ON THE EFFECTS OF PRE-LOADING ON THE FRACTURE TOUGHNESS OF A533B-1 STEEL

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ABSTRACT

Fracture toughness tests, covering fractures by cleavage and by ductile tearing, were carried out on a A533B-1 steel, and effects of monotonic or cyclic pre-loading history were evaluated. The results show that the pre-loading history has remarkable effects on cleavage fracture toughness and contributions of several factors are examined. At ductile fracture initiation, the total J-integral including pre-loading amount becomes a material constant regardless of pre-loading amount.

KEYWORDS

Pre-loading; elastic-plastic fracture toughness; cleavage fracture; J-integral; stretched zone.

INTRODUCTION

The plane-strain fracture toughness K_{Ic} or elastic-plastic fracture toughness J_{Ic} can be evaluated using a specimen that contains a idealy sharp crack without pre-loading history. For a specimen with pre-loading history, however, K_{Ic} or J_{Ic} is not necessarily effective as a fracture criterion. For instance, it is known that the cleavage fracture toughness may be affected by pre-loading history, although detailed studies concerning its effect have not yet been made.

Among the factors of pre-loading, tip acuity of a blunted crack, residual strain left in the wake of the crack and residual strain ahead of the crack may be considered to have an important role. In this paper, fracture toughness tests, covering fractures by cleavage and ductile tearing, were carried out on a A533B-1 steel, and effects of monotonic or cyclic pre-loading history were evaluated. Moreover, contributions of above-mentioned factors were examined.

MATERIAL AND EXPERIMENTAL PROCEDURE

The material used was a A533B-1 steel. The chemical composition is shown in Table 1.

TABLE 1 Chemical composition (wt. %)

C	Si	Mn	P	S	Ni	Mo
0.20	0.21	1.47	0.009	0.006	0.56	0.54

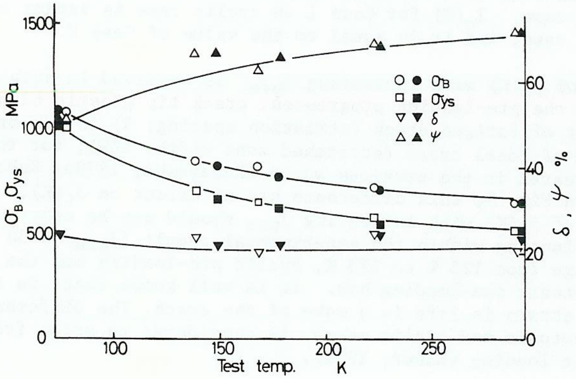

Fig. 1 Temperature dependence of mechanical properties.

The temperature dependence of mechanical properties is shown in Fig. 1 using open symbols. As this test program included a stress relief treatment (SR) for specimens after pre-loading, mechanical properties for the material after SR at 923 K for 1.5 hours were also examined. Results are shown also in Fig. 1 using solid symbols. Mechanical properties of the SR material are regared as the same as those of the non-SR material.

Specimens used were 12.7 mm (1/2 inch) compact type specimens. The specimens were pre-loaded by monotonic or cyclic load at room temperature. The stress intensity factor range in fatigue pre-cracking for monotonic pre-loading specimens was set $\Delta K_f = 15.5$ MPa√m and stress ratio R = 0.06. For cyclic pre-loading specimens, the fatigue crack was extended from a notch at the same ΔK_f value as that of cyclic pre-loading amount.

Fracture toughness tests in low temperature were conducted in three cases.

(1) Case 1 : Both pre-loading and unloading are given at room temperature, and re-loading is given at low temperature.
(2) Case 2 : Pre-loading is given at room temperature, and both unloading and re-loading are given at low temperature.
(3) Case 3 : pre-loading is given at room temperature, and re-loading is given at low temperature without unloading.

In Case 1, some specimens were stress relief annealed after pre-loading, and were re-loaded at low temperature.

For specimens that exhibited remarkable plastic behaviour (in the case of monotonic loading at 173 K,223 K and room temperature), the J-integral was calculated using the load versus load line displacement curve (Clarke, 1979). For another cases (in the case of monotonic loading at 77 K and 123 K ; in the case of cyclic loading), the K value was calculated from the load P, using the ASTM (1978) E399 instrumentation. To compare the both results, K(J) values were calculated from J values, and J(K) values were calculated from K values according to the relation,

$$J = (1 - \nu^2)\, K^2/E \tag{1}$$

where E is Young's modulus and ν is Poisson's ratio. The cleavage fracture toughnesses K_c, $K_c(J)$, J_c and $J_c(K)$, were defined as the value at unstable fracture, while the elastic-plastic fracture toughnesses J_{Ic} and $K_{Ic}(J)$ were defined as the value of fracture initiation.

RESULTS AND DISCUSSION

Temperature Dependence of Fracture Toughness

Temperature dependence of fracture toughness for specimens without pre-loading is shown in Fig.2, where $\Delta K_f = 15.5$ MPa√m. At 77 K, 123 K and 173 K, the mode of fracture initiation was cleavage, and at room temperature, the mode of fracture initiation was dimple. Between these two regions, the fracture initiated primarily by cleavage, but in a specimen, ductile stable fracture followed by cleavage unstable fracture was observed.

The fracture toughness value increases gradually with increasing temperature from 77 K to 173 K. Above 173 K, it increases rapidly and reaches upper shelf fracture toughness, J_{Ic} at room temperature.

Effect of Monotonic Pre-loading on Cleavage Fracture Toughness

The effect of pre-loading on cleavage fracture toughness $J_c(K)$ at 77 K is presented in Fig. 3, where J_{pre} is the J-integral at pre-loading. As shown by Fig. 3, the pre-loading history has a remarkable effect on $J_c(K)$, and different Cases, Case 1, Case 2 and Case 3, produce different results. To explain these phenomena, two engineering fracture criteria, the critical crack tip opening displacement $CTOD_c$ (Kanazawa, 1971) and the tensile yield zone size ω^+_c (Koshiga, 1970), have been proposed. According to these criteria, however, $J_c(K)$ should be constant in $J_{pre} > 2.7$ kJ/m²

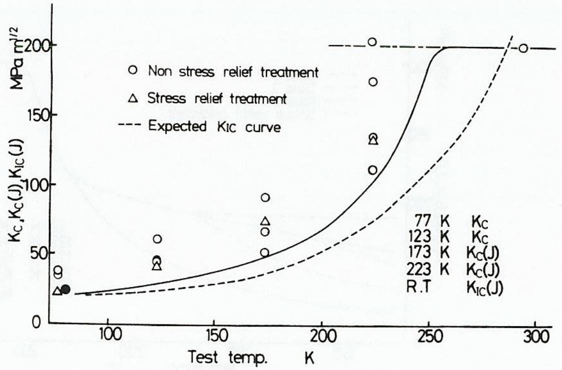

Fig. 2 Temperature dependence of fracture toughness

at 77 K, where the size of compressive yield zone ω^- ahead of the crack tip formed by unloading becomes larger than ω^+_c at 77 K. While results show that $J_c(K)$ increases with increasing J_{pre} until J_{pre} reaches 50 kJ/m^2, and it takes a constant value above that. So, further studies on the fracture criterion are needed. Figure 3 also shows that $J_c(K)$ becomes remarkably lower in case specimens are stress relief annealed after pre-loading, than that for non-SR specimens.

Pre-loading effect on $J_c(K)$ or J_c at 123 K and 173 K is similar to that at 77 K, qualitatively. At 223 K, pre-loading had no effect on J_c. When J_{pre} becomes larger than J_{Ic} at room temperature, a stable crack growth occurs. It should be noted, however, $J_c(K)$ or J_c is not affected by the crack growth at pre-loading.

The results at temperatures from 77 K to 223 K, are summarized in Fig. 4, where J_{pre} = 70 kJ/m^2. A solid line in Fig. 4 represents temperature dependence of fracture toughness for specimens without pre-loading. Increase of fracture toughness by pre-loading is remarkable in the order of Case 3, Case 2, Case 1 and SR-specimen. With increasing temperature, the effect of pre-loading is extinguished gradually, and in Case 3, fracture toughness does not depend on test temperature.

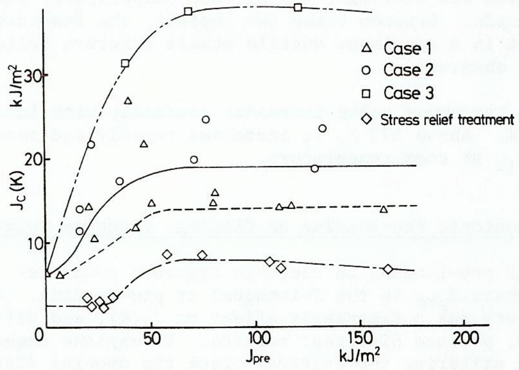

Fig. 3 Pre-loading effect on fracture toughness at 77 K (monotonic case).

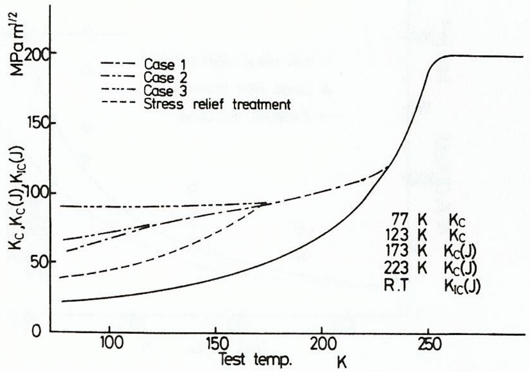

Fig. 4 Pre-loading effect on fracture toughness, as a function of temperature (J_{pre} = 70 kJ/m^2; monotonic case).

Effect of Cyclic Pre-loading on Cleavage Fracture Toughness

Figure 5 shows the effect of pre-loading on fracture toughness at 77 K, where open and solid symbols represent data for monotonic and cyclic pre-loading respectively. Results for Case 2, Case 3 and SR-specimen in cyclic case are similar to those in monotonic case. $J_c(K)$ for Case 1 in cyclic case is larger compared with that in monotonic case, and it is equal to the value of Case 2.

Increase of $J_c(K)$ with increasing J_{pre} is observed in both monotonic and cyclic cases. As the pre-loading progresses, crack tip plastic blunting occurs. The blunting amount of fatigue crack (striation spacing: S) is one order of magnitude smaller than that of ideal crack (stretched zone width: SZW), for the same J value, as authors have indicated in the previous works (Kobayashi, 1979a; Kobayashi, 1979b; Kobayashi, 1981). In Fig. 5, this difference has no effect on $J_c(K)$. So, the main reasen for increase of $J_c(K)$ with increasing J_{pre} should not be attributed to the crack tip plastic blunting within the experimental result (J_{pre} < 30 kJ/m^2). In the temperature range from 123 K to 173 K, cyclic pre-loading has the effect more remarkable than monotonic pre-loading has. It is well known that, in the cyclic loading, residual strain is left in a wake of the crack. The difference of the results between monotonic and cyclic cases is considered to arise from crack closure under the cyclic loading (Elber, 1971).

The results for cyclic pre-loading are summarized in Fig. 6, where J_{pre} = 20 kJ/m^2. The pre-loading effect as a function of temperature is similar to that in monotonic case as shown in Fig. 4.

Effect of Monotonic Pre-loading on Elastic-plastic Fracture Toughness

For A533B-1 steel, upper shelf elastic-plastic fracture toughness, J_{Ic}, exists in the temperature range from room temperature to 673 K (Hirano, 1979; Kobayashi,1980). On the other hand, in low temperature range, critical stretched zone width, SZW_c,

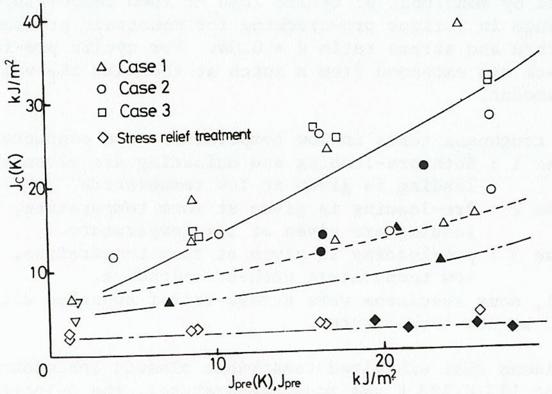

Fig. 5 Pre-loading effect on fracture toughness at 77 K.

becomes constant if some amounts of ductile tearing occur before the cleavage fracture (Ohtsuka, 1975). In this section, the effect of pre-loading on ductile (elastic-plastic) fracture toughness are discussed in relation to the upper shelf fracture toughness, from a point of view of a relation between stretched zone width, SZW, and J-integral (Kobayashi, 1977).

The effect of unloading on both the blunting line and SZW_c were examined. Specimens, which were pre-loaded, were re-loaded to a selected displacement. Then, fatigue marking was made. The values of SZW and total J-integral, J_{tot}, were measured, where J_{tot} is the J value calculated from total area A_1 of load versus load-line displacement curve as shown in Fig. 7.

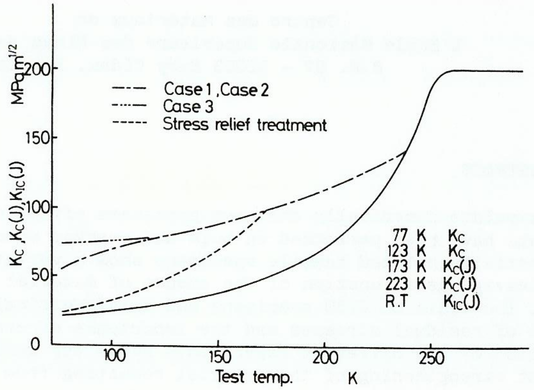

Fig. 6 Pre-loading effect on fracture toughness, as a function of temperature (J_{pre} = 20 kJ/m^2; cyclic case).

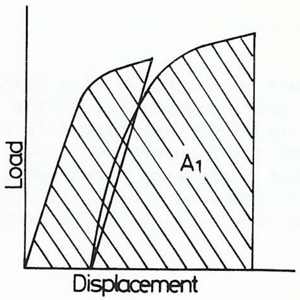

Fig. 7 Load versus load line displacement curve. (evaluation of J_{tot})

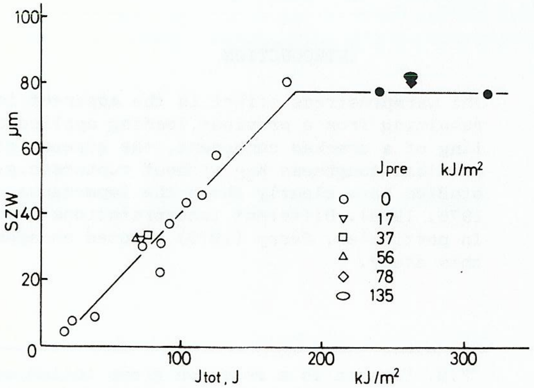

Fig. 8 Pre-loading effect on the relation between SZW and J at room temperature.

The relation between SZW and J_{tot} is presented in Fig. 8, where circle symbols represent the data for specimens without unloading. Solid and open symbols represent the data after and before the initiation of ductile tearing respectively. And a horizontal line shows the average value of SZW_c for specimens without unloading. Figure 8 shows that unloading has no effect on both the blunting line and SZW_c. So, J_{Ic} value at room temperature, determined at the intersection of the line SZW = SZW_c and the blunting line, is not influenced by monotonic pre-loading at room temperature, if the fracture toughness is evaluated by total J-integral including pre-loading amount.

The effect of monotonic pre-loading on ductile (elastic-plastic) fracture toughness, in fracture toughness transition temperature region, was examined. Figure 9 represents the relation between J_{tot} and J_{pre} at 223 K, where open symbols show the fractures by cleavage, while solid symbols show the fracture initiation by ductile tearing followed by cleavage fracture. The value of J_{tot} at fracture initiation by ductile tearing can be regarted as constant, which does not depend on J_{pre}. Moreover its value is nearly equal to the J_{Ic} value at room temperature. Considering the existence of upper shelf fracture toughness in the temperature range above room temperature, it may be concluded that the J value at fracture initiation by ductile tearing takes a nearly constant value for a wide temperature range from low to high. And its value is not influenced by monotonic pre-loading.

However, at test temperatures below upper shelf temperature, it should be noted that the J value at fracture initiation by ductile tearing has no meaning as elastic-plastic fracture toughness J_{Ic}, which does not depend on specimen sizes. That is, in a large specimen, a cleavage fracture may occure below its value, and the cleavage fracture toughness can decrease with increasing specimen sizes.

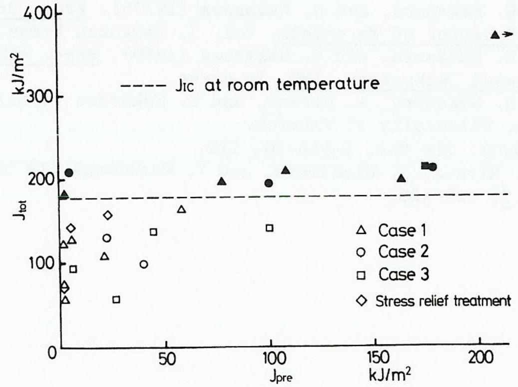

Fig. 9 Pre-loading effect on fracture initiation by ductile tearing at 223 K.

CONCLUSION

Fracture toughness tests, covering fractures by cleavage and by ductile tearing, were carried out on a A533B-1 steel, and effects of monotonic or cyclic pre-loading history were evaluated. The following is a summary of the results.

(1) The pre-loading history has remarkable effects on the cleavage fracture toughness at low temperature. Contributions of each factor, such as tip acuity of a blunted crack, residual strain left in a wake of the crack, residual strain ahead of the crack, to the cleavage fracture toughness are examined.

(2) At fracture initiation by ductile tearing, the total J-integral including pre-loading amount becomes a material constant regardless of pre-loading amount. Furthermore, its value is nearly equal to upper shelf elastic-plastic fracture toughness J_{Ic}.

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