FATIGUE CRACK PROPAGATION BEHAVIOUR OF A Ni-Cr-Mo STEEL DUE TO REST PERIOD AND OVERLOAD

Song-Hee Kim* and Weon-Pil Tai*

(Received March 9, 1991)

The aim of this study is to investigate the effects of an intermittent rest period at 300℃, overload in tension, and the combination of an overload and a subsequent rest period on fatigue crack growth in AISI 4340 steel. The intermittent rest period was found to stop fatigue crack growth completely near threshold level of ΔK. The alleviation effect of a rest period on crack growth was more distinct at the lower level of ΔK. In overload, the greater overload ratio (OLR=3) caused more alleviated effect on crack growth rate. The reduced stress intensity factor by crack branching and enhanced roughness of crack surface are proposed to contribute to the retardation and arrest of fatigue crack growth. The most distinct retardation of fatigue crack growth was found after the combined treatment of a overload and a subsequent rest period.

Key Words : Overload, Rest Period, Crack Branching, Strain-Age Hardening, Fatigue Crack Propagation, Crack Arrest and Retardation.

NOMENCLATURE

a	: Crack length in CT specimen
α	: Ratio of crack length to specimen width (a/w)
B	: Thickness of CT specimen
$COD(\Delta\delta)$	: Crack opening displacement
Dp	: Plastic ductility (Dp=ln 100/(100−RA(%)))
ef	: Elongation ductility
H_{RC}	: Rockwell hardness
ΔK	: Stress intensity factor range
ΔK_{eff}	: Effective stress intensity range defined as $K_{max}-K_{op}$ or $K_{max}-K_{cl}$
K_{max}	: Maximum stress intensity factor
$Kop(Kcl)$	: Crack opening (or close) stress intensity factor
ΔK_{th}	: Threshold stress intensity factor range
OLR	: Overload ratio (max. stress intensity factor during overload/max. stress intensity factor during constant load fatigue test)
ΔP	: Load range
P_{op}	: Opening load
R	: Load ratio defined as minimum load to maximum load
RA	: Reduction in area
σu	: Ultimate tensile strength
W	: Width of CT specimen
σ_y	: Yield strength
σ_{yc}	: Cyclic yield stress

1. INTRODUCTION

The commonly known methods of extending fatigue life are fatigue damage repair (Rose, 1980), residual stress (Kudva and Duquette, 1982 ; Elber, 1971 ; Bernard et al 1976) and rest periods (Miller and Hatter, 1972 ; Miller and Plumbridge, 1976 ; Harries and Smith, 1959). However, comparatively little progress has been made on the effects of rest periods on fatigue properties. Studies on this aspect remain unclear, as the result from the work of Miller and colleagues (1972, 1976) differed from that of Harris and Smith (1959).

Apart from the investigations conducted by Kim (1983, 1986), very little attention has been directed towards studying the effect of high temperature rest periods on the fatigue crack propagation behaviour during fatigue cycling.

Other research aspects include the introduction of residual stresses by shot peening (Kudva and Duquette, 1982) and tensile overloading during fatigue cycling to produce self-stresses (Elber, 1971 ; Bernard et.al,1976). Nevertheless, the effect of overload on the various levels of ΔK and the various fatigue stages has not yet been adequately explained. Furthermore no previous study has yet been made to investigate the combined effects of both overload and rest period. Therefore the aim of this study is to experimentally determine the effects of overload, rest period and their combined treatment during fatigue cycling on the fatigue crack behaviour at the various stages of crack propagation.

2. EXPERIMENTAL PROCEDURES

Quenched and tempered Fe-0.4C-1.8Ni-0.7Cr-0.17Mo steel (hereafter is referred to as AISI 4340 steel) was used. Hot-rolled material was solution-treated at 850℃ for 30 minutes and then quenched into oil. Finally the material was tempered at 600℃ for one hour. The chemical composition and tensile properties in L-T direction are shown in Table 1 and 2.

For fatigue crack propagation test, compact-tension (CT) specimens machined by electric discharged machining (EDM) were used. According to ASTM standard E647 (ASTM stan-

*Department of Materials Engineering, Kangweon National University, Chuncheon 200-701, Korea

Table 1 Chemical compositions of AISI 4340 steel

Element	C	Si	Mn	P	S	Cr	Ni	Mo
Wt%	0.42	0.18	0.67	0.018	0.015	0.69	1.80	0.17

Table 2 Mechanical properties of quenched and tempered (Q.T.) AISI 4340 steel

Orientation	σ_y(MPa)	σu(MPa)	ef(%)	RA(%)	Dp	H_{RC}
L−T	989.3	1087.2	17.4	57.9	0.87	34.9

dard E647, 1987), the geometry of the specimen and the testing method were employed and the following Eq. (1) was used for the calculations of the stress intensity factor range. For the validity of the equation $\alpha = a/w$ should be larger than 0.2.

$$\Delta K = \Delta P(2+\alpha)(0.886+4.64\alpha-13.32\alpha^2+14.72\alpha^3 -5.6\alpha^4)/[BW^{1/2}(1-\alpha^{3/2})] \quad (1)$$

The frequency of 10Hz and load control of sine-wave type were selected for the fatigue test. Load ratio, R, was maintained as 0.05 throughout the test. Servo hydraulic dynamic fatigue testing machine (SHIMADZU Servopulser, Controller Model No.4825) was used. According to ASTM standard E647 (ASTM standard E647,1987) ΔK_{th} was firstly measured by the load shedding method and then meaeurements of fatigue crack growth rate over the various ranges of ΔK were conducted. ΔK_{th} is defined as the threshold stress intensity factor range at which da/dN was equal to 2.5×10^{-10} m/cycle or below.

For the observation of the effect of rest period during fatigue crack propagation the specimens, after a certain number of fatigue cycles, were removed from the grip with extreme care and then were rested at 300℃ for 3hrs in high purity nitrogen atmosphere. The test was resumed at exactly the same condition as before the interruption. During the rest period nitrogen gas was supplied through $CaCl_2$ dryer and oxygen trapper using copper turnings heated at 500℃ to remove moisture and oxygen possibly existing in the gas. Specimens were handled with extreme care during the mounting and demounting from the grip. The rest period was given at 300℃ for 3 hrs that appeared to have the most distinct rest period effect due to strain aging from the previous research (Kim, 1983) with using AISI 4140 steel.

The overload ratios(OLR) in tension of 1.5 and 3 were employed. To observe the net effect due to overload, exactly the same stress intensity factor range was maintained just before and after overload.

To discover the combined effect of overload and rest period specimens were taken out from the testing machine after a half cycle overload in tension, and heat-treated at 300℃ for 3 hrs. The fatigue crack propagation tests were resumed under exactly the same condition as before the interruption.

A travelling optical microscope with a scale of 0.02 mm was employed for the measurement of the crack length, and a scanning electron microscope (AKASHI Model No. SS130) was used for fractographic study. For the efficient measurement of K_{op}(or P_{op}) a COD gage was attached at around 1mm behind the fatigue crack tip, even though COD gage was attemped to be stuck on the various positions along crack path to the fatigue crack.

3. RESULTS

3.1 Effects of Rest Period on Fatigue Crack Propagation

Typical fatigue crack propagation data without any rest period or overload are presented in Fig. 1. The threshold stress intensity factor range, ΔK_{th} was found to be 4.75 MPa $\sqrt{m}$. The fatigue crack propagation in stage Ⅱ could be presented in the form of the Paris equation as below.

da/dN $=1.82\times10^{-11}(\Delta K)^{2.67}$[unit ; m/cycle, MPa$\sqrt{m}$]

In Fig.2(a) da/dN at point A was 1.62×10^{-9}m/cycle at 5.75MPa$\sqrt{m}$. However after the rest period at 300℃ in nitrogen gas for 3hrs the fatigue crack propagation stopped completely, even after 1×10^5 fatigue cycles at the same ΔK level. Fig. 2(a) shows that after that rest period fatigue crack propagation did not progress at all until ΔK at point B was arbitrarily raised to 7.42 MPa$\sqrt{m}$. On the other hand the rest period effect on fatigue crack propagation at a higher level of ΔK appeared to be rather negligible. At the ΔK of 15.1MPa$\sqrt{m}$ da/dN before the rest period was 3.75×10^{-8}m/cycle at point A in Fig.2(b) while da/dN after the rest period was 3.28×10^{-8}m/cycle. These two values were quite close to each other. In spite of much effort to purify nitrogen gas, a very little amount of oxidation during the rest period could not be completely eliminated and thus a very slight coverage of pale blue colour was observed on the specimen surface.

3.2 Overload Effect on the Fatigue Crack Progpagation.

Fatigue crack growth rates were measured at various levels of ΔK and compared with the subsequent fatigue crack propagation data after overload in tension (OLR = 1.5 and 3).

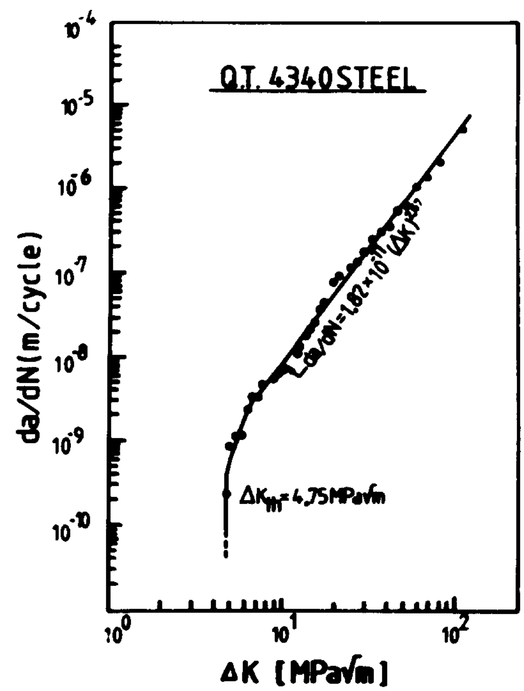


Fig. 1 The relationship between stress intensity factor range and crack growth rate of quenched and tempered AISI 4340 steel

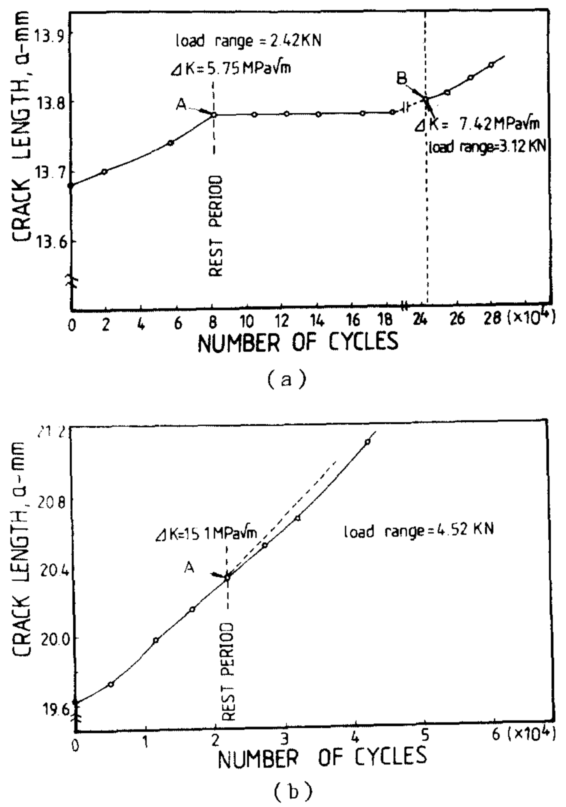


Fig. 2 Effect of 3hrs rest periods at 300℃ on fatigue crack growth rate in quenched and tempered AISI 4340 steel : (a) At low $\Delta K\,(da/dN \simeq 10^{-9}$m/cycle), (b) At relatively medium $\Delta K\,(da/dN \simeq 10^{-8}$m/cycle)

Figure 3(a) shows the effect of overload($OLR = 3$) on the fatigue crack growth rate, da/dN at a ΔK of 6.15 MPa$\sqrt{m}$. There was a distinct difference in that the da/dN before the overload was observed to be 2.9×10^{-9}m/cycle at a ΔK of 6.15 MPa$\sqrt{m}$ (refer to point A in Fig. 3(a)), while after overload in tension($OLR = 3$) crack propagation stopped completely. The crack had not grown at all until the level of ΔK was intentionally increased to 8.11 MPa$\sqrt{m}$ at B in Fig.3(a). On the other hand, in $OLR = 1.5$, only a slight retardation of fatigue cracking was observed at C in Fig.3(a) in which da/dN changed from 2.9×10^{-9} to 8.02×10^{-10}m/cycle.

It is shown in Fig.3(b) for $OLR = 3$ that the fatigue crack stopped growing completely at a medium level of ΔK(15.3 Mpa$\sqrt{m}$) for 3×10^{4} cycles just after the overload in tension (da/dN was 4.07×10^{-8}m/cycle at point A before overload), and then began to grow with much lower fatigue crack growth rate at B in Fig.3(b). On the other hand, da/dN at a ΔK of 15.4 MPa$\sqrt{m}$ slightly reduced from 4.58×10^{-8}m/cycle to 1.2×10^{-8}m/cycle for $OLR = 1.5$(point C in Fig.3(b)).

The overload effect($OLR = 3$) at around 23 MPa$\sqrt{m}$ is presented in Fig. 3(c) where temporary arrest of fatigue crack growth for 1×10^{4} cycles was found. In $OLR = 1.5$ no distinct retardation of crack growth was observed at the similar level of ΔK(=23.57MPa$\sqrt{m}$) at point B of Fig.3(c) in which da/dN changed from 1.25×10^{-7} to 1.0×10^{-7}m/cycle due to 1.5 OLR.

Consequently more distinct arrest and retardation were obtained at lower ΔK by applying higher value of overload ratio.

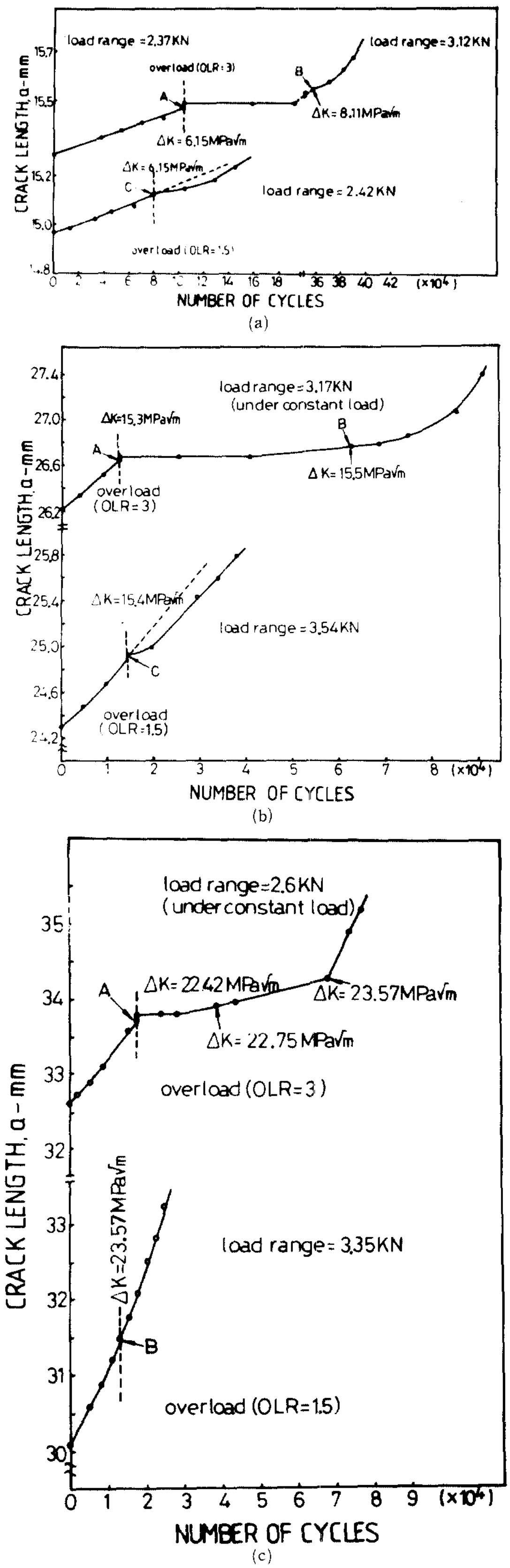


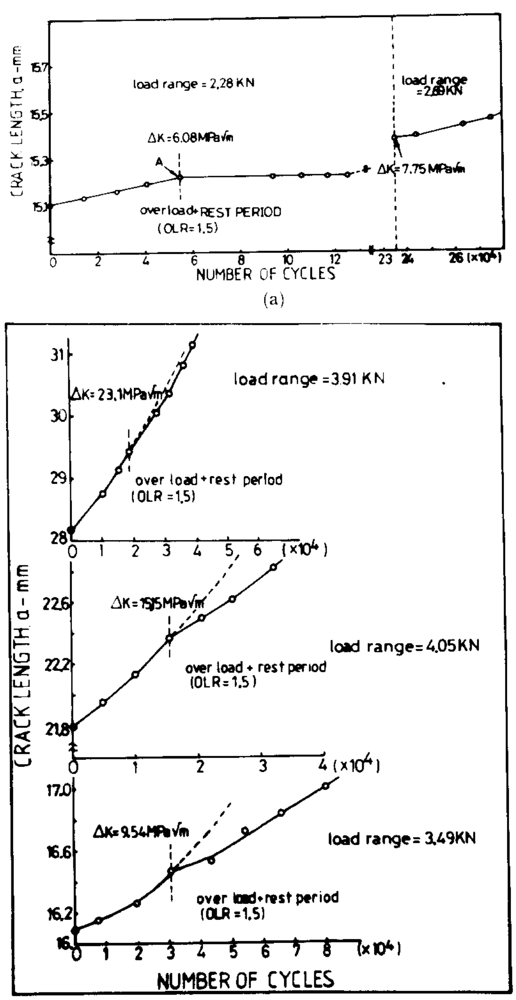
Fig. 3 Effect of overload on the fatigue crack propagation in quenched and tempered AISI 4340 steel : (a) At low ΔK $(da/dN \simeq 10^{-9}$m/cycle), (b) At medium $\Delta K\,(da/dN \simeq 10^{-8}$ m/cycle), (c) At relatively high $\Delta K\,(10^{-8} \leq da/dN \leq 10^{-7}$ m/cycle).

3.3 Combined Effect of Overload and Subsequent Rest Period on the Fatigue Crack Growth Behaviour.

The experimental data of fatigue crack propagation which were obtained during the following cycling after the combined treatment of an overload ($OLR=1.5$) and a subsequent rest period at 300℃ for 3 hrs are presented in Fig.4.

Figure 4(a) reveals the effect of the combined treatment near the threshold level of ΔK. After the combined treatment the fatigue crack did not extend at all even after 7×10^4 cycles at the ΔK of 6.08 MPa$\sqrt{m}$ while da/dN was 2.15×10^{-9} m/cycle before the combined treatment at point A in Fig.4(a). It had not resumed growing until ΔK became to 7.75 MPa$\sqrt{m}$. It is worth comparing this with Fig.3(a) where only a slight retardation of fatigue crack growth rate was observed when only the overload ratio of 1.5 was given alone.

On a medium level of ΔK(Fig.4(b)), however, the combined treatment of the overload and a subsequent rest period did not have a distinct effect on crack growth compared with the case(Fig.3(b)) including only the overload treatment of 1.5 OLR. Consequently the combined effect on the retardation of fatigue crack growth became more distinct with the decrease in ΔK level.



(b)

Fig. 4 Effect of 3hrs rest period at 300℃ following overload on fatigue crack growth rate in quenched and tempered AISI 4340 steel : (a) At low ΔK($da/dN\simeq10^{-9}$ m/cycle), (*b*) At relatively medium, high ΔK($da/dN\simeq10^{-8}$m/cycle)

4. DISCUSSION

4.1 Rest Period Effect on Fatigue Crack Growth

Fatigue crack growth retardation after rest period is believed to be strongly related to the increase in yield strength which results from the strain-age hardening in the plastically deformed zone in front of crack tip. A reason for the strain-age hardening during the rest period is the locking of dislocations by the diffusion of carbon or nitrogen atoms to dislocation site(Miller and Hatter, 1972; Miller and Plumbridge, 1976; Kim, 1983). Considering the works by Rice (1967) and Liu and colleagues(1982) the equations relating yield stress, crack opening displacement(COD) and fatigue crack growth rate have been suggested as eqs.(2) and (3).

$$COD(\Delta\delta)=\Delta K^2/(4E\sigma_{yc}) \quad (2)$$
$$da/dN=A(\Delta K^2/2E\sigma_{yc})^m \quad (3)$$

where A and m are constants, σ_{yc} is cyclic yield stress, ΔK is stress intensity factor range and $COD(\Delta\delta)$ is crack opening displacement.

The relationships have been experimentally proved by Liu and his colleagues(1982) and Garrett and Knott(1976). From Eqs.(2) and (3) COD and da/dN are expected to decrease with an increase in yield strength in a plastically deformed zone ahead of the crack tip due to the strain-age hardening which occurred during the rest period. Owing to the rest period at 300℃ the arrest of fatigue crack progpagation near the threshold was observed. It was depicted in Fig. 2 that the retardation effect on da/dN attenuates as ΔK levels increase. As ΔK becomes lower the effective stress intensity factor range, ΔK_{eff}, is expected to decrease more markedly. It is probably because K_{op} is relevant to a few possible crack closure mechanisms such as residual stress and oxide debris. However the effect of the above mechanisms on fatigue crack propagation is not affected by the increase of ΔK. K_{op} tends to be less changeable while K_{max} is absolutely dependent on the maximum load. This indicates that effective stress intensity factor range ratio, $\Delta K_{eff}/\Delta K$ decreases with increase of ΔK. Therefore the arrest and retardation of fatigue crack propagation become more obvious at lower ΔK where stage I fatigue crack growth behaviour is predominant.

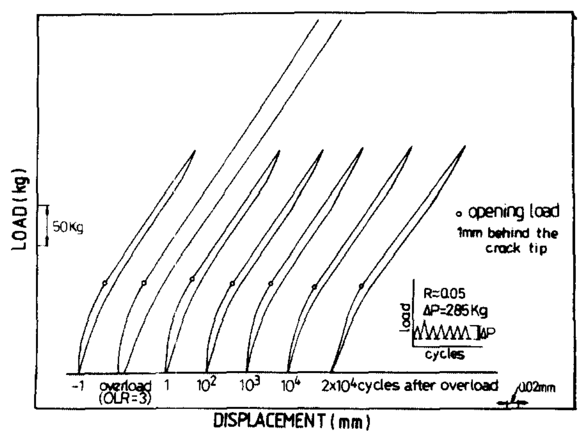
Since nitrogen gas was supplied through a preheated tubular furnace containing copper chips to trap water vapour in order to prevent oxidation, very little trace of oxidation was detected on the specimen surface after the rest period. Even though it is quite difficult to exclude the involvement of oxide crack closure, no quantitative analysis has yet been conducted in the present work.

The occurrence of strain-age hardening near the crack tip during the rest period at 300℃ was indirectly verified by measuring the change in hardness between rest periods at 300℃ of the low cycle fatigue specimen, to determine the strain-age hardening of the plastic-deformed zone near crack tip. The hardness of the specimen was 31 H_{RC} before the rest, and 33.7 H_{RC} after the rest. Therefore strain-age hardening near the crack tip is proposed as being responsible for both the arrest and retardation of crack growth.

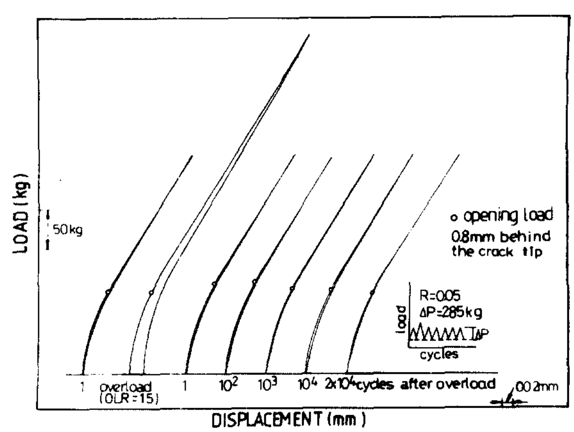
4.2 Overload Effect on Fatigue Crack Growth.

As shown in Fig.3 complete crack arrest was caused by 3

OLR while only crack growth retardation was obtained at 1. 5 *OLR*. Elber (1971) and Bernard and co-worker (1976) have reported that the arrest and retardation of fatigue crack growth after tension overloading were the result of induced compressive residual stress created by spring back force from the elastic zone surrounding the plastic zone near the crack tip. Residual stresses induced from higher overload ratio were generally considered to be more effective. This is referred to as "plasticity-induced crack closure." Clip gages were carefully attached at various places around the crack tip such as at crack mouth, at back face, behind crack tip and at crack tip to ensure the most accurate measurement to properly assess the plasticity-induced crack closure in accordance with the magnitude of overload ratio, and the result is presented in Fig.5. There was no distinct difference found with increase in overload ratio. However, crack branching was observed from the overloaded Ni-Cr-Mo steel specimens as in Fig.6 and schematically illustrated in Fig.7. According to the calculation of Bilby and co-workers (1977) a forked crack from branching is known to have 0.65 K_I in comparison with an undeflected crack. The formation of a forked crack is believed to relax stress concentration. Suresh (1983) also modelled the way in which crack branching during overload caused fatigue crack growth retardation. He has proposed a model to calculate ΔK_I at crack tip considering crack branching. Applying Bilby's calculation to our result, ΔK_I is



(a)



(b)

Fig. 5 Load vs. crack opening displacement record measured with using clip gage sticked at around 1 mm behind crack tip: (a) for 3 *OLR* at $\Delta K = 6.5\text{MPa}\sqrt{m}$, (b) for 1.5 *OLR* at $\Delta K = 6.4\text{MPa}\sqrt{m}$.

Fig. 6 Forked crack occurred in CT specimen by crack branching after an overload ($\Delta K = 6.5$ MPa$\sqrt{m}$, $OLR = 3$)

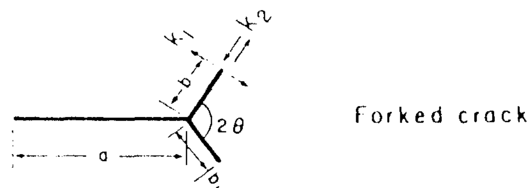
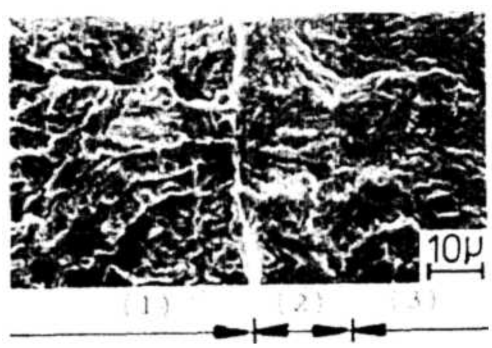


Fig. 7 Schematic illustration of a crack branching type after an overload (Suresh, 1983)



(a)

(b)

Fig. 8 Micrographs of fracture surface taken from overload region in the quenched and tempered AISI 4340 steel ($\Delta K = 15.3$ MPa $\sqrt{m}$, a = 26.66mm, $OLR = 3$) : (a) Fractography taken from low magnification ; the pre-overload zone (1), stretched zone (2), and the post-overload zone (3), (b) stretched zone.

reduced by crack branching from 6.5MPa$\sqrt{m}$ (when no crack branching is considered in Fig.5(a) and 6) to 4.3MPa$\sqrt{m}$ which is certainly below the ΔK_{th} of 4.75MPa$\sqrt{m}$.

A stretched zone made during the overload is observed in this study as in Fig.8. Fig.8(a) shows a micrograph in a low magnification of fracture surface during pre-overload, overload and post-overload. Fig.8(b) reveals the same but at higher magnification. More enhanced plastic deformation following in plane strain condition maximum shear stress at crack tip during tensile overload caused deflecting the crack path as depicted in Fig. 8.

On the other hand Suresh(1983, 1985) has proposed a delay of fatigue crack propagation by stretched zone as a way of deflecting the direction of the crack propagation path as the following equation. The terms used in the equation are defined in Fig. 9.

$$da/dN=[(D\cos\theta+S)/(D+S)](da/dN)_L \quad (4)$$

where $(da/dN)_L$ is undeflected Mode I fatigue crack growth rate, θ is the deflected angle, D is the crack length propagated along the deflected direction and S is the crack length propagated in Mode I after the deflected zone.

According to his proposal a deflected crack through the formation of stretched zone delayed crack propagation by $[(D\cos\theta+S)/(D+S)]$ more than the undeflected one as referred to in Fig. 9 and 10. it was already predicted by Suresh(1983, 1985) that certain parts of the crack surfaces close each other above a minimum load due to mismatching that could be enhanced by the increased roughness from stretching during overload. In considering the deflection of the crack the roughness-induced crack closure can not be simply disregarded. Crack blunting mechanism after overload is also known to assist the beneficial effect(Ward et al, 1989). However blunting effect was not noticeable in the present research.

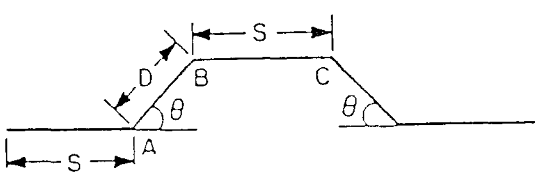


Fig. 9 Idealization of a small segment of a crack with periodic tilts(Suresh, 1983, 1985)

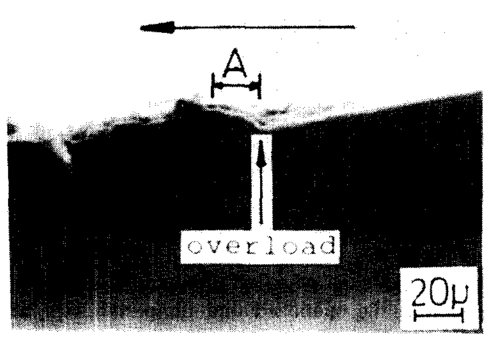


Fig. 10 Crack profile showing crack deflection due to overload(A indicating crack deflection (stretched zone) during overload($OLR=3$))

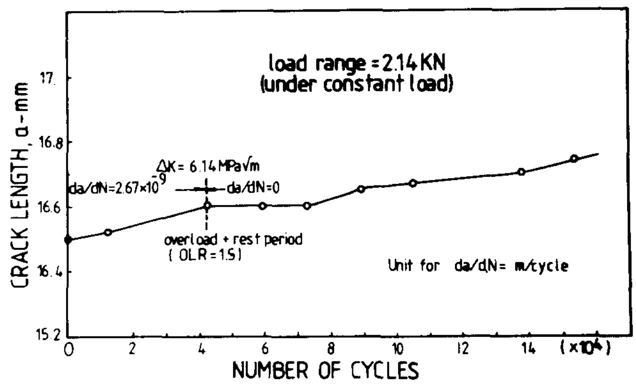


Fig. 11 The effect of a rest period at 120℃ for 30min. following overload with $OLR=1.5$ on fatigue crack growth rate in Q.T. AISI 4340 steel at low ΔK ($da/dN \simeq 10^{-9}$m/cycle)

4.3 Combined Effect of Overload and Rest Period

The combined treatment of overload (1.5 OLR) and subsequent rest period appeared to be most advantageous at low ΔK as already shown in Fig.4 ; the possible beneficial mechanisms of crack growth has been summarized as below. Firstly strain-age hardening in the plastically deformed zone near crack tip could reduce da/dN as described in Eqs. (2) and (3), which were empirically proved by Liu and his colleagues (1982) and Garrett and Knott(1976). Crack closure mechanisms due to residual stress and oxidation could be in operation as the second and third one.

Since no remarkable change in K_{op} after overload the second one appeared to be less important. However more comprehensive study on the effect of oxide-induced crack closure is left for future work.

The above proposal could be postulated by the supplementary result from Fig.11 where the effect of the rest period at 120℃ was less beneficial than that of the rest period at 300℃ even though more residual stress introduced by overload was expected to be better maintained by the rest period at lower temperature. Since no comprehensive analysis of oxide-induced crack closure has been conducted it was not possible to completely eliminate it.

5. CONCLUSIONS

From the present study the following conclusions were obtained.

(1) The retardation or arrest of fatigue crack propagation after rest period was more prominent at lower level of ΔK as indicated by the complete stoppage of fatigue crack growth near ΔK_{th}. This is proposed as relevant to the strain-age hardening in the plastically deformed zone near the crack tip and the possibility of oxides-induced crack closure can not be disregarded.

(2) The retardation or arrest of fatigue crack propagation after overload appeared to be more dominant with the increase in overload ratio and decrease in ΔK level. Crack branching (forked crack) was detected after overload and is believed to decrease stress intensity factor and thus assist the arrest or retardation of crack propagation together with residual stress and roughness of crack surface introduced during overload. From the measurement of crack opening load the effect of residual stress-induced crack closure

appeared to be minor.

(3) The combined treatment of both overload and subsequent rest period showed the most beneficial effect among the three methods proposed. These beneficial effects are proposed to be due to the combination of beneficial effects expected from the application of overload and rest period, respectively.

REFERENCES

ASTM Standard E647, 1987, "Standard Test Method for Constand Load Amplitude Fatigue Crack Growth Rates," 1987 Annual Book of ASTM Standard Vol.03, 01,pp.711~731.

Bernard, P.J.,Lindley,T.T.and Richards, C.E., 1976, "Mechanisms of Overload Retardation During Fatigue Crack Propagation," ASTM STP 595, pp. 78~97.

Bilby, B.A., Cardew, G.E. and Howards, I.C.,1977, "Stress intensity Factors at the tip of Kinked and Forked Cracks," in Fracture (Edited by Taplin.D.M.R.), 3, pp.197~200.

Elber, W., 1971, "The Significance of Fatigue Crack closure," ASTM STP 486, pp.230~242.

Garrett,G.G.and Knott,J.F.,1976, "On the Influence of Cyclic Hardening and Crack Opening Displacement (COD) on Crack Advance During Fatigue," Met. Trans. AIME, 7A,pp.884~887.

Harries,D.R.and Smith, G.C., 1959, "Fatigue Damage and Crack Formation in Pure Aluminum," J.Institute of Metals 88, pp.182~185.

Kim, S.H.,1983, "The Effect of Intermittent Rest Periods at Elevated Temperatures on the Fatigue Properties of 4140 steel," Proc. of the 4th International Conference on Mechanical Behaviour of Materials 2, Pergamon Press,pp.825~831.

Kim,S.H., 1986, "The Effect of Rest Period at 300℃ on Fatigue Crack Growth of 4140 Steel. The 10th Australasian Conference on the Mech. of Structure and Materials 2. Univ. of Adelaide, pp.483~488.

Dudva,S.M. and Duquette,D.J.,1982, "Effect of Surface Residual Stress on the Fretting Fatigue of 4340 Steel," ASTM STP 776, pp.195~203.

Liu,H.W.and Liu,D., 1982, "Near Threshold Fatigue Crack Growth Behaviour," Scr. Metall.16,pp.595~600.

Miller,K.J. and Hatter,D.J., 1972, "Increases in Fatigue Life Caused by the Introduction of Rest Periods," J.Strain Analysis 7,pp.69~73.

Miller, K.J. and Plumbridge,W.J.,1976, "Influence of a Zero-load Rest Period in Elevated Temperature Fatigue," J. Strain Analysis 11, pp. 235~239.

Rice.J.R., 1967, "Theory and Practice of Fracture Mechanics," Edited by R.I.Stephens, Dept. of Materials Eng., Monash Univ. Lecture, No.5.

Suresh, S.,1983, "Crack Deflection: Implication for the Growth of Long and Short Fatigue Cracks," Metall. Trans.A, 14A,pp.2375~2384.

Suresh,S.,1983, "Micromechanisms of Fatigue Crack Growth Retardation following overloads," Engng Fracture Mech., 18, pp.577~593.

Suresh,S.,1985, "Fatigue Crack Deflection and Fracture Surface Contact; Micromechanical Models," Metall. Trans. A 16A, pp.249~260.

Ward-Close,C.M.,Blom,A.F. and Ritchie,R.O.,1989, "Mechanisms Associated with Transient Fatigue Crack Growth under Variable-amplitude Loading: An Experimental and Numerical Study," Engng Mech., 32, pp.613~638.