Temperature Dependence of Mode II Fracture Toughness*

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This paper is concerned with the ductile-brittle transition behavior of steels under mode II loading. Mode II fracture tests were carried out on center-cracked thin-sheet specimens of HT 50 and S 20 C. Test temperature was changed from room temperature to -196°C . From mode II tests, it was found that the fracture appearance changed with temperature as follows: (i) in the region $T < T_b$, a cleavage crack initiates and extends, (ii) in the region $T > T_b$, a ductile crack initiates and extends, and (iii) in the region $T_b \leq T \leq T_d$, a ductile crack initiates and then extends as a brittle cleavage crack. The transition curve under mode II loading was shifted to lower temperature than that under the mode I loading condition. The direction of the cleavage crack was about 64° inclined to the precrack. The direction of the ductile crack coincided with that of the precrack.

Key Words: Fracture Toughness, Brittle Fracture, Ductile Fracture, Ductile-Brittle Transition, Mode II

1. Introduction

It is important to clarify the ductile-brittle transition behavior of a cracked specimen in order to evaluate the integrity of steel structures, and many studies have been carried out on the ductile-brittle transition behavior for various steels. However, these studies were concerned with mode I loading. It is also necessary to study the cases other than the mode I loading condition.

The authors investigated criteria for stable crack initiation and unstable fracture under mode II loading for center-cracked thin-sheet specimens of 2024-T3 Al alloy (thickness $B=1.0\text{ mm}$)^{(1),(2)}. In the present paper, mode I and mode II fracture tests were carried out on cracked specimens of two kind of steels to investigate the influence of the loading condition on the ductile-brittle transition behavior. In mode II testing a center-cracked specimen having the same

geometry as that used in mode I testing was used, and the in-plane shear load was directly applied to the edges of the specimen parallel to the crack plane, as shown in Fig. 1. Thus, the results of the mode II tests could be compared with those of the mode I tests without considering effects due to differences of the specimen geometry.

2. Method of Experiment

The materials tested in this study were a 50-kg-grade high-strength steel of HT50 (thickness $B=1.6$

Fig. 1 Mode I testing and Mode II testing

* Received 19th July, 1989. Paper No. 87-0931B

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mm) and a cold-rolled 0.2%C-steel of S20C ($B=1.6$ mm). The chemical composition and mechanical properties of these steels are shown in Table 1. Figure 2 shows the geometry of the center-cracked specimen tested. The specimen width was $W=70$ mm and the ratio of crack length to specimen width $\alpha=2c/W$ was 0.55 for both materials. Moreover, for S20C α was varied as $\alpha=0.3$ and 0.69 to examine the influence of the crack length. A fatigue precrack was introduced perpendicular to the rolling direction using a tension-tension fatigue testing machine. Mode I and mode II tests were carried out using the Instron-type testing machine at a crosshead speed of 2 mm/min. The loading apparatus⁽¹⁾ used in mode II testing is shown in Fig. 3. A cooling tub was attached to this apparatus in experiments at low temperatures. Test temperature was varied by controlling the amount of liquid nitrogen spraying on the specimen and was measured using two thermocouples (C-A type) attached in the neighborhood of the crack tip.

3. Experimental Results and Discussion

3.1 Fracture appearance

Examples of specimens of S20C fractured under mode II loading are shown in Fig. 4 ($\alpha=0.55$, arrows show the shear direction). The specimens tested at room temperature and at -196°C are shown in Figs. 4 (a) and (b), respectively. Under mode I loading,

Table 1 Chemical composition (wt.%) and mechanical properties of the materials tested

material	C	Si	Mn	P	S	Cu	Ni	Ti
S20C	0.22	0.21	0.41	0.02	0.01	0.20	0.06	--
HT50	0.10	0.24	0.68	0.74	0.14	0.28	--	0.42

material	Temp.	Yield Stress σ_y (MPa)	Tensile Strength σ_B (MPa)	Reduction of Area (%)
S20C	Room	448.1	568.3	61.27
	-196°C	--	1008.6	4.00
HT50	Room	376.3	516.9	44.03
	-196°C	912.2	984.2	28.94

Center-Cracked Specimen

Fig. 2 Geometry of the specimen tested

the direction of crack was perpendicular to the tensile axis at all temperatures. On the other hand, under mode II loading, the direction of crack varied from (a) to (b) in accordance with the ductile-brittle transition. In the case of (a), a ductile crack with large plastic deformation initiated and extended in the shear direction as in the 2024-T3 Al alloy reported in the previous paper⁽¹⁾. In the case of (b), the brittle cleavage crack initiated and extended to the direction inclined to the precrack plane at an angle of about 64° (at the same time, a symmetrically branched small crack was observed at the tip of the precrack). Between (a) and (b), there is a temperature region in which a ductile crack initiated in the shear direction, and then extended as a brittle cleavage crack in the direction inclined at an angle of about 64° to the precrack plane. In this case, a plastic zone was formed at the tip of the precrack as in case (a).

Thus, three temperature regions, $T > T_d$, $T_b \leq T \leq T_d$, and $T < T_b$, were distinguished with respect to

Fig. 3 Mode II loading apparatus

Fig. 4 Typical macroscopic appearance of mode II fracture (S20C)

fracture appearance: (i) in the region $T > T_D$, a ductile crack initiates and extends, (ii) in the region $T_B \leq T \leq T_D$, a ductile crack first initiates and then extends in cleavage manner, and (iii) in the region $T < T_B$, a cleavage crack initiates and extends. The load-displacement curve up to the maximum load was non linear in cases (i) and (ii), but was linear in case (iii). These changes of fracture appearance with temperature were the same as in the fracture of thick specimens under mode I loading.

The microscopic fracture appearance in the neighborhood of the precrack tip was observed using the scanning electron microscope, and is shown in Figs. 5(a) and (b). A shear dimple elongated in the shear direction was observed in the case of (a), and the river pattern was observed in the case of (b). The river pattern observed in mode II has the same feature as that observed in mode I. The fracture appearance of HT50 was the same as stated above.

3.2 σ_c , τ_c , K_{cI} , K_{cII} - T relation

Temperature dependences of the tensile fracture stress σ_c under mode I loading and the shear fracture stress τ_c under mode II loading for both materials are shown in Figs. 6(a) and (b), respectively. σ_c and τ_c were defined as the maximum load divided by the initial net cross-sectional area. The temperature dependences of the yield stress σ_y and the tensile strength σ_B for the smooth specimen are also shown. The symbols $\circ$, $\bullet$ and $\blacktriangle$ correspond to the three temperature regions $T < T_B$, $T_B \leq T \leq T_D$ and $T > T_D$, respectively. In mode I testing, the intermediate region was observed for HT50, but not for S20C.

Temperature dependences of the apparent critical stress intensity factor K_{cI} under mode I loading and K_{cII} under mode II loading are shown in Figs. 7(a) and (b), respectively. The values of K_{cI} and K_{cII} were obtained at the maximum load using the initial crack length. For the stress intensity factors of the center-cracked specimen under mode I and mode II loading, the same expressions were used as those used in the previous paper⁽¹⁾.

(a) Ductile fracture (b) Brittle fracture

Fig. 5 Scanning electron micrograph of a typical mode II fracture surface (S20C)

From Figs. 6 and 7, it is seen that the transition curves (σ_c - T , τ_c - T , K_{cI} - T , K_{cII} - T curves) for both materials under mode II loading are shifted to lower temperature than the ones under mode I loading. In mode II, the temperature T_B which defines the region $T \leq T_B$ almost agreed with T_{max} which is the temperature of the peak of the transition curve in mode II, and the temperature T_D which defines the region $T > T_D$ was higher than T_{max} (In the case of S20C, there is a possibility that T_B is lower than T_{max} , and further experiments seem necessary.) On the other hand, in mode I, T_B was nearly equal to T_D , and T_B and T_D almost coincide with T_{max} . In practice, the relative magnitude of T_D in mode I and T_D in mode II is important. For HT50, T_D in mode I almost coincides with T_D in mode II, but for S20C, T_D in mode II was lower than T_D in mode I. It is generally recognized that the transition curve under mode I loading moves

(a) S20C

(b) HT50

Fig. 6 Temperature dependence of σ_c and τ_c

(a) S20C

(b) HT50

Fig. 7 Temperature dependence of K_{cI} and K_{cII}

to high temperature with increase in the specimen thickness. On the other hand, it seems that the transition curve in mode II is almost independent of the thickness for the following reason. In mode I, the degree of the stress triaxiality increases, and cleavage fracture tends to occur with increase in the thickness. In mode II, triaxial stress states do not develop even in a thick specimen⁽⁴⁾, and hence the transition temperature does not seem to depend on the thickness. Therefore, it seems that the transition temperature in mode II is always located at lower temperatures than that in mode I independent of the specimen thickness.

From Fig. 7, it is seen that K_{cII} is larger than K_{cI} in the temperature range of $T < T_B$ and that the ratio of K_{cII}/K_{cI} at -196°C is 2.6 for S20C and is 2.8 for HT50 (for the specimen with $\alpha=0.5$). These values are somewhat different from the value of $K_{cII}/K_{cI}=0.71$ predicted by the maximum tangential stress criterion⁽⁵⁾ and the experimental values in brittle fracture, $K_{cII}/K_{cI}=1.09$ for 4340 steel⁽⁶⁾ and $K_{cII}/K_{cI}=0.7\sim 0.9$ for 0.04% carbon steel⁽⁷⁾. This may be due to the fact that the lower shelf of the tested material under mode II loading is lower than -196°C . In a previous paper⁽⁸⁾, $K_{cII}/K_{cI}=1.11$ was obtained for PMMA (thickness $B=3.0\text{ mm}$) using the same loading apparatus as in the present paper.

From the results for S20C, it is seen that K_{cI} and K_{cII} depend on the crack length in the temperature range $T > T_D$ but σ_c and τ_c are almost constant, independent of the crack length. Therefore, the net stress seems to be the effective fracture parameter in this region. In the region $T > T_D$, the fracture stress ratio τ_c/σ_c is almost constant, independent of temperature, and τ_c/σ_c is 0.65 for S20C and 0.71 for HT50. On the other hand, in the region $T < T_B$, the dependence of K_{cI} and that of σ_c on the crack length are almost the same. This is due to the fact that in the expression of the stress intensity factor $K = \sigma_{net}(1-\alpha)\sqrt{\pi c} \cdot F(\alpha)$, $(1-\alpha)\sqrt{\pi c} \cdot F(\alpha)$ is almost constant in the present experiment. $(1-\alpha)\sqrt{\pi c} \cdot F(\alpha)$ is 2.4 to $2.2\text{ mm}^{1/2}$ for $0.3 < \alpha < 0.7$. The relation between K_{cII} and the crack length is not clear within the experimental range in this study.

3.3 θ - T relation

The relation between the crack angle θ and temperature under mode II loading is shown in Fig. 8. θ is defined as the angle from the precrack plane. For the intermediate region $T_B \leq T \leq T_D$, both the ductile crack initiation angle and the cleavage crack extension angle are shown using the symbol $\odot$. The angle of cleavage crack θ was almost constant, independent of the temperature and the crack length for both materials. The average value of θ was 63.8° . This

Fig. 8 Temperature dependence of the crack angle θ

value is a little smaller than the value of 70.5° predicted by the maximum tangential stress criterion⁽⁵⁾, but within the experimental values in the literature^{(6),(7)} ($60\sim 75^\circ$ in reference 6 and 70.0° , 75° in reference 7). The angles of cleavage crack extension were almost the same for both the regions $T < T_B$ and $T_B \leq T \leq T_D$. From Fig. 8, it is seen that the direction of ductile crack agrees with the precrack direction. That is, θ is nearly equal to 0° .

4. Conclusions

From the results of mode I and mode II fracture tests for S20C and HT50 using center-cracked specimens at various temperatures, the following conclusions were obtained.

(1) With respect to fracture appearance under mode II loading, three temperature regions, $T < T_B$, $T_B \leq T \leq T_D$ and $T > T_D$, were distinguished: (i) in the region $T < T_B$, a cleavage crack initiates and extends, (ii) in the region $T > T_D$, a ductile crack initiates and extends, and (iii) in the region $T_B \leq T \leq T_D$, a ductile crack initiates and then extends as a brittle cleavage crack.

(2) The transition curve under mode II loading (fracture-stress-vs-temperature curve, and apparent-critical-stress-intensity-factor-vs-temperature curve) was shifted to lower temperature than that under mode I loading for both materials.

(3) The fracture stress defined as the maximum load divided by the net cross-sectional area was almost constant, independent of the crack length in the temperature range $T > T_D$.

(4) The angle of the cleavage crack was about 64° inclined to the precrack direction in both the regions $T \leq T_B$ and $T_B \leq T \leq T_D$. The direction of the ductile crack coincided with the precrack direction.

Acknowledgements

This study was supported by a grant-in-aid for

scientific research from the Japanese Ministry of Education, Science and Culture. The authors wish to express their thanks to Dr. S. Tanaka, president of the University of Electro-Communication for his advice concerning the present study. The authors also wish to thank Mr. J. Sato and Mr. H. Kato for their help in the experiments.

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