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Material research on RPV in decommissioning Hamaoka unit-1 (Progress report)

Hideki YUYA[1,*], Masataka OYAMA[1], Ryoya KOBAYASHI[2], Kohey OTOMO[2] and Akihiko KIMURA[3]

[1] *Nuclear safety R&D center, Chubu Electric Power, Co., Inc., 5561 Sakura, Omaezaki, Shizuoka 437-1695, Japan*
[2] *Graduate School of Energy Science, Kyoto University, Yoshidahonmachi, Sakyou-ku, Kyoto 606-8501, Japan*
[3] *Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan*

ABSTRACT

Chubu electric power (Chubu) is now under investigation of radiation effects on the reactor pressure vessel (RPV) steel of a decommissioning BWR-4 in the Hamaoka unit-1 plant to confirm the validity of the current maintenance methodology and resultantly safety tolerance up to now. As a part of this program, we planned to survey the irradiation responses of the base metal just beneath the inner cladding of RPV. In this paper we report the results of Charpy impact and fracture toughness tests of a mock-up block of the archive material of RPV. The impact test using 1/3 sized specimens showed that the ductile brittle transition temperature (DBTT) of the base metal and cladding-HAZ (heat affected zone) were almost same, and the difference in the upper shelf energy (USE) between base metal and cladding-HAZ is within a scatter band. Fracture toughness test using compact tension (CT) specimens are successfully done and the results were compared with that in literature. Our data set of fracture toughness are considered to be consistent with a temperature dependent curve composed of past data.

KEYWORDS

Decommissioning, Hamaoka, RPV, Harvesting, Irradiation embrittlement, cladding HAZ

ARTICLE INFORMATION

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1. Introduction

Chubu shut down the Hamaoka units 1 & 2 of nuclear power plant in 2009. During decommissioning, a remote sampling device from the reactor core components was developed for survey of the radioactivity concentration. Since small portions from the actual components provided us a good opportunity to investigate aging behavior of structural materials, which was thought to be useful for long term operation of nuclear power plants by reconfirmation of the effectiveness of current maintenance methodology. Neutron irradiation embrittlement of RPV has been the major issues which can occur in nuclear power plants. Especially in this program, we are focusing on the irradiation responses of the base metal just beneath the inner cladding to investigate the effects of heating during cladding process. In this report, the mechanical properties of base metal and that of just beneath the cladding of a mock-up block of archive material of RPV are compared to investigate the effects of cladding heat on the mechanical properties, such as hardness distribution, tensile properties, impact properties and fracture toughness.

2. Experimental

2.1. Materials

A mock-up block of the archive material of RPV steel, A533B.cl.1, was used in this research. The

*Corresponding author, E-mail: Yuya.Hideki@chuden.co.jp

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block consisted of the base metal of the A533B steel and electro-submerged cladding of SUS309L. The chemical compositions of the RPV steel and cladding are shown in Table 1, indicating that the steel is a low alloy steel with a bainitic structure. The clad block was heat treated to simulate the temperature history during post-cladding heat treatment. The heat treatment conditions are shown in Table 2.

Table 1. Chemical compositions of A533B cl.1 and SUS309L

wt%	C	Si	Mn	P	S	Ni	Cr	Mo	Cu	Co
A533B	0.17	0.28	1.39	0.01	0.01	0.56	-	0.49	0.09	-
SUS309L	0.033	0.44	1.37	0.024	0.014	9.33	20.7	0.12	-	0.15

Table 2. Heat treatment conditions for post-cladding heat treatment

Process	Starting Temp.	Ending Temp.	Conditions
Heating	300℃	595℃ (610℃)*	Heating rate: 43℃/h (max.)
Holding	595℃	595℃	Holding period:1.87h (0.63 h at 610℃±2℃)
Cooling	595℃ (610℃)*	300℃	Cooling rate: 44℃/h (max.)

*target temperature

The 1/6 sized CT and 1/3 sized Charpy test specimens were prepared from an archive material to investigate the properties beneath the cladding as a reference of un-irradiated RPV steel. The sampling features are shown in Fig. 1.

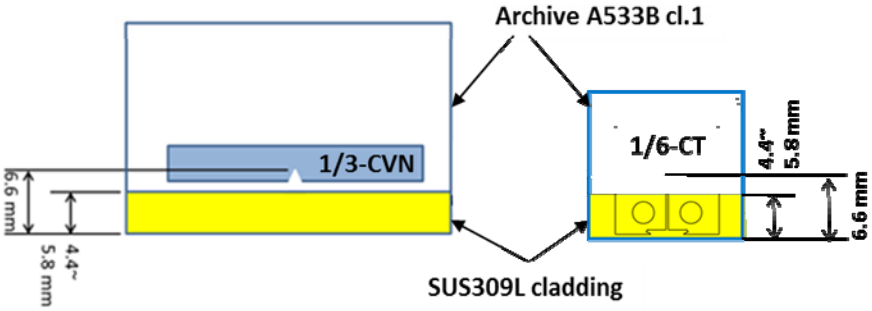
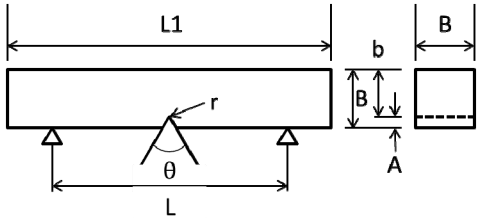


Fig. 1. Sampling features of Charpy test specimens (1/3-CVN) and fracture toughness specimens (1/6-CT) sampled from a mock-up block of the archive material of RPV steel, A533B.cl.1 clad with SUS309L

2.2. Miniaturized specimens

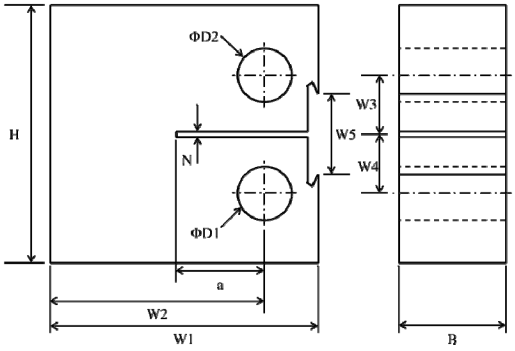
Because of the limitation of sampling volume of the boat sample and the investigation of localized area in RPV steel just beneath the cladding, standard size test specimens were not available from the boat samples as well as a block of archive material. Finally, we adopted small specimen test technique to investigate radiation effects on the RPV steel, which received cladding heat, with use of miniaturized Charpy test specimens (1/3-CVN: 3.3 mm x 3.3 mm x 27.5 mm) and compact tension specimens (1/6-CT: 9.6 mm x 10 mm x 4 mm) of which the specimen geometries are shown in Fig. 2.

(a)



[mm]	L1	B	A	b	r	θ[°]	L
1/3-CVN	27.5	3.3	0.6	2.7	0.08	30	20

(b)



B[mm]	W1[mm]	W2[mm]	W3=W4[mm]	W5[mm]	H[mm]	ϕ D1= ϕ D2[mm]	a[mm]
4	10	8	2.2	3	9.6	ϕ 2	3.3

Fig. 2. Specimen geometries of (a) Charpy test specimen (1/3-CVN) and (b) compact tenssion specimen (1/6-CT)

2.3. Testing methodology

Charpy impact test specimens were set up in a temperature controlled furnace, and cooled or heated to the target temperatures. After reaching to the target test temperature, the specimen was put on the specimen holder and fractured. During tests, the load and displacement were measured, and the fracture energy, *E*, was estimated as an area below the load-displacement curve. The fracture energy was measured at different temperatures, and the data were curve fitted using a hyperbolic tangent function of the following equation (1):

$$E = a + b \tanh [C (T - d)] \quad (1)$$

where *E* is the absorbed energy (J), *a*, *b*, *c* are constants, *d* = constant = DBTT, *a* + *b* = USE, *T* is the test temperature (K).

Fracture toughness tests were carried out in accordance with ASTM E 1921-02 standard test method for determination of reference temperature, T_0, for ferritic steels in the transition range. The continuous tensile loading method was applied for measuring the K_{Jc} with a clip strain gage. A digitally controlled INSTRON 8562 testing machine equipped with cold bath for the tests at temperatures from -160 °C to 50 °C. Before the fracture toughness test, fatigue pre-cracking was introduced to a ratio of the pre-crack length to specimen width of about 0.55. The temperature dependence of the median toughness of 25.4 mm thick specimen (1T) in the transition region of steels is given by the so-called ASTM master curve of equation (2), where the reference temperature T_0 corresponds to the temperature where the median fracture toughness for a 25.4 mm thick specimen has the value 100 MPa $m^{1/2}$. More detail can be explained by the ASTM 1921.

$$K_{Jc(med)} = 30 + 70 \exp[0.019 (T-T_0)] \quad (2)$$

3. Results

3.1. Charpy impact test

For the evaluation of ductile-brittle transition temperature (DBTT) of the localized area just beneath the cladding, 1/3 size Charpy test specimens were fabricated and tested. As for the standard size specimens, of which the cross sectional area is 10 mm x 10 mm, no specimen was available because of the limited volume of cladding-heat affected zone. However, the DBTT evaluation traditionally has been carried out with use of standard size specimens. It is well known that the impact properties, DBTT and upper shelf energy (USE), depend on the specimen size: both the DBTT and USE are decreased with decreasing specimen size. The effort to estimate the DBTT of standard size specimens from the DBTT of miniaturized specimens has been made by several researches [1-7], and it was shown that a volume normalization method often successfully estimate the USE of standard size specimens from that of miniaturized specimens. As for DBTT, it was also shown that there are several correlation method between the DBTT obtained with use of different sizes of specimens. In this research, the DBTT and USE were measured by using 1/3-CVN specimens as well as the specimen size effect on the impact properties was also investigated for the base metal because of the limitation of the volume of cladding-HAZ region.

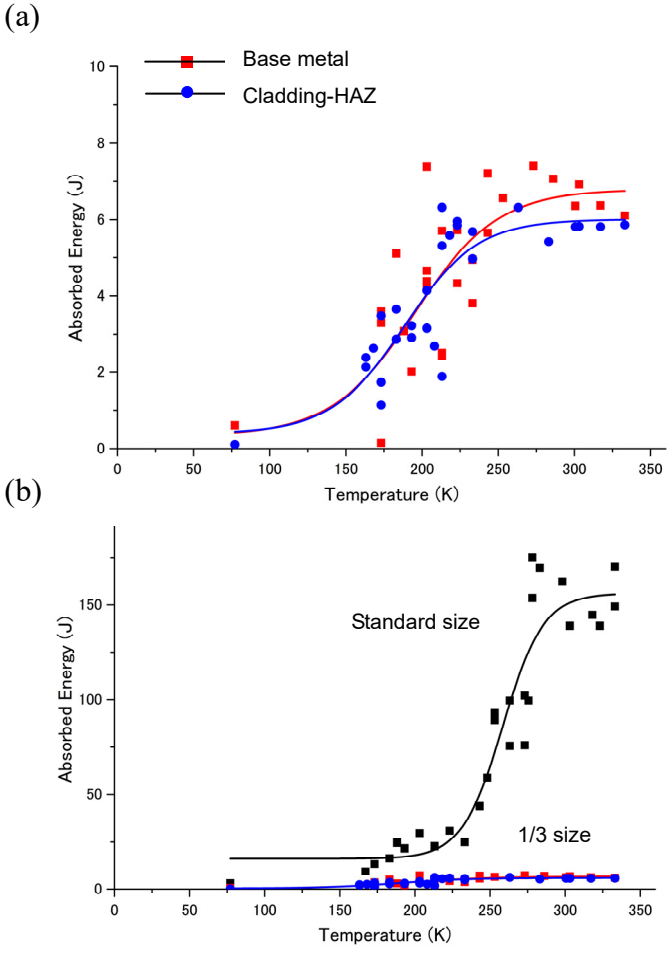


Fig. 3. Ductile-brittle transition behavior obtained with (a) 1/3 sized CVN for base metal (■) and cladding-HAZ (●), and (b) standard size base metal and 1/3 sized specimens. The USE of 1/3-sized specimens are smaller than 8 J, while those of standard size specimens are around 160 J.

Figure 3(a) shows the ductile brittle transition behavior obtained with use of 1/3 sized CVN specimens for base metal and cladding-HAZ, indicating that the DBTT of the base metal and HAZ were almost same. Despite the USE after hyperbolic tangent fitting shows small difference between base metal and cladding-HAZ, the discrepancy is not essential since it is reasonably smaller than the scatter of toughness data in the temperature region. This suggests that the cladding heat effect is not remarkable to affect toughness of the material. Figure 3(b) compares the ductile brittle transition behavior between 1/3 sized specimens and standard size specimens. As expected, the smaller the size of specimens, the lower the DBTT, USE and LSE are. Figure 4 shows the fracture surfaces of specimens after impact tests at lower temperature region than DBTT, namely, lower shelf energy region. All the specimens show brittle transgranular cleavage fracture mode irrespective of specimen size and temperature history, namely, base metal or cladding-HAZ. As shown in Fig. 3, the ductile brittle transition behavior is not significantly affected by heating during cladding, which can be expected from the fractography showing river patterns on the fracture surfaces of the impact tested specimens.

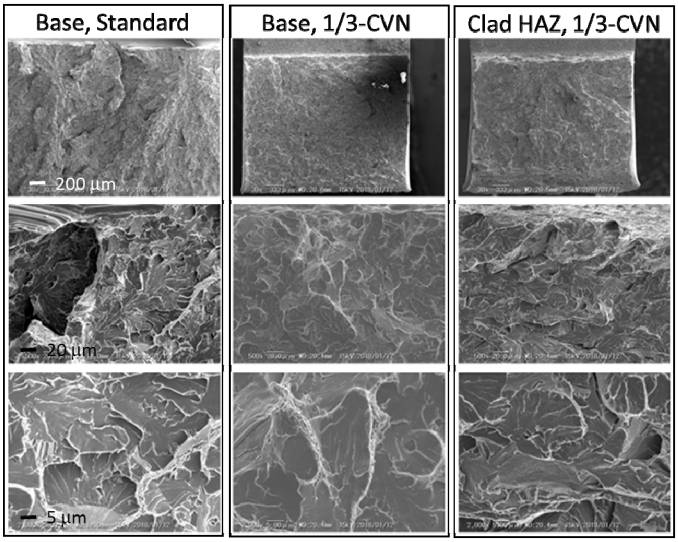


Fig. 4. The fracture surfaces of specimens after impact tests at lower temperature region than DBTT, namely, lower shelf energy region

3.2. Fracture toughness tests

The load - crack opening distance curves of fracture toughness tests of the RPV steel beneath the cladding were obtained and the resultant fracture toughness parameters are summarized in Table 3, where K_{Jc} is converted to the values for standard size specimen from the values obtained with 1/6-CT specimens by the following equation (3):

$$K_{Jc(1T)} = K_{min} + [K_{Jc} - K_{min}]\left(\frac{B_0}{B_{1T}}\right)^{1/4} \quad (3)$$

where K_{min} is 20 MPa$\sqrt{}$m, B_0 = 4 mm (specimen thickness of 1/6-CT), B_{1T} = 25.4 mm (specimen thickness of 1TCT, standard size). The fracture surface observation revealed that the pre-cracked area was symmetry and the crack front was almost straight indicating the pre-cracks were introduced successfully for judging the validity of evaluation results.

Following the single temperature measurement method, T_0 was derived according to the master curve shown by equation (2) and summarized in Table 4. The reference temperature of the cladding HAZ of RPV steel was evaluated to be – 104 °C as a valid value for the fracture toughness.

Table 3. Results of fracture toughness measurements

No.	Temp. (℃)	Loading Rate (mm/min)	$K_{jc(limit)}$ (MPa$\sqrt{m}$)	K_{jc} (MPa$\sqrt{m}$)	$K_{jc(1T)}$ (MPa$\sqrt{m}$)	judge
3	-150	0.27	170.4	100.0	70.4	OK
4			170.5	66.4	49.2	OK
5			170.0	94.9	67.2	OK
7			170.3	81.9	59.0	OK
9			170.4	80.9	58.4	OK
10			170.4	100.1	70.5	OK
12			170.5	77.3	56.1	OK

Table 4. Estimated reference temperature, T_0, tested at -150 ℃

$K_{Jc(med)}$ (MPa·m$^{1/2}$)	Effective K_{Jc}	T_0 (T_{0Q}) (℃)	T - T_{0Q} (℃)	validity
58.96	8	-103.55	-46.45	OK

4. Conclusion

Almost of all the preliminary tests have been completed until FY2017. At this moment, it can be said that there is no significant effect of cladding heat on the mechanical properties of un-irradiated RPV steel. Several tests such as fracture toughness test, atom-probe analysis and Charpy impact test are planned for actual RPV steel in FY2018.

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