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FRACTURE TOUGHNESS EVALUATION OF WELD-HAZ IN RPV STEEL USING MINI-C(T) SPECIMENS

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ABSTRACT

According to Japan Electric Association Code (JEAC) 4201-2007 [2013 addendum], the surveillance specimens of reactor pressure vessel are taken from base metal at a quarter thickness, weld metal and heat affected zone (HAZ) produced by butt-welding as representative materials. The fracture toughness values of HAZ may show a large uncertainty due to inhomogeneous metallurgical structures. Also, the inhomogeneous microstructure in HAZ may influence on the degree of uncertainty in the fracture toughness and the sensitivity to irradiation embrittlement.

We investigated the fracture toughness in HAZ of unirradiated material with respect to its distance from the fusion line of welds, where the amount of mixed microstructures change due to the thermal history during the welding. Mini-C(T) specimens of HAZ were harvested from the crack position at 0.5 mm, 1 mm and 2 mm from the fusion line of welds, where is acceptable region defined in JEAC 4201. The uncertainty of fracture toughness in HAZ, from the fusion line at 0.5 mm in particular, was larger than those of base metal at a quarter thickness. From the results of fracture toughness evaluation considering the standard deviation, there was the difference of reference temperature, T_0 in each position of HAZ. T_0 in all positions of HAZ was significantly lower than that of base metal, which means the fracture toughness in HAZ was greater than that of base metal at a quarter thickness. We have a plan to evaluate the fracture toughness of HAZ after irradiation, because the inhomogeneous microstructure in HAZ may be different sensitivity to irradiation embrittlement.

INTRODUCTION

For the structural integrity assessment of reactor pressure vessel (RPV), monitoring of irradiation embrittlement has been conducted in surveillance program. According to Japan Electric Association Code (JEAC) 4201-2007 [2013 addendum] (JEA, 2013), the surveillance specimens are taken from base metal at a quarter thickness (1/4T, T means wall thickness of RPV), weld metal and heat affected zone (HAZ) produced by butt-welding as representative materials. Recently, the monitoring and testing requirement of HAZ in surveillance program were eliminated in U.S. (10 CFR 50 Appendix H) (NRC federal); the Charpy T_{41J} of HAZ is considered to be generally lower than that of base metal including the irradiated data, even the data scatter of HAZ is larger than those of base metal and weld metal. The data scatter in here means the standard deviation of T_{41J} of ductile-to-brittle transition curve.

Meanwhile, the large uncertainty in each fracture toughness value of HAZ is caused by inhomogeneity of metallurgical structures due to the thermal history during the welding. The multi-layered welding for thick plates with 200 mm generates complicated metallurgical structures with the continuous change from the boundary between weld and base metal. J. Katsuyama et al. studied that the correlation between the microstructural characterization and the mechanical properties of HAZ in RPV steels, which were simulated the grain sizes and phases at each part of HAZ through the thermal treatment; the simulated HAZ close to weld metal indicated higher toughness than that of base metal, while simulated HAZ close to base metal indicated equivalent or slightly lower toughness than that of base metal due to their metallurgical phases.

In order that the fracture toughness of base metal can be representative of HAZ, it is necessary to clarify the effect of inhomogeneously mixed microstructure in actual HAZ on the degree of uncertainty in the fracture toughness and the sensitivity to irradiation embrittlement. In this study, we investigated the difference of fracture toughness in actual HAZ, and compared with the fracture toughness of base metal at 1/4T. The fracture toughness of the HAZ with respect to its distance from the fusion line was evaluated. The uncertainty of fracture toughness in each evaluated HAZ is confirmed. Also, the difference of reference temperature of fracture toughness, T_0, and its standard deviation from HAZ and base metal were compared.

EXPERIMENT

As shown in Table 1, the material used in this study was an A533B class 1 type, which was manufactured with high-Cu contents (0.13 wt.%) as the target for long-term operated RPV steel. Mechanical properties of the material at 1/4T are summarized in Table 2. Two plates with 200 mm of thickness were butt-welded along with longitudinal rolling direction of the base metal, which harvesting direction was the same as surveillance specimen. The butt-welding and post weld heat treatment was performed as same conditions with fabricating of the RPV steel. The width of HAZ region from the fusion line of weld metal to the base metal was 3~4 mm.

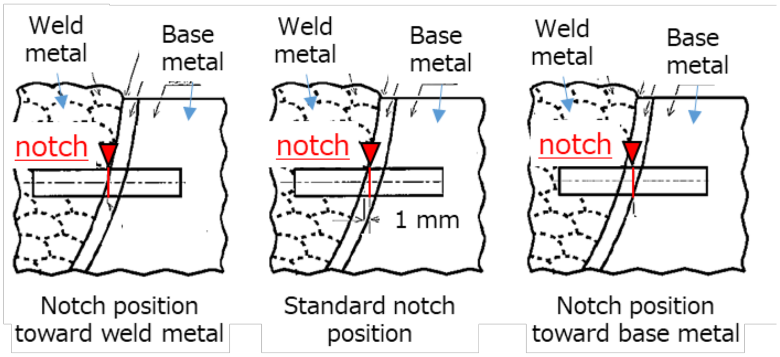
Table 1: Chemical composition of the base material (wt.%) [Ha Y. et al., 2021]

C	Si	Mn	P	S	Cu	Ni	Mo
0.19	0.25	1.46	0.011	0.014	0.13	0.59	0.5

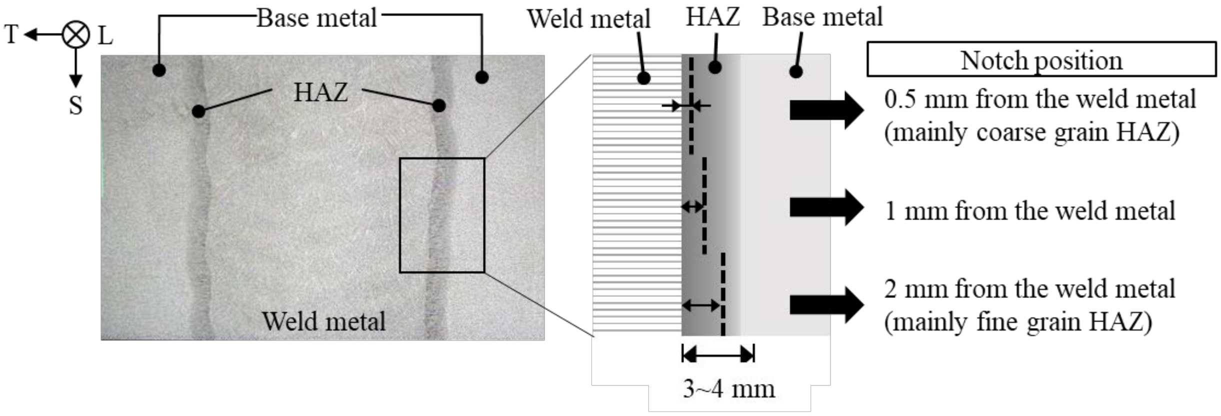
Table 2: Mechanical properties of the base material at 1/4T

Yield stress at room temperature (σ_y)	Ultimate tensile strength at room temperature (σ_u)	Charpy T_{41J} (T_{41J})	Upper shelf energy (USE)
482 MPa	592 MPa	-27°C	122 J

Figure 1 (a) shows the acceptable region of HAZ specimen harvesting defined in JEAC 4201. To evaluate fracture toughness of HAZ, miniature compact tension (Mini-C(T)) specimen was adopted. Mini-C(T) specimen is suitable to evaluate the fracture toughness of the materials within narrow area or from small amount such as HAZ. Mini-C(T) specimens of HAZ were harvested at 0.5 mm (mainly coarse grain HAZ), 1 mm and 2 mm (mainly fine grain HAZ, but the different amounts of mixed microstructures by thermal history during the welding) from the fusion line as shown in Figure 1(b). The specimens were taken from transverse (loading)-longitudinal (crack growth) direction with rolling direction. Fabrication of Mini-C(T) specimen without side groove (Figure 2), fracture toughness test and evaluation were performed based on the master curve method according to JEAC 4216-2015 (JEA, 2015).



(a) The acceptable region of HAZ specimen harvesting defined in JEAC4201



(b) Notch positions in HAZ
Figure 1 The specimen positions taken from HAZ

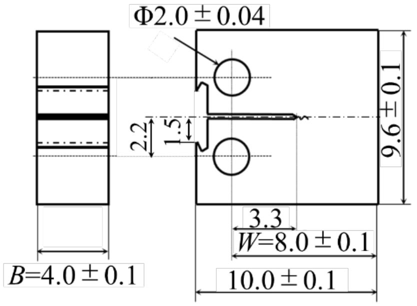


Figure 2 Geometry of Mini-C(T) specimen

Fatigue precracking was introduced in Mini-C(T) specimen using the compliance calibration method. Fracture toughness, K_{Jc}, was determined given by:

$$K_{Jc} = \sqrt{\frac{EJ_c}{1-v^2}} \tag{1}$$

E is the Young's modulus, and v is the Poisson's ratio. J_c is J-integral as the sum in J-integral values of elastic and plastic components at the fracture point, it can be calculated from the load-displacement curve obtained from fracture toughness tests. According to JEAC 4216-2015, Young's modulus at the test temperature was determined, and the fracture toughness values were converted to its equivalence of 1T-C(T) specimen. In addition, the validity of the fracture toughness was confirmed using an upper limit ($K_{Jc(\mathrm{limit})}$).

The fracture toughness value correlated the temperature can be described as follows:

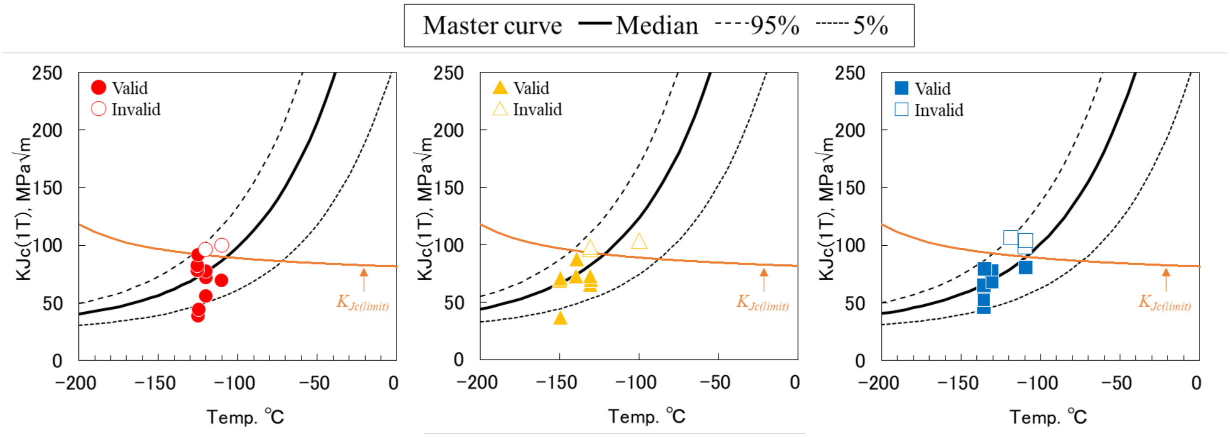
$$K_{Jc(0.xx)} = 20 + \left[ln\left(\frac{1}{1-0.xx}\right)\right]^{\frac{1}{4}}\{11 + 77\exp[0.019(T - T_0)]\} \tag{2}$$

Where 0.xx represents the selected cumulative probability level of fracture; for example, for the 50% in median value of the probability, 0.50. The fracture toughness $K_{Jc\,(0.50)}$ at each temperature can be curved by equation (2), so called master curve. T is test temperature, and T_o is reference temperature when $K_{Jc\,(0.50)}$ =100 MPa$\sqrt{}$m.

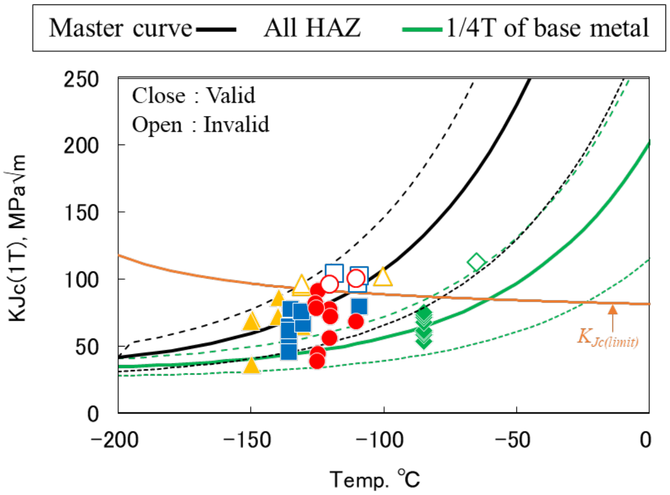
RESULTS AND DISCUSSION

Fracture toughness and master curves of HAZ

The values of fracture toughness from three positions in HAZ were different from each other due to the amounts of inhomogeneous microstructures. Figure 3 (a)~(c) shows the data and the master curve of each position. All fracture toughness at each tested temperature were converted to equivalent fracture toughness of 1T-C(T) specimen, $K_{Jc(1T)}$. In this study, there was no discarded data, and all invalid data of 2~3 points at each position were caused by greater values than $K_{Jc(\mathrm{limit})}$. In addition, no inclusions or dimple fracture surfaces were observed in all specimens. Master curves of fracture toughness from all positions in HAZ (black lines) and the base metal at 1/4T (green lines) were plotted in Figure 3 (d). The master curve of the base metal at 1/4T is remarkably at high temperature area (the right side), which means the brittle fracture occurred by at higher temperature.



(a) 0.5 mm HAZ (b) 1 mm HAZ (c) 2 mm HAZ



(d) All positions of HAZ and the base metal at 1/4T [Ha Y. et al., 2021]
Figure 3 Fracture toughness and master curve at each case of positions

The uncertainty of fracture toughness in HAZ

To investigate the uncertainty of fracture toughness in HAZ, Weibull probability distribution of the data set of T_0 was confirmed. The cumulative fracture probability, P_f, is given by:

$$P_f = \frac{i-0.3}{N+0.4} \tag{3}$$

where i is the ascending order of valid data and N is total tests number. The Weibull distribution of fracture toughness can be plotted by correlation between the cumulative fracture probability and the fracture toughness, so its slope as shown in Figure 4 indicates the magnitude of the uncertainty of fracture toughness in each case. Since the uncertainty depends on the material, test temperature and so on, the slope values are varied in experiment. When the slope value is low, the fracture toughness is largely scattered. The fracture toughness data obtained at different tested temperature were converted as to be those were equivalent to the fracture toughness at the temperature T=T_0−30℃ for adjusting the uncertainty depending on temperature described in eq. (2). The uncertainty was larger where the HAZ was close to the fusion line (HAZ at 0.5 mm). The Weibull distribution of HAZ at 2 mm was almost equal to 4, otherwise that of base metal was 5.6. Understandably, the uncertainty is related to the tested number, however, all the data resulted from 11~12 data set. We investigated the uncertainty of fracture toughness in all HAZ positions tested 34 specimens as shown in Figure 4. The data of green symbols in graph looks like the bimodal slope. The mono slope of Weibull distribution indicates 2.8, that was also low value with large uncertainty. We have the plan to test more enough to screen the data using by SINTAP method for inhomogeneous data in ASTM E1921 [ASTM international, 2022], and it will be confirmed that the Weibull slope of the data at each position and all data of HAZ will be similar or not.

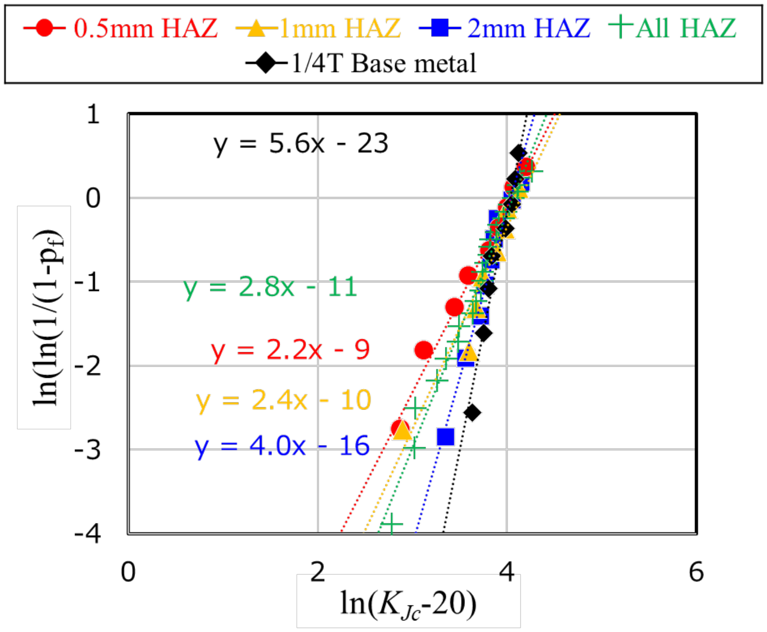


Figure 4 Weibull slopes of each data set of fracture toughness

Reference temperature of fracture toughness in HAZ

Figure 5 shows the reference temperature, T_0 of each position, including the T_0 obtained from base metal at 1/4T [Ha Y. et al. 2021]. Standard deviation of T_0 is calculated according to JEAC 4206-2016 given by:

$$\sigma_{T_0} = \frac{(K_{Jc(\mathrm{med})}-20)}{(K_{Jc(\mathrm{med})}-30)} \times \frac{14.7}{\sqrt{r}} \tag{5}$$

Here, r is the number of valid data when obtain T_0.

T_0 obtained from HAZ at 0.5 mm and 2 mm from the weld metal were higher than those from HAZ at 1 mm. The difference of T_0 obtained from three positions in HAZ was maximally around 15°C, which was greater than the difference of those standard deviations which is around ± 7°C. T_0 in three HAZ positions were definitely lower than those of base metal. That means the fracture toughness in HAZ of unirradiated material was better than that of base metal. Considering that the inhomogeneous microstructures in HAZ may be different sensitivity to irradiation embrittlement, the fracture toughness of HAZ after irradiation will be evaluated.

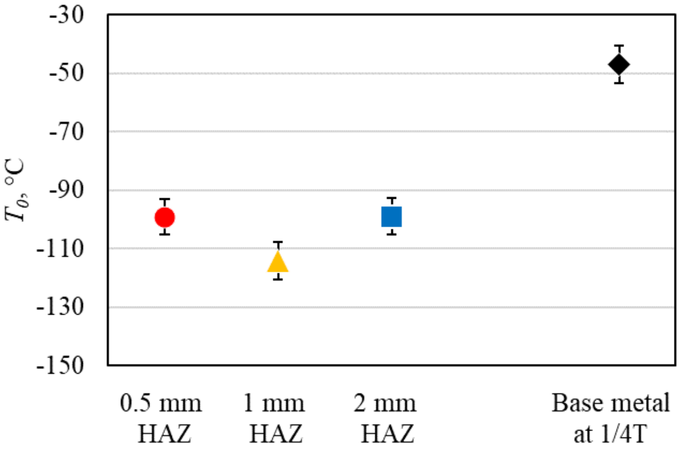


Figure 5 Comparison of T_0 obtained from each position of HAZ and base metal at 1/4T

CONCLUSIONS

We investigated the fracture toughness of three positions in HAZ, where Mini-C(T) specimens were harvested from the crack position at 0.5 mm, 1 mm and 2 mm from the welded fusion line. In addition, the magnitude of uncertainty in the data set of the fracture toughness was confirmed. The conclusions were drawn from the results obtained in this study as follows:

- The uncertainty of the fracture toughness in HAZ was larger where the position of HAZ was close to the fusion line (The magnitude of uncertainty; HAZ at 0.5 mm > 1 mm > 2 mm). The large uncertainty in the fracture toughness of all positions of HAZ was obtained and the Weibull slope looks like bimodal slope, which was influenced by inhomogeneous metallurgical structures.
- T_0 in each position of HAZ was remarkably lower than that of base metal, which means that the fracture toughness of HAZ was greater than that of base metal.

Synthetically, the fracture toughness of HAZ was greater than that of base metal, when evaluated each case of separated position and all positions in HAZ.

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