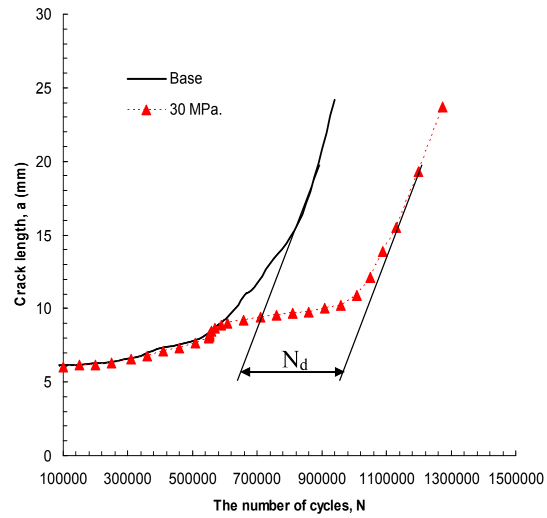

Figure-6. The definition of the number of delay cycles, N_d.

Figure-7 shows the effect of the overload magnitude to the number of delay cycles. The solid circle and the square, respectively, represent the overload with and without the hold period as well as the dashed and continue line indicating the expectation trend. It is usual that as the magnitude of the overload is increase, the number of delay cycles is increase also, and after reaching the maximum number of delay cycles, the increasing of the overload magnitude reduces the number of delay cycles [4]. This also occurs in the present study, even when the overload is as high as 40 MPa., the effect of the overload is not pronounced. However, when the overload is held in the certain period as conducted in this study, the number of delay cycles is decrease as the overload magnitude increases, even the value of the number of delay cycles is negative when the overload is 40 MPa., it means that the fatigue life is shorter that the base.

The results of the study present that the hold period of the overload affects the crack propagation behaviour on which the number of delay cycles is reduced by the hold period, and as the result the fatigue life is shorter in comparison to the crack propagation which is only overloaded. This is caused by the residual stress condition associated with the plastic strain developing in front of the crack tip during holding period, and it will discussed in detail in the next section.

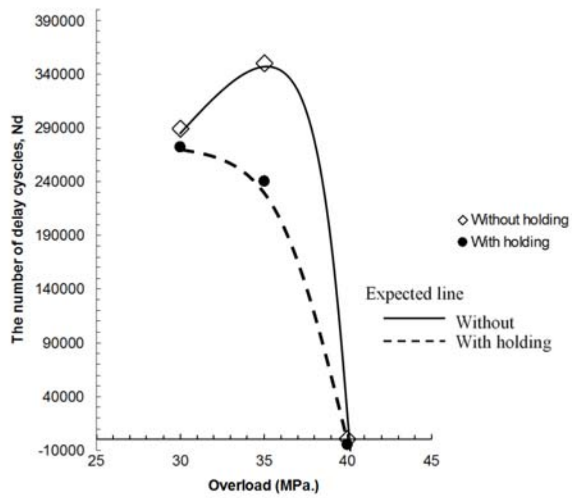

Figure-7. The effect of overload magnitude to the number of delay cycles.

4. DISCUSSIONS

It has been already known that the crack propagation behaviour following a single tensile overload is affected by the residual stress state in front of the crack tip, and the state of the residual stress depends on the stress ratio of constant amplitude load following an overload [2-6, 8-10]. For that reason, thus, in present study, the stress analysis carried out was focused on the region in front of the crack upon overloading. Figure-8 shows the example of stress contour of the specimen overloaded as high as 35 MPa., and then held in 60 minutes in which the arrows pointed the crack tip. The figure shows the stress condition for every load step, which is referred to the Figure-2. The red color indicates that the tensile stress concentrates in front of the crack tip as shown in the load step 1 and 2, respectively. However, after being held in overload the maximum value of the stress is higher in the load step 2. Upon being unloaded to zero load or in the load step 3, the color of contour in front of the crack tip becomes blue. It is an indication that the stress condition is in compressive. Because the compressive stress is still exist although the load is zero, thus, that is called as the compressive residual stress.

For convenient, the stress distribution including the stress state and its magnitude in front of the crack tip as shown in the Figure-8 is summarized in the Fig.9, and the distance from the crack tip on which the overload had been applied is denoted as *x* (mm). The figure shows that the stress varies as the distance increases. After being held for 60 minutes in the overload point (load step 2), the stress is higher than that of load step 1,and after some distances from the crack tip the stress gradually converges to the stress level of load step 1. The compressive residual stress develops just in front of the crack tip after being unloaded to zero load in the load step 3, although the tensile residual stress develops after some distance from the crack tip, however, its magnitude is lower than the compressive residual stress just in front of the crack tip.

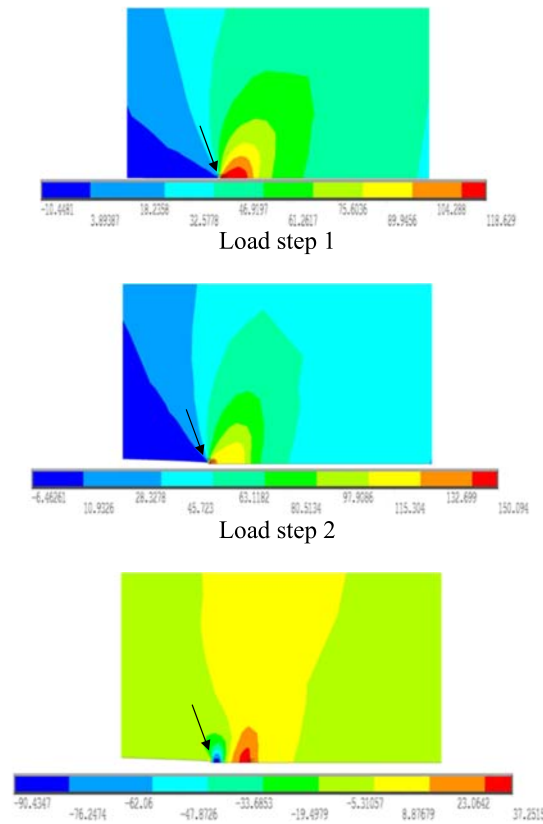

Figure-8. The example of stress contour in front of the crack tip of 35 MPa. overload with hold period.

Because the residual stress developing in the zone just in front of the crack tip strongly relates to the plastic strain [2-6], thus, the plastic strain affected by the hold period of the overload in that zone was investigated also, and the Figure-10 shows the strain contour in the case of 35 MPa. of overload combined with hold period. It can be seen in the figure that the plastic strain concentrates in zone immediately in front of the crack tip as pointed by the arrows. The plastic strain in the zone of the load step 2 in which after being held in the overload level is higher than that occurs in the load step 1, and after being unloaded to zero load or in the load step 3, the plastic strain slightly decreases in comparison to that in the load step 2. Because the direction of the plastic strain in zero load (load step 3) is maintained to be the same as the overload direction, therefore, the residual stress developing in front of the crack tip is in compressive state. As shown as in the stress distribution, Figure-11 shows the summary of the strain distribution in front of the crack tip. The figure shows that the plastic deformation is high in the crack tip, and then gradually decreases as the distance from the crack tip increases in which the effect of the overload becomes gradually to be less pronounced. In addition, it can be seen that after being held in the overload level, that is, in the load step 2, the plastic deformation is higher than that in overload point or load step 1, and upon unloading to zero load the plastic strain in the crack tip is slightly reduced.

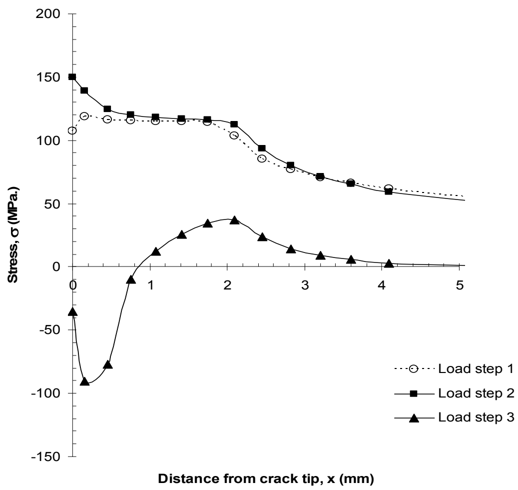

Figure-9. The summary stress distribution in front of the crack tip of 35 MPa. Overload with hold period.

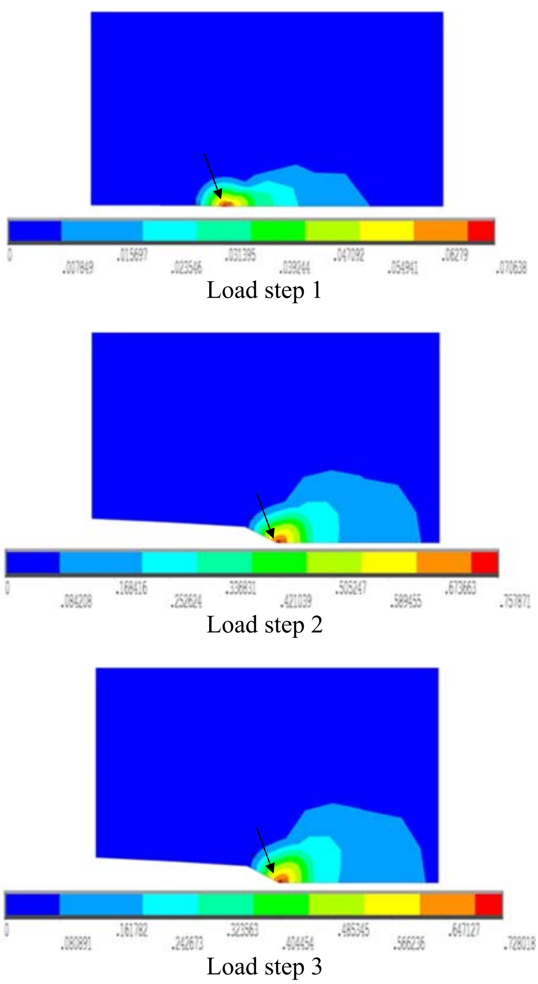

Figure-10. The example of strain contour in front of the crack tip of 35 MPa. overload with hold period.

With respect to the previous works stating that the condition of the residual stress developing in the zone in front crack tip after being overloaded affects the subsequent crack propagation behaviour when it is recycled under constant amplitude load [2-10]. Therefore, the residual stress in the zone developing after being overloaded, which is in the load step 3 as schematically depicted in the Figure-2 in the present study is shown for every test condition in the Figure-12. The Figure shows that the magnitude of the compressive residual stress that develops in the zone being very near by the crack tip is reduced by the hold period of the overload, respectively, for each overload magnitude. After reaching to the minimum value of the compressive residual stress, it gradually increases as the distance from the crack tip increases, and then the condition of the residual stress changes to be tensile after certain distances from the crack tip. The tensile residual stress does not affect the crack propagation behaviour due to this takes place considerably far away from the crack tip, and that zone in which the condition of the residual stress is tensile is almost not plastically deformed as indicated in the strain distribution of load step 3 in the Figure-13.

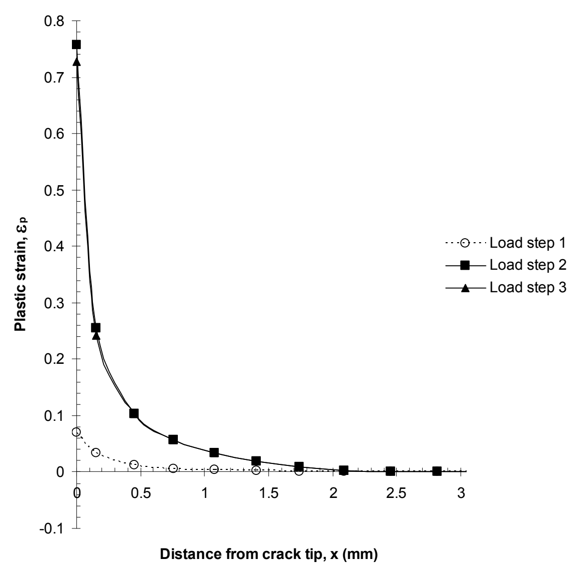

Figure-11. The summary strain distribution in front of the crack tip of 35 MPa. overload with hold period.

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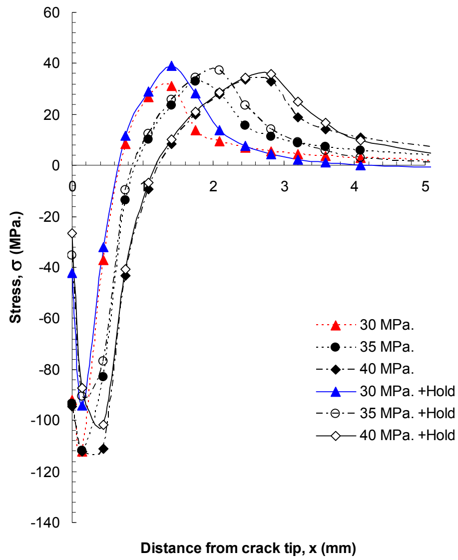

Figure-12. The stress distribution after overloading.

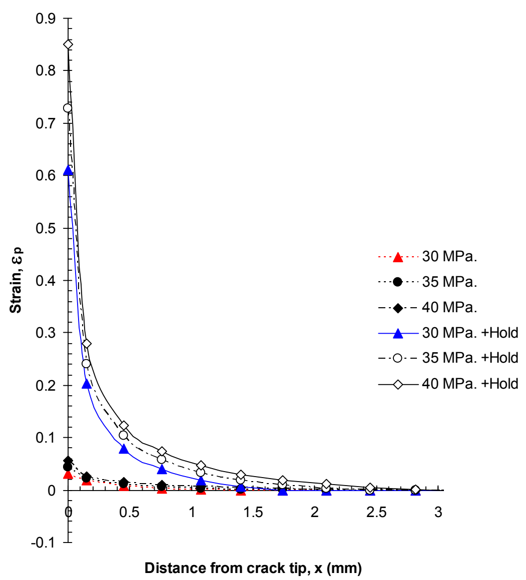

Figure-13. The strain distribution after overloading.

As mentioned previously that the residual stress condition immediately in front of the crack tip affects the following crack propagation after overloading, and this residual stress associates with plastic deformation, thus, with respect to the values of the plastic strain and the stress in the crack tip, the Figure-14 explains schematically how the residual stress related to the plastic strain develops. The circles in the figure denote the load step. The load steps 1-2-3 and 1-3, respectively, indicate the load steps for with and without hold period during the overload. In the case of the application of the overload alone, upon being overloaded (load step 1) the element material in the very near by crack tip is stretched in the overload direction, and after being unloaded to zero load (load step 3) and due to the deformation is not reversible, thus, as shown in the figure the plastic deformation is almost the same as in the load step 1. Because of it, the compressive residual stress develops in the load step 3. When the overload is combined with the hold period, the stress and the plastic strain significantly increases as indicated in the load step 2 in the Figure-14. After being continues to the load step 3, the compressive residual stress also develops; however, its magnitude is lower than that occurs in the case overload without hold period. That is caused by the plastic deformation being too high, and it is in the overload direction, which in tensile state. In addition, due to the unloading to zero load is not enough to reverse the direction, hence, the region just in front of the crack tip is not dominated by the compressive stress only. Therefore, this leads to the magnitude of the compressive residual is lower than that without hold period. Besides that, the indication of the too high plastic strain is indicated by the crack tip condition as shown in the Figure-15.

Figure-15 shows the crack tip shapes after being unloaded to the zero load from the overload point combined with the hold period, and the arrows point the crack tip for every magnitude of the overload. The shapes in the case of an overload alone are not different to the overload cases combined with the hold period. When the overload as high as 35 MPa., the crack tip remains sharp as before being overloaded, and the crack faces behind the crack tip still contact each other. As the magnitude of the overload is increased, the crack tip becomes blunting, thus, it leads the crack faces behind the crack tip to not contact each other anymore. These take place on the crack tip when the magnitude of the overloads are 35 and 40 MPa., respectively. However, the blunting in the crack tip after being overloaded as high as 40 MPa.is much severe compared to that occurs on the 35 MPa. of the overload. The blunting of the crack tip and the crack face that is not contact each other are indications that the plastic deformation in the region in front of the crack tip being very near by the tip is excessive. As the result, the magnitude of the compressive residual stress develops in that region is decrease, and it causes the number of delay cycles to be decrease, even, when the magnitude of the overload was 40 MPa., the overload did not retard the crack propagation.

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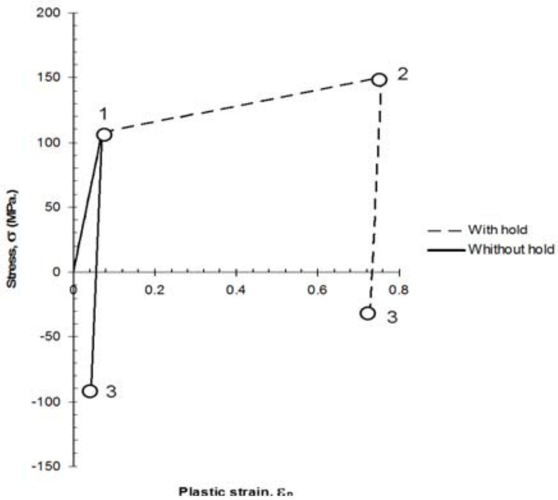
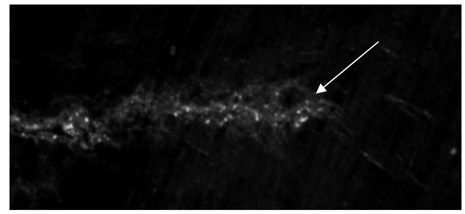


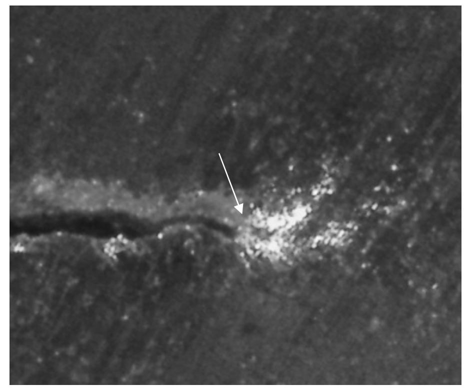
Figure-14. The relation of the stress and plastic strain in crack tip.

In the present investigation, there is a contradictive issue, that is, the relation between compressive residual stress developing in front of the crack tip and the crack propagation behaviour as well as the number of delay cycles on 40 MPa. of overload case. In this case, with respect to the stress analysis results showing that the compressive residual stress occurs in front the crack tip, however the crack was not retarded when the crack tip traversed in the zone in front of the crack tip affected by the overload, and it is indicated by the fatigue life being almost the same to the base. The possible reason for that phenomenon is the excessive deformation in the zone in front of the crack tip affected by the overload leading to voids to be formed [1], and these may weaken locally the strength of material in that zone. Therefore, it causes the compressive residual developing by the overload in front of the crack tip does not affect the crack propagation behaviour.

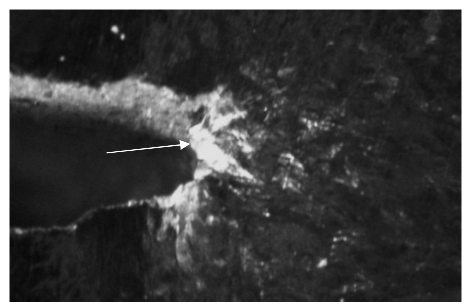
With respect to the Figures 9 and 12 show that after development of the compressive residual stress immediately in front of the crack tip, the state of the residual stress gradually changes to the tensile state, and the tensile residual stress diminishes in the zone, which is not affected by the overload. The tensile residual stress seems to be no effect to the crack propagation. This probably relates to the crack size and stress condition in the front of the crack tip when the crack tip traverses in zone in which the tensile residual stress exists. If the crack size becomes too long, the any stress condition may not effect to the crack propagation. Unfortunately, in the present study has not been confirmed yet, and the investigation associates with that will carried out in near future.



(a). 30 MPa.



(b). 35 MPa.



0.2 mm

(c). 40 MPa.

Figure-15. The crack tip shape after being overloaded together with hold period.

5. CONCLUSIONS

The investigation concludes that the crack propagation behaviour from the crack tip after being overloaded is affected by the hold period of the overload and the overload magnitude. The crack propagation behaviour following the overload is affected by the compressive residual stress developing just in front of the crack tip, and the retardation of the crack occurs as indicated by the increasing of the number of delay cucles. The residual stress is caused by the plastic deformation upon overloading in front of the crack tip, and the deformation is increased by the hold period of the overload. The increasing plastic deformation reduces the magnitude of the compressive residual stress because it causes the crack tip to be blunt, which indicates that there is excessive plastic deformation in the crack tip at the point of the overload. Therefore, the hold period reduces the number of delay cycles after the overload.

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