Effect of temperature gradient on crack initiation

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Compact tension (CT) specimens of pressure vessel steel A533B have been subjected to linear distributions of temperature along the crack line. The temperature dependence of fracture toughness for the A533B steel creates a fracture toughness gradient in such a specimen. The specimens simulated an irradiated pressure vessel wall and a functionally gradient material. The CT specimens subjected to linear distributions of temperature were tested to evaluate the fracture toughness for crack initiation. In all tests, the temperature at the crack tip was kept at -10°C or -55°C. If the value of the temperature gradient ahead of the crack tip exceeded a critical value, the fracture toughness deviated from the toughness obtained under a uniform temperature of -10°C or -55°C.

1 INTRODUCTION

Nuclear reactor pressure vessel walls are exposed to irradiation at their inner surfaces during the normal operation of power plant and damage of the wall material due to the irradiation varies gradually through the wall thickness. Pressurized thermal shock (PTS) has a potential to grow a crack in the embrittled pressure vessel wall in an unstable manner. Therefore, PTS crack growth problems have been studied experimentally and analytically.1-5

These previous studies, however, were mainly concerned with the investigation of dynamic effects on fast crack propagation and arrest events. In the reported works it is always assumed that the material resistance against the crack growth is dominated by the material properties just at the crack tip.

On the other hand, experimental results obtained by K. Kussmaul et al.4 indicated that when a specimen was subjected to a linearly varying temperature along the specimen width, the crack initiation fracture toughness of the MoV steel was remarkably enhanced in comparison with the toughness in the specimen kept at the same uniform temperature as that at the crack tip in the temperature gradient test. When the PTS crack growth is evaluated to assess the integrity of pressure vessels exposed to irradiation, the crack initiation criterion for the nonhomogeneous materials is an important problem to be clarified. In addition functionally gradient materials are being developed for utilization in structural components operated under ultra-severe conditions. The above problem is also intrinsic to the evaluation of the fracture toughness for such materials.

The aims of the present work are to generate experimental data on the crack initiation toughness for nonhomogeneous materials regarding their mechanical properties and to establish a crack initiation criterion for such materials. In the experiment, nonhomogeneity of...
the mechanical properties in specimens is created by generating a temperature gradient in the specimen since the mechanical properties of steel are known to be especially susceptible to the temperature.

2 EXPERIMENTAL PROCEDURES

2.1 Material and specimens

The material used in the experiment was A533B Cl.1 steel such as is used for nuclear pressure vessels. The chemical compositions and mechanical properties of this material are shown in Tables 1 and 2. The specimen configuration and dimensions are shown in Fig. 1. A 10 mm thick three-point bend specimen was used to measure temperature dependence of the fracture toughness of this steel. A 100 mm wide and 12 mm thick compact tension specimen was used for fracture test under the temperature gradient. The multiple specimen method was used to evaluate the elastic-plastic fracture toughness $J_{fc}$. Six specimens having the same dimensions were prepared in each test.

2.2 Cooling system

The experiments to illustrate the temperature dependence of the fracture toughness were carried out in a container filled with a cooling medium. A roller for loading was fixed inside the container. A three-point bend specimen was immersed in a mixture of liquid methanol and frozen methanol cubes chilled to $-100^\circ$C.

The temperature gradient tests were conducted by use of a cooling/ heating system. The cooling system used in the test is schematically shown in Fig. 2(a). Isopentane, cooled in a liquid nitrogen bath, was circulated by a magnetic pump. Two small heat exchangers were attached on the specimen surfaces as shown in Fig. 2(b). In the test series, the ligament side, or the notch mouth side, was cooled and the other side was heated by nichrome wires to achieve a negative or positive temperature gradient across the specimen width.

A heat exchanger was assembled into two separate parts so designed that it would not prevent the specimen deforming. A voltage applied to the nichrome wires was set to keep the temperature at the specimen end constant. The specimen surfaces were totally covered with thermal insulation. Much attention was paid to hold the temperature at the crack tip at $-10^\circ$C or $-55^\circ$C in the test series.

2.3 Fracture toughness tests

All the fracture toughness tests were conducted in accordance with the method developed by the

<table>
<thead>
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<th>Table 2. Mechanical properties of A533B steel</th>
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<tr>
<td>Yield strength (MPa)</td>
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<tr>
<td>----------------------</td>
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<tr>
<td>550</td>
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Table 1. Chemical composition of A533B steel (wt%)

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<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
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<td>0.18</td>
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<td>0.005</td>
<td>0.002</td>
<td>0.65</td>
<td>0.12</td>
<td>0.52</td>
<td>0.16</td>
<td>0.0098</td>
</tr>
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</table>

Fig. 1. Specimen dimensions.
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3 EXPERIMENTAL RESULTS

3.1 Temperature dependence of fracture toughness

A crack growth resistance curve at a test temperature of \(-60^\circ C\) is shown in Fig. 3. In the fracture toughness test at a temperature of \(-100^\circ C\), the specimen fractured in a brittle manner and the fracture toughness \(K_{ic}\) evaluated by the ASTM E399 standard method. In the figure the solid symbols along the blunting line indicate the stretched zone width and the open symbols indicate the extension of a crack, including the stretched zone width and the physical crack growth amount. The critical value of the J-integral for crack initiation is defined as the value at the crossing point of the two lines. The critical J-integral can be interpreted as the initiation fracture toughness at the onset of stable crack growth whereas the \(J_{ic}\) value obtained by the ASTM–E813 method is the crack growth resistance value at the physical crack extension of more than 0.2 mm.

The J-integral values for crack initiation, \(J_{ic}\), are plotted as a function of the test temperature.
According to ASTM-E813, the size required for a plane strain condition to be obtained is 10 mm for the specimen thickness at the test temperature of -10°C. Therefore all of the $J_{IN}$ values shown in Fig. 4 were obtained under the plane strain condition. The $J_{IN}$ is converted to $K_{IC}$ by the following formula:

$$K_{IC} = \sqrt{\frac{J_{IN}E}{1 - \nu^2}}$$

where $E$ is Young's modulus and $\nu$ is Poisson's ratio.

In Fig. 5, the calculated $K_{IC}$ is plotted as a function of the test temperature. The upper shelf fracture toughness is around 230 MPa$\sqrt{\text{m}}$ for the temperature above -30°C. Since the fracture toughness steeply decreases below the temperature of -50°C, the temperature at the crack tip was set to -55°C for two of the three temperature gradient tests.

### 3.2 Fracture toughness test under temperature gradient

The temperature in the specimen was monitored by using six thermocouples mounted on the specimen surface. The fracture toughness tests were conducted for three temperature gradients. One example of the measured temperature distribution in the specimens is shown for the negative temperature gradient in Fig. 6. The ligament end of the specimen was chilled at around -120°C and the notch mouth end was kept at -10°C. Six specimens were used for $J_{IC}$ test under this temperature gradient. The temperature distribution was almost identical for the six specimens. It was linear near the center of the specimen but a steep change occurred near the specimen ends because of imperfect thermal insulation. The crack tip was located at the origin of the abscissa. The temperature at the point was around -55°C and the temperature gradient there as -0.58°C/mm.

Since the temperature distribution in the specimen can be regarded as a straight line, thermal stresses are not brought out in the specimen. The Young's modulus of the steel is approximately independent of the temperature in the range of the experiment. Considering the above conditions we will use the J-integral in an
engineering sense to evaluate the fracture toughness without rigorous discussion of the path independence of the J-integral for the non-homogeneous material regarding the plastic flow properties in this work.

The crack growth resistance curve was obtained for the specimens by using multiple specimens subjected to the negative temperature gradient shown in Fig. 6. The result is shown in Fig. 7(a). Since the result for the crack extension of 1.5 mm deviates significantly from the other results, the crack growth resistance curve is drawn for the data excluding this one. The crack growth resistance curves were measured in a similar way as mentioned above for the other two temperature gradients. One of them is shown for a crack tip temperature of $-55^\circ$C and its gradient of $0.26^\circ$C/mm in Fig. 7(b). $J_{IN}$ values obtained for all of the test series are listed in Table 3.

$$\Delta K_{OC} / \Delta x = -1.27 \text{ (MPa m/mm)}$$
$$\Delta T / \Delta x = -0.58 \text{ (}{^\circ}\text{C/mm)}$$
$$J_{IN} = 144 \text{ (kN/m)}$$

4 DISCUSSION

From the temperature dependence of fracture toughness obtained in Fig. 5, and the temperature distribution in the specimen as shown in Fig. 6, it is possible to estimate the fracture toughness distribution in the specimen. This fracture toughness gradient is plotted for this case in Fig. 8, where it is also compared with the actual fracture toughness obtained by fracturing the specimen with the negative temperature gradient (negative fracture toughness gradient) which agrees well with the results obtained under uniform temperature tests in this case.

In Fig. 3, the intersection point of the blunting line and the crack growth resistance line gives the critical stretched zone width (SZW) for crack initiation. The critical SZW is also measured on the fractographs of the specimens used to draw the crack growth resistance line. This is based on the hypothesis that the critical SZW does not change in size after the crack initiation. In Figs 9, 10 and 11, the SZW is plotted as a function of the J-integral for the uniform temperature of $-60^\circ$C, and the negative and positive temperature gradients. The critical SZW is smaller in the

![Fig. 7](image-url) Crack growth resistance curves for temperature gradient tests. (Crack tip temperature: $-55^\circ$C).

![Fig. 8](image-url) Comparison of estimated fracture toughness with the result of a negative temperature gradient test.

<table>
<thead>
<tr>
<th>Temperature gradient ($^\circ$C/mm)</th>
<th>Crack tip temperature ($^\circ$C)</th>
<th>$\Delta K_{OC} / \Delta x$ (MPa m/mm)</th>
<th>$J_{IN}$ (R-curve) (kN/m)</th>
<th>$J_{IN}$ (SZW) (kN/m)</th>
</tr>
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<tbody>
<tr>
<td>-0.8</td>
<td>-10</td>
<td>-1.27</td>
<td>-1.41</td>
<td>2.19</td>
</tr>
<tr>
<td>-0.5</td>
<td>-55</td>
<td>-1.57</td>
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<td>1.44</td>
</tr>
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<td>0.0</td>
<td>-60</td>
<td>0</td>
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<td>0.3</td>
<td>-55</td>
<td>0.55</td>
<td>2.31</td>
<td>3.01</td>
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Table 3. $J_{IN}$ values obtained by temperature gradient tests
Fig. 9. Stretched zone width as a function of J-integral value for a uniform temperature.

Fig. 10. Stretched zone width as a function of J-integral value for a negative temperature gradient.

Fig. 11. Stretched zone width as a function of J-integral value for a positive temperature gradient.

Fig. 12. Change of fracture toughness with fracture toughness gradient.
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toughness gradient in Fig. 12. When the fracture toughness gradient is \(-1.27 \text{ MPaVm/mm}\), the fracture toughness decreases by approximately 12%. On the other hand, when the fracture toughness gradient is positive of an amount of \(0.5 \text{ MPaVm/mm}\), the fracture toughness increases by approximately 30%. It should be noted that the effect of a positive fracture toughness gradient is much larger than that of a negative one.

Similar temperature gradient tests have been reported for polymethylmethacrylate (PMMA). In those tests, the temperature at the crack tip was fixed at 30°C. When the fracture toughness gradient at the crack tip was in the range of \(6.0 \times 10^{-3}\) to \(-6.0 \times 10^{-3} \text{ MPaVm/mm}\), the fracture toughness was almost constant for the range of zero to \(-6.0 \times 10^{-3} \text{ MPaVm/mm}\). Since the fracture toughness values for both the materials are remarkably different from each other, the direct comparison of the fracture toughness gradient is meaningless. Then, the gradients described above, \(-1.0 \text{ MPaVm/mm}\) and \(-6.0 \times 10^{-3} \text{ MPaVm/mm}\) are normalized with the fracture toughness value under the uniform temperature. They are \(5.5 \times 10^{-3} \text{ (l/mm)}\) for the A533B steel and \(5.3 \times 10^{-3} \text{ (l/mm)}\) for the PMMA. Although, the relative gradients of fracture toughness are approximately the same for both the materials, the effect of fracture toughness gradient appears significantly varied for the A533B steel. Linear elastic fracture mechanics can be applied to evaluate the fracture toughness of PMMA whereas elastic–plastic fracture mechanics has to be applied for evaluation of the fracture toughness for A533B steel. This means that a fracture process zone of the PMMA is quite smaller than that of the A533B steel and a plastic deformation zone is also restricted near the crack tip in the PMMA whereas it spreads widely in the A533B steel. The larger the fracture process zone and the plastic deformation zone are, the more sensitive the crack growth behavior is to inhomogeneity of the mechanical properties ahead of the crack tip.

The fracture toughness of PMMA also increases steeply as the fracture toughness gradient increases. The reason why the effect of a positive fracture toughness gradient on fracture toughness is much larger than that of a negative gradient is not yet clear.

5 SUMMARY

Inhomogeneity of the mechanical properties of pressure vessel steel A533B due to irradiation was simulated by the steel subjected to a temperature gradient since the mechanical properties of steel vary with the temperature. Fracture toughness tests were carried out under three temperature gradients. If the temperature gradient is small, the fracture toughness under the temperature gradient is the same as that under the uniform temperature. When the gradient is large, one apparent effect of the temperature gradient appears especially on the fracture toughness under a positive temperature gradient. Further investigations are necessary to clarify the effect of the temperature gradient in a quantitative manner.

ACKNOWLEDGEMENTS

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