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The Effect of Strain Aging on Threshold Value for Surface Crack

Propagation of S45C Round Bar in Rotatory Bending*

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Both specimens fatigue-stressed at room temperature to introduce a surface crack in the range of length 50 μm to 1.5mm and ones annealed to remove the prestress history were fatigued in rotatory bending at elevated temperatures. Pre-cracked specimens fatigue-stressed at elevated temperatures were fatigued at room temperature also. The threshold values for fatigue crack propagation were examined. The following results were obtained.

(1) The valleys and the peaks in the threshold-temperature relations for both the prestressed and annealed specimens appear at about 200°C and 375°C, respectively. These peaks are due to a rapid strain aging.

(2) While the threshold values at the peaking temperature is increased by the room temperature stress history, those at room temperature are decreased by the same stress history.

(3) The threshold values at room temperature are increased by the peaking temperature stress history.

1. Introduction

According to previous investigations⁽¹⁾⁻⁽³⁾ on the rotatory bending specimen with a circumferential crack and on the in-plane bending specimen with an edge crack, the threshold stress intensity factor ΔK_{th} of a low carbon steel takes a maximum value at about 375°C due to the rapid strain aging during cyclic stressing and takes a minimum value at about 200°C. According to another result of rotatory bending fatigue tests⁽⁴⁾⁽⁵⁾ on plain specimens of a carbon steel with temperature changing from the peaking temperature to other temperatures, the fatigue lives after the temperature change, especially at room temperature, are increased by a stress history at the peaking temperature.

In the preceding investigation⁽⁶⁾, the rotatory bending fatigue tests with temperature changing from 375°C to room temperature were carried out to clarify the effect of stress history at the peaking temperature (cyclic strain aging history) on the growth rate of microscopic surface cracks in plain specimens. The result indicates that the stress history above the fatigue limit at 375°C contributes not only to the increase in the number of cycles for crack initiation n_c at room temperature, but also to the increase in the number of cycles for crack propagation n_p , by decreasing the crack growth rates dl/dn completely in the crack propagation process. The stress history at 200°C contributes to the decrease in dl/dn at room temperature, though the fatigue life, the fatigue limit and ΔK_{th} take minimum values at

200°C in the constant temperature tests. But the contribution of stress history at 200°C is inferior to that at 375°C.

As described above, it is clear that the cyclic strain aging history contributes to the decrease in dl/dn of surface cracks in plain specimens. As is generally known, however, the linear fracture mechanics cannot be applied often to the estimation of dl/dn . Kitagawa et al.⁽⁷⁾ suggested adoption of a cyclic strain intensity factor based on the total strain range on the specimen surface instead of ΔK . Hoshida et al.⁽⁸⁾ tried to apply the cyclic J -integral ΔJ to a three dimensional microscopic surface crack, comparing with a large scale two dimensional through crack. There are many uncertainties in the controlling fracture mechanics parameters of dl/dn of the microscopic surface cracks. It is still difficult to calculate K of the surface crack under rotatory bending. In the preceding investigation, where it was assumed that $\Delta K = \Delta \sigma \sqrt{l/2}$, dl/dn - ΔK relations depended on $\Delta \sigma$ at room temperature, even for the same stress history.

In the latest investigation by Kitagawa et al.⁽⁹⁾, the threshold values of microscopic surface crack propagation under pulsating tension were obtained. It was suggested that the linear fracture mechanics might be well applied to estimate the threshold values of microscopic surface cracks greater than a certain limited length but ΔK_{th} of smaller size cracks tends to be underestimated. Nakai et al.⁽¹⁰⁾ suggested that, even for the through cracks, ΔK_{th} of microcracks depended on the crack length and the grain size and did not any longer become a constant for the crack length. The reason for such a result was attributed to different ΔK_{th} with different degree of a restraint for plastic deformation in the crack tip region.

As mentioned above, the fracture mechanics estimation of the growth rate and threshold value of microscopic surface crack has been established. However, practical information on the propagation behavior of surface cracks under

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rotatory bending is sometimes required. In the present investigation, the following subjects are examined by rotatory bending fatigue tests on the same 0.45% carbon steel as the one in the preceding investigation⁽⁶⁾.

(1) Examination of the effect of cyclic strain aging on the threshold values of microscopic surface crack propagation, comparing with the threshold values of circumferential crack propagation under small scale yielding in rotatory bending.

(2) Examination of the effect of cyclic strain aging history on the threshold values of crack propagation at room temperature, in relation to the effect of cyclic strain aging history on dl/dn at room temperature in the preceding investigation⁽⁶⁾.

For the crack length and loading condition which are used in this investigation, it is difficult to apply the linear fracture mechanics. Therefore, the above two subjects are estimated using σ_{th} in nominal stress on an original section and σ_{nth} on a net section at the crack tip.

2. Experimental procedure

2.1 Fatigue specimen

Plain specimens of 0.45% carbon steel were used. Chemical compositions, mechanical properties and heat treatments are the same as those in the preceding investigation⁽⁶⁾. The shape of specimen is shown in Fig.1. Specimens were notched horizontally at the center to 0.1mm depth and 2.5mm root radius so that the surface cracks might be observed easily by limiting the location of crack initiation. The fatigue tests were carried out with a rotatory bending fatigue testing machine for elevated temperature at a frequency of 3600 rpm.

2.2 Experiment for subject (1)

Referring to the preceding investigation, the surface cracks were introduced to the length, l_0 , of less than 50 μm , 500 μm and 1500 μm by cyclic overstressing at 32 kgf/mm² which was about 40% higher than the fatigue limit at room temperature, 23 kgf/mm². These specimens are called room temperature prestressed (RT-prestressed) specimens, because cyclic overstress history at room temperature remains in these specimens. The specimens in which the cyclic overstress history is removed by annealing at 700°C for one hour in a vacuum after prestressing are called annealed specimens. For annealed and RT-prestressed specimens, $S-N$ curves are obtained at room temperature, 200°C and 375°C. Threshold values σ_{th} and σ_{nth} are determined from these curves. Peaking phenomenon of the threshold values due to the strain aging and the effect of cyclic overstress history at room temperature on the peaking phenomenon are investigated.

2.3 Experiment for subject (2)

Pre-cracks of the same lengths as above described were introduced at 375°C at 36 kgf/mm² which was about 40% higher than the fatigue limit at 375°C, 26 kgf/mm². Those pre-cracked specimens are called 375°C-prestressed specimens, because the cyclic overstress history at 375°C remains in those specimens. The specimens which are pre-cracked at 33 kgf/mm² above the fatigue limit at 200°C, 22 kgf/mm², are called

200°C-prestressed specimens. After electro-polishing the surface of these prestressed specimens by about 10 μm , $S-N$ curves were obtained and the threshold values were determined at room temperature. The effect of cyclic strain aging history on the threshold values at room temperature is investigated.

Plastic deformation zones which contain multiplied free dislocations released from initial locking⁽¹¹⁾ by cyclic overstressing should exist in the surface layers of RT-prestressed specimens. Therefore, the threshold values of RT-prestressed specimens may possibly be smaller than those of annealed specimens which are influenced by intensive initial locking. On the other hand, an intensive relocking structure of multiplied dislocations is formed in the surface layers of 375°C-prestressed specimens, due to rapid strain aging during cyclic overstressing at 375°C. Therefore, the threshold values of 375°C-prestressed specimens may possibly be greater than those of annealed specimens. The relocking structure may be formed in the surface layers of 200°C-prestressed specimens too. In fact, the decrease in dl/dn at room temperature is recognized in 200°C-prestressed specimens due to cyclic stress history at 200°C⁽⁶⁾. It is inferred that the threshold values of 200°C-prestressed specimens at room temperature are greater than those of annealed specimens to some extent.

3. Experimental result

3.1 Definition of σ_{th} and σ_{nth}

In the unbroken specimen at 10^7 cycles near the threshold, every precrack once begins to propagate and soon after becomes non-propagative. Propagation behavior of a non-propagating crack is shown in Fig.2. As shown in Fig.3, let l_0 and t_0 denote the length and depth of the precrack, l and t denote those of nonpropagating cracks, respectively. Relationships between l_0 and t_0 and between l and t for identical annealed and prestressed specimens are shown

Fig.1 Shape of fatigue specimen.

Fig.2 Crack growth curve at σ_{th} (annealed).

Fig.3 Geometry of surface crack.

Fig.4 Relationships between crack length and crack depth (annealed).

Fig.5 Relationships between crack length and crack depth (prestressed).

Fig.6 An example of nonpropagating crack.

in Figs.4 and 5, respectively. The depth t_0 and t were measured on the fracture surface of a fatigue specimen fractured by impact of bending in liquid nitrogen. An example of the fracture surface is shown in Fig.6. The precrack could be distinguished easily from the later growing part by different degrees of heat tinting. In annealed specimens, the values of t_0/l_0 of precracks and t/l of arrested cracks are 0.31–0.43 and 0.33–0.46, respectively. These values in prestressed specimens are 0.21–0.39 and 0.26–0.40, respectively. Although some cracks show a very large growth in the direction of length, the growth of those cracks in the direction of depth is not so large. Relationships between t_0 and t and between l_0 and l are shown in Figs.7 and 8 for reference. Maximum values of crack growth in the direction of depth and length are about 40 and 60 percent of the precrack depth and length, respectively.

Fig.7 Relationships between precrack depth and nonpropagating crack depth.

Fig.8 Relationships between precrack length and nonpropagating crack length.

As described above, nonpropagating cracks are recognized near the threshold (fatigue limit for fracture of precracked specimens). A critical stress required to propagate a precrack must be still lower, but it is not obtained in this investigation. The stress amplitude corresponding to the fatigue limit for fracture of precracked specimens is defined as σ_{th} . The critical stress on the net section σ_{nth} is determined in the same manner as σ_{th} . The diameter of net section is given as the original diameter minus the depth of notch and nonpropagating crack. The effects of cyclic strain aging on σ_{th} and σ_{nth} are evaluated in relation to the precrack length l_0 and the nonpropagating crack depth, respectively. Since there is a quite large scattering in the precrack length as shown in Figs.4 and 5, σ_{th} cannot be determined exactly corresponding to a certain fixed precrack length l_0 . The same expression holds for σ_{th} . Therefore, as later described, $\sigma_{th}-l_0$ and $\sigma_{nth}-t$ curves are determined to obtain the critical cyclic stresses corresponding to various crack sizes.

3.2 The effect of cyclic strain aging on the threshold values σ_{th} and σ_{nth}

Relationships between the nominal stress σ and the precrack length l_0 of the annealed and RT-prestressed specimens at room temperature, 200°C and 375°C are shown in Figs.9 and 10, respectively. Experimental results only near the threshold values are plotted to avoid the

Fig.9 $\sigma - l_0$ curves (annealed). Fig.11 $\sigma_{nth} - t$ curves (annealed). Fig.10 $\sigma - l_0$ curves (prestressed). Fig.12 $\sigma_{nth} - t$ curves (prestressed).

complications in figures. Experimental results with no precrack are plotted at the location of $l_0 = 2\mu\text{m}$. In these figures, $\sigma_{th} - l_0$ curves are determined considering as follows. For smaller crack than the nonpropagating crack length at the fatigue limit of plain specimens l_{npc} , that is, when $l_0 < 50\mu\text{m}$, σ_{th} is assumed constant⁽¹²⁾. For greater l_0 , σ_{th} is assumed to come at the boundary between open and solid symbols in these figures.

In Figs.11 and 12, $\sigma_{nth} - t$ curves of annealed and RT-prestressed specimens are shown respectively. Values of t for smaller l than $50\mu\text{m}$ were calculated using the experimental values of l , assuming $t/l = 0.4$, because the cracks were so small that the specimens could not be fractured by impact. In the experimental results on RT-prestressed specimens (Figs.10 and 12), the results on σ_{th} and σ_{nth} at room temperature are represented only by the curves and they will be plotted later using the results on elevated temperature prestressed specimens.

Values of σ_{th} corresponding to three values of l_0 are shown in Table 1. In this table, the

increasing rate of σ_{th} under various conditions as compared with that at room temperature, r , are shown too. Relationships between r and testing temperatures T are shown in Fig.13. Values of σ_{nth} which were obtained from $\sigma_{nth} - t$ curves with respect to the depth of precrack are shown in Table 2. However $r - T$ curves for σ_{nth} are not shown because of the same tendency as those for σ_{th} . In Figs.11 and 12, $\sigma_{nth} - t$ curves at room temperature and the curves of annealed specimens at 200°C satisfy the following equation derived by Kobayashi et al.⁽¹³⁾, over a wide range of t .

$$(\sigma_{nth})^m t = C_1 \quad (1)$$

The curves of RT-prestressed specimen at 200°C and the curves at 375°C become constant regardless of t in the region of greater t .

$$\sigma_{nth} = C_2 \quad (2)$$

Values of m and C_1 obtained from the inclined part of $\sigma_{nth} - t$ curves are shown in Table 3.

According to these figures and tables, it is clear that the threshold value takes a maximum

Table 1 Values of σ_{th} .

	test temperature	$l \leq 50\mu\text{m}$		$l = 500\mu\text{m}$		$l = 1500\mu\text{m}$	
		σ_{th} kgf/mm ²	r %	σ_{th} kgf/mm ²	r %	σ_{th} kgf/mm ²	r %
annealed	room temperature	23.5	0.0	20.0	0.0	18.0	0.0
	200°C	21.6	-8.1	17.6	-12.0	15.6	-13.8
	375°C	27.5	17.0	22.0	10.0	21.5	19.4
RT-prestressed	room temperature	23.0	-2.1	19.4	-3.0	17.6	-2.2
	200°C	21.2	-9.8	16.2	-19.0	15.2	-15.6
	375°C	28.4	20.9	24.2	21.0	23.5	30.6
200°C-prestressed	room temperature	26.5	12.8	21.5	7.5	19.0	5.6
375°C-prestressed	room temperature	25.0	6.4	21.5	7.5	19.8	10.0

Fig.13 Relationships between r and test temperature.

value at about 375°C and a minimum value at about 200°C regardless of the cyclic stress history at room temperature, whichever is used as the threshold value σ_{th} or σ_{nth} . In other words, the threshold value for surface crack takes a maximum value at 375°C, because of the rapid strain aging during cyclic stressing, in the same manner as a circumferential crack. As shown in Tables 1 and 2, due to the cyclic overstress history at room temperature, σ_{th} and σ_{nth} decrease by 2~6% and 2~3%, respectively, but the threshold values at 375°C increase. Values of r for σ_{th} and σ_{nth} of annealed specimens at 375°C are about 8~22% and 10~20%, respectively. Corresponding values of r of RT-prestressed specimens are still greater and they are about 15~30% and 20~30%, respectively. These results are interpreted to be caused for the following reasons. As described in the experimental procedure, RT-prestressed specimens contain plastic deformation zones which consist of multiplied free dislocations in the surface layer. In the subsequent fatigue tests at 375°C, these multi-

Fig.14 $\sigma - l_0$ curves (prestressed at elevated temperature).

Fig.15 $\sigma_{nth} - t$ curves (prestressed at elevated temperature).

Table 2 Values of σ_{nth} .

	test temperature	$t = 20 \mu\text{m}$		$t = 150 \mu\text{m}$		$t = 500 \mu\text{m}$	
		σ_{nth} kgf/mm ²	r %	σ_{nth} kgf/mm ²	r %	σ_{nth} kgf/mm ²	r %
annealed	room temperature	23.5	0.0	20.0	0.0	18.0	0.0
	200°C	21.6	-8.1	17.6	-12.0	15.6	-13.3
	375°C	27.5	17.0	22.0	10.0	21.5	19.4
RT-prestressed	room temperature	23.0	-2.1	19.4	-3.0	17.6	-2.2
	200°C	21.2	-9.8	16.2	-19.0	15.2	-15.6
	375°C	28.4	20.9	24.2	21.0	23.5	30.6
200°C-prestressed	room temperature	26.5	12.8	21.5	7.5	19.0	5.6
375°C-prestressed	room temperature	25.0	6.4	21.5	7.5	19.8	10.0

Table 3 Experimental values of m and C_1 in the equation $(\sigma_{nth})^m t = C_1$.

	test temperature	m	C_1
annealed	room temperature	12.07	7.13×10^{14}
	200°C	9.89	3.17×10^{11}
	375°C	9.03	1.99×10^{11}
RT-prestressed	room temperature	12.03	4.80×10^{14}
	200°C	7.49	1.72×10^8
	375°C	12.59	3.97×10^{16}
200°C-prestressed	room temperature	9.68	1.18×10^{12}
375°C-prestressed	room temperature	13.80	3.96×10^{17}

where σ_{nth} : kgf/mm², t : mm.

plied dislocations are locked again during temperature raise up to the testing temperature and in the early stage of fatigue tests. Consequently the values of r for RT-prestressed specimens become greater than those for annealed specimens with relatively lower dislocation density.

3.3 The effect of cyclic overstress history at elevated temperatures on σ_{th} and σ_{nth} at room temperature

In Fig.14, $\sigma_{th}-l_0$ curves of RT-, 200°C- and 375°C-prestressed specimens at room temperature are shown. Corresponding $\sigma_{nth}-t$ curves are shown in Fig.15. In these cases, each $\sigma_{nth}-t$ curves satisfies the equation (1). The threshold values and the values of r obtained are shown in Tables 1 and 2. Cyclic overstress history at room temperature increases σ_{th} and σ_{nth} at room temperature by 2~6% and 2~3%, respectively. On the contrary, cyclic overstress history at 375°C increases σ_{th} and σ_{nth} at room temperature by 6~7% and 6~10%, respectively. It can be said that the cyclic strain aging history at 375°C contributes not only to the decrease in dl/dn at room temperature⁽⁶⁾ but also to the increase in the threshold values at room temperature.

Values of r for 200°C-prestressed specimens at room temperature are still large and sometimes greater than those for 375°C-prestressed specimens, but the reason for it cannot be given clearly. The cyclic overstress history at 200°C increases σ_{th} and σ_{nth} at room temperature by 3~9% and 5~13%, respectively. Thus the cyclic overstress history at elevated temperatures increases the threshold values at room temperature. But the values of r in such cases are considerably smaller than those at 375°C at which the cyclic strain aging occurs rapidly.

4. Discussion

Kobayashi et al.⁽¹³⁾ proposed the equation (1) and indicated that the values of m and C at room temperature are 4 and 9000, respectively, independently of carbon contents. The units of σ_{nth} and t in the equation (1) are kgf/mm² and mm, respectively. Using the equation (1), authors' previous results⁽¹⁾ on σ_{nth} of the circumferential crack in annealed specimens of low carbon steels under rotatory bending are rearranged. The tests were carried out at room temperature and 375°C in the range of $t = 150 \sim 1400 \mu\text{m}$. The

Fig.16 Comparison of $\sigma_{nth}-t$ curves for surface crack with those for circumferential crack.

results were compared with the results on surface cracks in this investigation.

In Fig.16, $\sigma_{nth}-t$ curves of the surface cracks and the circumferential cracks⁽¹⁾ in annealed specimens are shown. As shown in Table 2, σ_{nth} of the surface crack increases by about 10~19% due to the cyclic strain aging. However there is no correlation between r and t . On the other hand, values of r for the circumferential cracks are about 40~110% and it becomes greater as t increases. Values of r for surface cracks in this investigation are considerably smaller than those for circumferential cracks, though there are some differences in the range of t and the properties of materials between both investigations.

According to Fig.16, there is a large difference between the shapes of $\sigma_{nth}-t$ curves of surface cracks and those of circumferential cracks. Values of m obtained from the slopes of curves are 2.13 and 4.15 for circumferential cracks at room temperature and 375°C, and 11.9 and 9.1 for surface cracks at those temperatures respectively. Values of m for surface cracks are considerably greater than those for circumferential cracks. The fact that the values of m become greater indicates that the slopes of $\sigma_{nth}-t$ curves become smaller and that σ_{nth} becomes less sensitive to changes in the crack depth t . There are some cases when the values of σ_{nth} for greater t are independent of t , as shown in the results at 375°C. The values of m in this investigation are decidedly greater than those by Kobayashi et al.⁽¹³⁾ and those for circumferential cracks by authors. As described later, greater values of m in this investigation may be attributed to the fatigue testing under conditions to which the linear fracture mechanics cannot be applied.

A problem of what to choose as a parameter expressing the threshold value arises including the nonlinear region too. Ohji et al.⁽¹⁴⁾ suggest that, even in small scale yielding, the strain amplitude at the crack tip area is held constant as the threshold value for increasing crack length rather than ΔK_{th} . Shimada et al.⁽¹⁵⁾ indicate that the strain amplitude at the crack tip area can be an effective parameter controlling the crack growth rates including the nonlinear region. Hence it is assumed that the threshold condition is determined by the strain range at the crack tip area $\Delta \epsilon$, that is,

$$\Delta \epsilon = \Delta \epsilon_{th} \quad (3)$$

Next, the stress dependence and the crack depth dependence of $\Delta \epsilon$ becomes an undecided problem. Nishitani⁽¹⁶⁾ investigated the σ -dependence and l -dependence of the size of cyclic plastic deformation area, r_{pc} , considering that the crack growth rate dl/dn is proportional to r_{pc} , to deduce the crack propagation law including the nonlinear region. Assuming that r_{pc}/l depends on σ^n , an equation $dl/dn = C_0 \sigma^n l$ is obtained. Although the value of n is about 2 in linear region, it becomes greater in nonlinear region because of an increase in the stress dependence of r_{pc}/l . The experimental value of n is about 7~8. In the preceding investigation by authors⁽⁶⁾, the value of n at room temperature is about 8.4. If these assumption are applied to the stress dependence and the crack length dependence of $\Delta \epsilon$, the following expression should hold,

$$\Delta \epsilon = C_3 \sigma_{nth}^m t \quad (4)$$

Therefore, the value of m becomes smaller in the linear region and becomes greater in the non-linear region because of an increase in stress dependence of strain amplitude at the crack tip area. Equation (1) is obtained by combining the equations (3) and (4) and by substitution $\sigma_n = \sigma_{nth}$ when $\Delta\epsilon = \Delta\epsilon_{th}$.

Estimating the threshold values for circumferential crack by ΔK_{th} as well as the equation (1), ΔK_{th} at 375°C is about 70% higher than that at room temperature⁽¹⁾. Thus, for the circumferential crack to which the linear fracture mechanics can be applied, the value of m according to the equation (1) takes a smaller value of about 2~4. However, because the threshold value σ_{nth} in this investigation belongs to the nonlinear region, the value of m is increased to greater value of about 7~14.

5. Conclusions

Rotatory bending fatigue tests on a 0.45% carbon steel were carried out to investigate the effect of cyclic strain aging on the threshold value of surface cracks of 50~1500 μm long which were introduced in plain specimens by cyclic overstressing at elevated temperatures. The investigation in which the nominal stress σ_{th} and the nominal stress at net section σ_{nth} were used leads to the following conclusions.

(1) The threshold value of surface cracks σ_{th} and σ_{nth} as well as the threshold value of circumferential cracks in low carbon steel takes a maximum value at 375°C due to a rapid strain aging and a minimum value at 200°C. Due to cyclic overstress history at room temperature, the threshold values at 375°C are increased while those at room temperature are decreased.

(2) When the surface cracks are introduced by cyclic overstressing at 375°C at which a rapid strain aging occurs, the cyclic overstress history, that is, the cyclic strain aging history increases the threshold values σ_{th} and σ_{nth} at room temperature. Even when the surface cracks are introduced at 200°C, the cyclic overstress history increases the threshold values at room temperature. For small size cracks the increases by cyclic overstress history at 200°C are greater than those at 375°C.

(3) By rearranging the experimental results with σ_{nth} and t , the following equation according to Kobayashi et al.⁽¹³⁾ is satisfied. $(\sigma_{nth})^m t = C_1$. However, both σ_{nth} at 375°C and that at 200°C with cyclic overstress history at room temperature become constant regardless of t in the range of greater t . For the circumferential crack for which the threshold condition is determined with ΔK_{th} , the values of m are about 2~4. On the other hand, for the surface cracks in this

investigation, the values of m are about 7~14. This increase in the values of m is attributed to the conditions of tests to which the linear fracture mechanics cannot be applied.

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