A NEW EXPERIMENTAL METHOD ON
BRITTLE FRACTURE PROPAGATION ARREST CHARACTERISTICS
OF WELDED STEEL PLATE.

K. MIYA
Nuclear Engineering Research Laboratory, University of Tokyo, Tokai-mura, Ibaraki-ken, Japan

K. MINAMI
Product Research and Development Laboratories,
Nippon Steel Company, Fuchinobe, Sagamihara-shi, Japan

Y. ANDO
Department of Nuclear Engineering, University of Tokyo, Bunkyo-ku, Tokyo, Japan

SUMMARY

It is widely believed that a brittle crack usually does not propagate along a weld bead of steel plate because of welded residual compression stress near notch root. From such a viewpoint the WES rule in Japan is related to the fracture toughness of base plate only. The basic concept of the rule is referred to the fact that brittle fracture accidents of welded steel structures may be prevented if the base metal used has higher fracture toughness than that prescribed in the rule in accordance with the crack size. On the other hand the fact shows that there has been many accidental examples where the brittle crack had gone along the welded bead more than a few meters long. And so the fracture toughness of welded parts should be examined to guarantee the safety of the steel structure.

The usual ESSO test has not been successful for the propagation arrest test of the welded part. The paper shows a new type specimen which is a modification of the usual ESSO specimen with regard to notch geometry. It is machined with a chevron notch instead of a usual straight one. The brittle crack that starts from the chevron notch root goes along the weld bead because of higher mechanical constraint near the notch root. Three kinds of steels were here used and welded by three kinds of welding methods: manual welding, submerged arc welding, and electro-gas welding. In order to search the correlation between Charpy impact test results and fracture toughness, Charpy tests by 2 mm V-notch and chevron notch were conducted. The transition temperature of chevron notch is higher than that of 2 mm V-notch because of higher mechanical constraint.

With regard to the brittle fracture propagation arrest characteristics of welded steel plate, the following conclusions were obtained.

1. It is possible to get the propagation-arrest characteristics of welded parts if the chevron notched ESSO specimen is used.
2. $K_c$ values of welded parts are strongly affected by the welding conditions, for example, heat input, presence of reinforcement, geometry of fusion line.
3. The fracture toughness of the welded part is considerably lower than that of the base metal.
4. The correlation between $K_c$ values and absorbed energy of Charpy impact test is not in agreement with the WES rule in Japan.
I. Introduction

The WES rule[1] is considered to be very useful for a criterion of a propagation-arrest characteristics of a brittle crack initiated in structural steel plate. But it assumes that the brittle crack will turn aside from a welded bead into a base metal, and therefore the rule is not available when the crack which initiates from the welded defect arrests at a welded part after the propagation of long distance along the bead. Examples of such accidents are reported in Ref.[2]. Now that it is necessary to get the propagation-arrest characteristics of the welded part.

Many investigations [3], [4], [5], [6] have been already made with regard to an effect of welded residual stress on conditions of the propagation of the crack, but experiments in which the brittle crack may go along the bead and arrest there have been few.

The modified ESSO Test specimen that is machined with a chevron notch instead of usual straight one has been here developed. There is so strong mechanical constraint by the chevron notch that the brittle crack may be forced to propagate along the welded bead.

Here are investigated effects of some factors, for examples, welding conditions, on the fracture toughness of three kind of structural steels.

II Experimental Method

(1) Material

Materials tested here are a 60 kg/mm² class high tensile strength steel for large welding heat input (HT-60S), a usual 60 kg/mm² class high tensile steel (WT-60) and a 50 kg/mm² class steel (SM-50B). Chemical composition and mechanical properties are summarised in Tab.1 and Tab.2 respectively. A 25 mm thick plates of HT-60S and WT-60 were for submerged arc welding and a 32 mm thick plates were for electro gas welding. SM-50B was for submerged arc welding only.

(2) Welding Condition

The welding conditions are shown in Fig.1. Groove geometries of manual welding, submerged arc welding and electro gas welding are of V type, asymmetric X type and asymmetric X and V type respectively. The welding heat inputs were about 190 KJ/cm for V groove and 70 KJ/cm - 120 KJ/cm for another types.

(3) Configuration of specimen

The configurations of specimens and notch details are shown in Fig.2. The most of specimens used were shown in Fig.2-(a). The compression residual stress at the notch root in Fig.3 is nearly equal to yield stress and so that it may be difficult to start a brittle crack from the part in case of a lower
gross stress (σ < 13 kg/mm²). The specimen of T-joint in Fig.2-(b) is for the test where the brittle crack should start easily under the lower gross stress. In fact such specimens were machined with chevron notch.

(4) Experimental method

The brittle crack should be apt to pass into a base metal from a welded bead because of welded residual stress, gradient of temperature near the notch root, inhomogeneity of the material etc.

The specimen was given the temperature gradient which was lower near the notch root than other part. The temperature at the notch should be enough low to initiate the brittle crack by a constant hammer impact, even if gross stress is lower, but the crack would go into the base metal if the temperature is below -120°C. The specimen was with a slight angular distortion to superpose a tensile bending stress at the notch root of which a situation is shown in Fig.4. The angular distortion is θ = 3/500. Evaluation of K-value is given in the figure.

In addition to the modified ESSO Test with chevron notch, the Charpy impact test of a welded part was conducted, where two notch geometries of 2 mm V notch and chevron notch were applied.

III Consideration on the Experimental Results

(1) Charpy impact test

The test results are shown in Fig.5 - Fig.9. The transition temperature of the chevron notched specimen is higher than that of 2 mm V notch specimen, and the shear energy of the former is smaller than that of the latter. It has been explained by the author(7) that an absorbed energy necessary to initiate crack from the chevron notch root was smaller than the usual crack, because of a higher mechanical constraint. A tip of chevron notch could be machined to locate at a correct place whereas the 2 mm V notch passed through not only a bonded part but also a base metal in case of an inclined fusion line to result in the scatter of data which could not give a true characteristics of the bonded part.

The toughnesses of deposit metal, bonded part and heat affected zone are shown in Fig.5. The absorbed energy of HT-60S is more than that of WT-60. This suggests that the fracture toughness (Kc - value) of HT-60S should be better. The test results in case of the submerged arc welding and the electro gas welding are shown in Fig.6,7 and Fig.8,9 respectively. The impact values become smaller as the heat input is greater, and a comparison of them with regard to HT-60S and WT-60 is as follows;

X groove (Electro gas Weld.) > Submerged Arc Weld.

> V groove (Electro gas Weld.)

The transition temperatures, VTₜ and VTₖ of 2 mm V notch are listed in Tab.3.
(2) The propagation-arrest characteristics
Stress intensity factor $K$ can be given in eq.(1) in case that a bending
moment is superposed to an applied tensile stress:$^8$

$$K = K_T + K_B$$  \hspace{1cm} (1)

$K_T$-value due to the tensile gross stress is given as follows;

$$K_T = \sigma \cdot f(C/B) \sqrt{\pi C}$$  \hspace{1cm} (2)

where

- $C$ = crack length
- $B$ = breadth of the specimen
- $\sigma$ = applied gross stress

$$f(C/B) = \sqrt{\frac{B}{W C} \tan\left(\frac{\pi C}{B}\right)}$$

$K_B$ - value is given in eq.(3)$^9$

$$K_B = 6M \cdot g(C/B)(B - C)^{-\frac{3}{2}}$$  \hspace{1cm} (3)

where

- $M$ = bending moment
- $g$ = modification factor

From eq.(1), (2) and (3), $K$ value is given as follows;

$$K = \sigma \cdot f(C/B) \sqrt{\pi C} + 6Mg(C/B)(B - C)^{-\frac{3}{2}}$$  \hspace{1cm} (4)

All the experimental results are shown in the figures. The relations between
modified gross stress and arrest temperature are shown in Fig.10 - Fig.13.
Arrest temperature of HT-60S is considerably lower than those of WT-60 and
SM-50B as shown in Fig.10. Arrest temperatures when a design stress is
assumed to be $\sigma_Y/3$ ($\sigma_Y$ = yield stress) are summarised in Tab.4 where the
yield stresses are 51 kg/mm$^2$ for HT-60S and WT-60 and 39 kg/mm$^2$ for SM-50B.

It is apparent from these results that the arrest temperature shifts to
a region of higher temperature in case with reinforcement. The results on
the electro gas welding of HT-60S and WT-60 shown in Fig.11 agrees with that
of the Charpy test results in Fig.8 and 9.

The results of HT-60S shown in Fig.12 shows that the arrest temperature
shifts to the region of higher temperature as the heat input becomes larger.

The arrest temperature of WT-60 welded with submerged arc welding is
lower than that with electro gas welding as shown in Fig.13 and this result
coincides with the Charpy test result in Fig.9. Temperature dependences of
$K_C$ values for three welded materials are shown in Fig.14 - Fig.17 in which
K_C-values were calculated with eq.(2) because K_B-values are considerably small in comparison with K_T-values as shown in eq.(3) if crack length is below 300 mm and uniform bending moment would not applied if the crack is long (>300 mm).

K_C-values of the welded part show the same temperature dependence of Arrhenius type as the case of the base metal. The fracture toughness of HT-60S is the best of three materials as shown in Fig.14.

The effects of various factors on K_C value are summarised as follows;
(a) The fracture toughness is almost insensitive to the welding method but extremely sensitive to heat input.
(b) If a number of welding pass (for example, manual welding) is more, the toughness becomes better.
(c) If the fusion line is straight, the toughness is not good.
(d) The reinforcement gives a lower K_C-value because of a stress concentration at a toe.
(e) K_C-value of the bonded part is larger as the impact value is higher.

(3) Fracture appearance of specimen
Some examples of the crack path are shown in Photo.1. The location of the arresting crack tip is shown in Photo.2. It can be seen that the brittle crack propagates along the welding bead and stops near the welded part.

IV Conclusion
As to the brittle fracture propagation-arrest characteristics of welded steel plate, the following conclusions were made clear.
(1) It is successful to get the propagation-arrest characteristics of welded part if the chevron notched ESSO specimen is applied.
(2) K_C values of welded bond are influenced by welding conditions, for examples, heat input, presence of reinforcement, geometry of fusion line.
(3) Material that has higher absorbed energy in charpy impact test shows higher K_C values. And so fracture toughness of welded bond is considerably low comparing with that of base metal.
(4) Evaluation of safety of steel structure should be based on the fracture toughness of the welded part which may be given, for examples, by the chevron notched ESSO specimen.

Acknowledgement
Thanks are due to Dr. S.Kanazawa for his grateful advices and Mr. M.Satoh for his positive aid.
References

[1] WES Rule: Japan Welding Association

### Table 1 Chemical Compositions of Steels of Steels Used

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Ni</th>
<th>Ti</th>
<th>V</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HT-60S</td>
<td>0.132</td>
<td>0.28</td>
<td>1.34</td>
<td>0.012</td>
<td>0.008</td>
<td>0.23</td>
<td>0.25</td>
<td>0.019</td>
<td>—</td>
<td>25 &amp; 32</td>
</tr>
<tr>
<td>WT-60</td>
<td>0.15</td>
<td>0.30</td>
<td>1.30</td>
<td>0.011</td>
<td>0.005</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.03</td>
<td>25</td>
</tr>
<tr>
<td>SM-50B</td>
<td>0.16</td>
<td>0.31</td>
<td>1.42</td>
<td>0.015</td>
<td>0.009</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>32</td>
</tr>
</tbody>
</table>

### Table 2 Mechanical Properties of Steels Used

<table>
<thead>
<tr>
<th>Steel</th>
<th>Thickness (mm)</th>
<th>Yield stress (Kg/mm²)</th>
<th>Tensile strength (Kg/mm²)</th>
<th>Elongation (%)</th>
<th>v_Trs (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
<td>62.1*</td>
<td>69.7*</td>
<td>19.0*</td>
<td>-88</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>53.1</td>
<td>64.5</td>
<td>28.5</td>
<td>-77</td>
</tr>
<tr>
<td>WT-60</td>
<td>25</td>
<td>51.0</td>
<td>65.0</td>
<td>32.0</td>
<td>-56</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>55.0</td>
<td>67.0</td>
<td>32.0</td>
<td>-50</td>
</tr>
<tr>
<td>SM-50B</td>
<td>25</td>
<td>39.0</td>
<td>56.0</td>
<td>24.0</td>
<td>-13</td>
</tr>
<tr>
<td>Steel</td>
<td>Submerged arc welding</td>
<td>Electro gas Welding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>------------------------</td>
<td>---------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>vTs vTe</td>
<td>X Groove vTs vTe</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HT-60S</td>
<td>-28 -3</td>
<td>0 -18 -28 -20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WT-60</td>
<td>-15 -9</td>
<td>+5 -0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SM-50B</td>
<td>-8 +23</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4 Arrest Temperature at design stress \( \sigma_p = \frac{1}{3} \sigma_y \)

<table>
<thead>
<tr>
<th>Steel</th>
<th>Base metal</th>
<th>Submerged arc welding</th>
<th>Electro gas welding</th>
<th>Manual welding</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>X groove vTe</td>
<td></td>
</tr>
<tr>
<td>HT-60S</td>
<td>-40</td>
<td>-29</td>
<td>-32 0</td>
<td></td>
</tr>
<tr>
<td>WT-60</td>
<td>-15</td>
<td>+4</td>
<td>+20 +30</td>
<td>-28</td>
</tr>
<tr>
<td>SM-50B</td>
<td></td>
<td>-3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 1** Welding conditions
Fig. 2  Configurations of specimens and notch details

Fig. 3  Distribution of residual stress perpendicular to welded line for chevron notched ESSO specimen

Fig. 4  Testing apparatus

Fig. 5  Distribution of charpy impact values at various locations
Fig. 6 Test results of 2 mm V notch charpy for HT-60S, WT-60 and SM-50B (Bond)

Fig. 7 Test results of chevron notched charpy for HT-60S, WT-60 and SM-50B (Bond)

Fig. 8 Results of charpy test for HT-60S (Bond)

Fig. 9 Results of charpy test for WT-60 (Bond)
Fig. 10  Relation between modified gross stress and arrest temperature (Submerged arc welding)

Fig. 11  Relation between modified gross stress and arrest temperature (Electro gas welding)

Fig. 12  Relation between modified gross stress and arrest temperature (HT-60S)

Fig. 13  Relation between modified gross stress and arrest temperature (WT-60)
Fig. 14 Temperature dependence of $K_c$ value in case of submerged arc welding

Fig. 15 Temperature dependence of $K_c$ value in case of electro gas welding

Fig. 16 Temperature dependence of $K_c$ value for HT-60S

Fig. 17 Temperature dependence of $K_c$ value for WT-60
manual welding (WT-60)

submerged arc welding (HT-60S)

x groove
ev groove
electro gas welding (WT-60)
electro gas welding (HT-60S)

HT-60S v groove

WT-60 v groove
electro gas welding