The Thickness Effects of the Side-Grooved CCT Specimen
(Fracture Toughness of SUS 316 Steel)

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$J_{ic}$ tests were carried out on SUS 316 steel by means of the JSME $R$-curve method as well as the JSME stretched-zone width ($SZW$) method. The effects of side-grooves on the $J_{in}$ value at the onset of stable crack growth were investigated using CCT specimens of two thicknesses ($B=1$ mm and 2 mm). The ratio of the net thickness to the gross thickness was maintained at 0.5. The $J_{in}$ values of the side-grooved CCT specimens of both thicknesses were considerably smaller than those of the 1 TCT specimen. The $J_{in}$ value of the side-grooved specimen of 2 mm thickness was smaller than that of the standard CCT specimen. Further, as the thickness of the specimen became thinner, the $J_{in}$ value decreased. In the case of 1 mm-thick CCT specimens with or without a side-groove, the contraction percentage of thickness was very large so that it was not appropriate to use these specimens for the fracture toughness test. In the case of the thin or side-grooved CCT specimens, the $J$-value, which is evaluated from the load versus displacement curve using Rice's formula, cannot estimate the $J$-integral at the central part of the specimen. Therefore, a $J$-integral estimation method would have to be established using 3-D elastic-plastic analysis.

Key Words: Fracture, Thickness Effect, Fracture Toughness, Side-grooved, $R$-curve, Stretched-zone Width, $J$-integral

1. Introduction

The $J_{ic}$ values are obtained by means of the JSME $R$-curve method as well as the JSME stretched-zone width ($SZW$) method. However, the $J_{ic}$ values obtained by both methods do not agree. Thus, there are several problems to be discussed. Particularly, the difference between $J_{ic}$ values obtained by means of both methods is very large for the low strength and high toughness materials. Recently, for the safety assessment of the nuclear reactor, it has become very important to clarify the nucleation and the growth behavior of the crack at the inner wall of the nuclear vessel. However, the thickness of the available specimens which were irradiated with neutrons is about 1 mm, even for the thickest specimen. Therefore, the standard method used to determine the elastic-plastic fracture toughness from such thin specimens should be established as quickly as possible. The CT and three-point bend specimens are recommended by JSME standards. However, both types of specimens have a hinge of tension and compression, and as the specimen thickness decreases, the possibility of causing the buckling increases. Therefore, it is considered that the CCT (center-cracked tension) specimen is more appropriate than the two above-mentioned specimens for the test of the stable crack growth or the fracture toughness using the thin specimen.

For the thin specimen, since the plane-stress state becomes predominant, the stress triaxiality near the crack front decreases while the contraction of the thickness becomes very large. There are numerous reports stating that, by machining a side-groove, the constraint along the thickness direction is increased and the plane-strain state is easily produced. Accordingly, the effect of a side-groove is expected in the thin specimen.

In this paper, the fracture toughness tests are carried out by the 50% side-grooved CCT specimens of two thicknesses ($B=1$ mm and 2 mm) for the SUS 316 steel which is a strong candidate for the material of the inner wall of the fusion reactor. The $J_{in}$ values, the $J$-values at the onset of the stable crack growth, are obtained by means of the $R$-curve
and $SZW$ methods, and are compared with the $J_{in}$ value obtained by the 1 TCT specimens. Moreover, the deformation behavior of the thin specimen is discussed by comparing the crack opening configuration measured on the sectional photo at the central part of the specimen with the stretched-zone width measured on the photo of the fractured surface.

2. Materials and Specimens

The material used in the experiment was an austenite stainless steel, SUS 316. The chemical composition and the mechanical properties are shown in Tables 1 and 2, respectively. The specimens were 1 TCT and CCT specimens; their configurations are shown in Fig. 1. The thickness of the 1 TCT specimen was 25.4 mm and that of the CCT specimens was 1 mm and 2 mm. The fatigue precrack was introduced with $\Delta K$, which is much lower than that recommended by JSME. The CCT specimens were nonside-grooved and 50% side-grooved specimens. $B_0$ and $B_n$ in Fig. 1 denote the gross thickness and the net thickness, respectively. The ratio of the net thickness to the gross thickness is maintained at 0.5. The displacement measurements are carried out by the displacement gage installed at the two pins which are attached at a distance of 30 mm on both sides of the crack line.

The $J$-value is estimated from the load versus displacement curve by using Rice's formula\textsuperscript{10}, expressed as follows:

$$J_s = G + \frac{b}{P} \left[ \int d\delta_{\text{plastic}} + \frac{1}{2} \delta_{\text{plastic}} \right]$$  \hspace{1cm} (1)

where $G$ is the strain energy release rate, $b$ is the ligament width, $P$ is the load per thickness and $\delta_{\text{plastic}}$ is the plastic part of the displacement.

<table>
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<th>Specimen</th>
<th>C</th>
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<th>Mn</th>
<th>P</th>
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<td>$B_0=2\text{mm}$</td>
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<table>
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<th>Cr</th>
<th>Mo</th>
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<td>11.13</td>
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Table 1 Chemical compositions

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<th>$d_Y$</th>
<th>$d_{TS}$</th>
<th>$d_{fs}$</th>
<th>T.E.</th>
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<tr>
<td>(MPa)</td>
<td>(MPa)</td>
<td>(MPa)</td>
<td>(%)</td>
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<td>278.5</td>
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</table>

Table 2 Mechanical properties

(a) 1 TCT specimen

(b) Side-grooved CCT specimen

Fig. 1 Specimen configurations
3. Experimental Results and Discussion

3.1 Deformation near the crack tip

Figure 2 shows the photos of the fractured surface of the 50% side-grooved CCT specimens of 2 mm thickness before and after the stable crack growth. The stretched zone is only slightly created near the free surface and the width of this zone increases up to the central part of the specimen. Even before the initiation of the stable crack growth, necking occurs near the free surface in front of the stretched zone. Dimples are found in the stretched zone and a large number of slip lines exist perpendicular to the direction of the crack propagation. The configuration of the dimple zone is very irregular, and as the deformation proceeds, the thickness decreases markedly as the result of the necking.

Figure 3 shows the relation between the \( J \)-values and the contraction percentage of the thickness, \( \phi \), which is expressed as follows:

\[
\phi = \frac{B_0 - B}{B_0} \times 100(\%) \quad (2)
\]

where \( B_0 \) is the gross thickness and \( B \) is the minimum thickness of the necking part. Furthermore, in the case of the side-grooved specimen, the net thickness, \( B_n \) is used instead of \( B_0 \). Hereafter, \( B_0 \) and \( B_n \) in the figures denote the nonside-grooved and the side-grooved specimens, respectively.

For the nonside-grooved and side-grooved specimens of 2 mm thickness, when the deformation is small, the contraction percentage of the thickness increases linearly with an increase in the \( J \)-value. As the \( J \)-value exceeds 500 kN/m, the contraction percentage of the thickness becomes the maximum which is about 50%. For the specimens of 1 mm thickness, the same tendency is recognized, but the maximum contraction percentage of thickness is 80%, which is very large in comparison with the above case. For the side-grooved specimen of 1 mm thickness, the contraction percentage of the thickness increases linearly with an increase in the \( J \)-value. Thus, the effect of the side-groove is not recognized remarkably. On the other hand, the contraction percentage of thickness for the side-grooved specimen of 2 mm thickness is small in comparison with that of the 1 mm-thick

\[
J = 263.4 \text{kN/m} \quad J = 128.4 \text{kN/m}
\]

Fig. 2 Photos of fractured surface

Fig. 3 Relation between \( J \) and contraction percentage of thickness

Fig. 4 Schematic illustration of the crack tip
specimen, and the constraint effect on the thickness direction by the side-groove is recognized.

Figure 4 shows the schematic illustration of the crack tip geometry. Point A denotes the intersection of the straight and curved lines on the fatigue pre-crack profile measured on the sectional photo at the central part of the specimen. Point B denotes the crack front measured on the photo of the fractured surface. $X_0$ is the distance between A and B. The specimens were polished up to the central part of the specimen and the photos of the part of the crack tip are taken. $X_0$-values measured on these photos are shown in Fig. 5. Although, the deviation of the $X_0$-values is large, it is found that the $X_0$-value increases as the $J$-value increases. Thus, the thin specimens contract in the thickness direction and accompany the large plastic flows in the direction of the crack propagation.

### 3.2 Load versus displacement and $J$-versus displacement curves

Figure 6 shows the load versus displacement curves of the side-grooved CCT specimens of 1 and 2 mm thicknesses. The specimen thickness, $B$, is used as the normalizing parameter of the ordinate. In the case of the side-grooved specimen, the net thickness, $B_n$, is used. For the side-grooved specimens of 1 and 2 mm thicknesses, the load versus displacement curves are almost identical. The same is true for the nonside-grooved specimens of 1 and 2 mm thicknesses. The loads of the side-grooved specimens are about 80% higher than those of the nonside-grooved specimens up to a maximum load. As seen in the CT specimens, it is supposed that the plastic deformations at the crack tip and the part of the ligament are restrained and the stress triaxiality near the crack tip is elevated by the side-groove.

Figure 7 shows the relation between the $J$-values evaluated by Rice's formula and the displacements. The $J$-values of the side-grooved specimens of 1 mm thickness are slightly lower than those of the side-grooved specimens of 2 mm thickness, but both curves vary similarly. For the nonside-grooved specimens, both curves show good agreement. In the region in which the $J$-value is lower than 300 kN/m, the displacements of the nonside-grooved specimens are about 80% larger than those of the side-grooved specimens at the same $J$-value.

### 3.3 $J$ versus $SZW$ curves

The fracture toughness tests were carried out in accordance with the JSME standards. The $SZW$ of the 50% side-grooved specimens of 1 and 2 mm thicknesses are shown in Fig. 8. Hereafter, the open symbol denotes the point before the stable crack growth initiation and the cross symbol denotes the point which does not satisfy the requirements of the JSME standards. As proposed by Ohji et al., the experiments are adjusted so that many points gather in the vicinity of the stable crack growth initiation. In the case of the side-grooved specimens of 2 mm thickness, the critical stretched-zone width ($ SZW_c $) is about 0.091 mm and changes only slightly after the stable
crack growth initiation. Accordingly, SZWc is not affected by the plastic deformation after the stable crack growth.

Ohji et al.\(^3\) divided the development of the SZW into three main stages, as follows:

1. **Stage 1:** From the initiation of loading to the point of the stable crack growth initiation.
2. **Stage 2:** From the stable crack growth initiation to the point where the stable crack occurs along the entire fatigue precrack front.
3. **Stage 3:** The region where the \(SZWc\) is deformed under the stable crack growth.

They indicated that for the low strength and high toughness materials, the \(SZWc\) increased with an increase in the \(J\)-value at the 2nd and 3rd stages. Mutoh et al.\(^6\) also pointed out that for the SUS 316 steel, the small cracks occurred at the blunting part before the initiation of the stable crack growth, and they were expanded with an increase in the deformation and thus affected the apparent value of \(SZWc\). In our experimental results for the nonside-grooved and side-grooved specimens of 1 mm thickness, the \(SZW\) showed a large increase even at the 3rd stage and the valid \(J_m\) value could not be obtained using those specimens. The obtained \(J_m\) values were 249 and 175 kN/m, respectively for the side-grooved specimens with 2 mm and 1 mm thicknesses. The former was about 49% higher than the latter. The \(J_m\) values, obtained in the aforementioned specimens of 2 mm and 1 mm thicknesses, using the \(SZW\) only at the central part of the specimen were 244 and 175 kN/m, respectively. In the case of the side-grooved specimens, the \(J_m\) value obtained using the \(SZW\) at the central part of the specimen agree well with that obtained using the average \(SZW\).

Figure 9 shows the \(J\)-value versus \(SZW\) curves for the 1 TCT specimen and the nonside-grooved and side-grooved CCT specimens of 2 mm thickness. The \(J_m\) values of each specimen are respectively 491, 358, and 249 kN/m, which show a very large difference. Moreover, the \(SZWc\) for each is 0.199, 0.141 and 0.091 mm, respectively and decreases with a decrease in the thickness. In the author's previous study using the rolled steel SS 41\(^7\), it was found that the \(SZWc\) of the CCT specimen is lower than that of the CT specimen and decreases with a decrease in the thickness. This same tendency is, therefore, recognized in SUS 316 steel.

Nakamura et al.\(^8\) indicated that the valid \(J_m\) value could be obtained by the \(SZW\) method using the 1.5 mm-thick CT specimens of the titanium alloy steel. Ohtsuka\(^9\) indicated that the valid \(J_m\) value could be obtained using the 1 mm-thick CT specimens of A 204 Gr A (C-1/2 Mo) steel. However, these two steels are low toughness steels and there is no report for a high toughness steel such as SUS 316. As shown in Fig. 9, the valid \(J_m\) values are not obtained using the nonside-grooved and side-grooved CCT specimens of 2 mm thickness.

### 3.4 \(J-R\) Curves

The shape of the stable crack front varies considerably along the thickness and is very irregular, as
shown in Fig. 2. Especially, the stable crack front becomes a thumbnail shape which projects only at the central part of the largely necking specimens. Therefore, the stable crack extension at the central part of the specimens is used as $\Delta a$. Figure 10 shows the $J$-$R$ curves of the side-grooved specimens of 2 and 1 mm thicknesses. Both $J_{in}$ values are 242 and 153 kN/m, respectively. For the side-grooved specimens of 2 mm thickness, the $J_{in}$ value obtained by means of the $R$-curve method nearly coincides with that obtained by means of the $SZW$ method. On the other hand, for the side-grooved specimen of 1 mm thickness, the former is about 23% lower than the latter.

The $J$-$R$ curves for the 1 TCT specimen, the nonside-grooved and side-grooved specimens of 2 mm thickness are shown in Fig. 11. Their $J_{in}$ values are 444, 349 and 242 kN/m, respectively. The $J_{in}$ value obtained by means of the $R$-curve method for the 1 TCT specimen is about 10% lower than that obtained by means of the $SZW$ method, while the $J_{in}$ values obtained by means of both methods for the CCT specimens nearly coincide.

The $J_{in}$ values of the nonside-grooved and side-grooved CCT specimens of 2 mm thickness are 21% and 45% lower, respectively, than that of 1 TCT. Thus, the valid $J_{in}$ value cannot be obtained even by means of the $R$-curve method, as in the $SZW$ method. From the above results, it is clear that there are many problems in the fracture toughness testing procedure of the low strength and high toughness thin specimen.

The first problem is to determine how the stress triaxiality varies near the crack tip. McMeeking et al.\textsuperscript{(10)} indicated that the stress triaxiality of the bend type specimen is higher than that of the tension type specimen. The minimum specimen size requirement for a valid $J_{in}$ test is discussed by the scalar, $M$, expressed as follows:

$$M = L/(\sigma_0)$$

where $L$ denotes the ligament width and $\sigma_0$ denotes the yield stress.

For the CT specimens, McMeeking et al.\textsuperscript{(10)} and Landes et al.\textsuperscript{(11)} proposed that the $M$ value equals 25. This requirement is employed in the JSM\textsuperscript{(12)} and ASTM\textsuperscript{(12)} standards. However, there are some reports which indicate that the valid $J_{in}$ value can be obtained even though the specimen does not satisfy the size requirement. Although the $M$ value of 10.5 was somewhat smaller than 25, the valid $J_{in}$ value was obtained by Ohitsuka\textsuperscript{(19)}.

For the CCT specimens, the valid $J_{in}$ value of the general rolled steel was obtained up to the conditions that $M = 20$ and $M_0 = 9.5$.\textsuperscript{(17)} The minimum specimen size requirement has been discussed from the experimental aspect which is lower than $M = 200$.

From the stress-strain field near the crack tip obtained by McMeeking\textsuperscript{(10)}, the distributions of stress and the equivalent plastic strain of edge-cracked bend-type specimens agree well with those of the small scale yielding in the region that $R/(\sigma_0) = 1.0$ up to $M = 9$. Here $R$ denotes the distance from the crack tip. For the CCT specimens, the stress distribution agrees well with that of the small scale yielding in the region that $R/(\sigma_0) = 0.5$, while the distribution of the equivalent plastic strain.

**Fig. 10** $J$-$\Delta a$ curves

**Fig. 11** $J$-$\Delta a$ curves
rises gradually with a decrease in $M$. Therefore, it is ambiguous to determine the end of $J$-dominance. The above results were obtained by the 2-D elastic-plastic finite element analyses, and more conclusive evidence is yet to be gained by the 3-D elastic-plastic analyses. However, we can presume that the equivalent plastic strain increases with a decrease in the thickness. Ohtsuka et al.\(^{(13,14)}\) indicated that the equivalent plastic strain at the onset of the stable crack growth becomes constant in the region that $\sigma_e/\bar{\sigma}$ is larger than 1.2. Here $\sigma_e$ denotes the hydrostatic stress and $\bar{\sigma}$ denotes the equivalent stress. We can assume that when the average equivalent plastic strain over a certain region ahead of the crack tip, which corresponds to the mean free path of inclusions or precipitate particles, reaches the critical equivalent plastic strain at the initiation of the stable crack growth, the stable crack growth is initiated by the coalescence of cracks and voids. Then, the $J$-value at the moment when the equivalent plastic strain in this region reaches the critical value, decreases gradually with a decrease in the thickness or the ligament width of the specimen. Accordingly, it is qualitatively considered that the $J_m$ value decreases with a decrease in the thickness.

The second problem is how we estimate the $J$-value of the CCT specimen. The $J$-value evaluated by Rice's formula can estimate the $J$-value at the central part of the specimen for the specimen thicker than 6 mm, but the difference between both $J$-values increases with a decrease in the thickness\(^{(15)}\). Further, the side-grooved CCT specimens have not been analyzed until now so that the $J$-estimation method must await the further 3-D elastic-plastic analyses.

The final problem is how the stable crack growth under the plane stress state differs with that under the plane-strain state. Dimples are observed on the stable crack growth zone of both states, but further detailed observations, including the comparison between the dimple geometries on both fractured surfaces may be necessary to determine the condition of the stable crack growth initiation.

### 4. Summary

From the fracture toughness tests of the side-grooved thin CCT specimens of SUS 316, the following conclusions are derived:

1. The $J_m$ values of the side-grooved CCT specimens of 1 and 2 mm thicknesses are considerably lower than those of the 1 TCT specimen in either the $R$-curve or SZW methods.
2. The $J_m$ value of the side-grooved specimen of 2 mm thickness is smaller than that of the standard CCT specimen. Further, as the thickness of the specimen becomes thinner, the $J_m$ value decreases.
3. In the case of the 1 mm-thick CCT specimen with or without a side-groove, the contraction percentage of the thickness is very large so that it is not appropriate to use these specimens for the fracture toughness test.
4. There are many unknown points in a $J$-integral estimation method of the side-grooved thin CCT specimens. Therefore, the $J$-integral estimation method would have to be established by the 3-D elastic-plastic analyses.
5. The criterion of the initiation of the stable crack growth under the plane stress state has to be discussed after further detailed experiments.

### References

1. JSME standards, JSME S 001-1981.

