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Fracture Toughness Evaluation of Kori-1 RPV Beltline Weld for a Long-Term Operation

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1. Introduction

Irradiation embrittlement of RPV (reactor pressure vessel) material is the most important aging issue for a long-term operation of nuclear power plants. KORI unit 1, which is the first PWR in Korea, is approaching its initial licensing life of 30 years. In order to operate the reactor for another 10 years and more, it should be demonstrated that the irradiation embrittlement of the reactor will be adequately managed by ensuring that the fracture toughness properties have a certain level of the safety margin. The current regulation requires Charpy V-notch impact data through conventional surveillance tests. It is based on the assumption that Charpy impact test results are well correlated with the fracture toughness properties of many engineering steels.

However, Charpy V-notch impact data may not be adequate to estimate the fracture toughness of certain materials, such as Linde 80 welds. During the last decade, a tremendous number of fracture toughness data on many RPV steels have been produced in accordance with the new standard test method, the so-called master curve method [1]. ASTM E1921 represents a revolutionary advance in characterizing fracture toughness of RPV steels, since it permits establishing the ductile to brittle transition portion of the fracture toughness curve with direct measurements on a relatively small number of relatively small specimens, such as pre-cracked Charpy specimens. Actual fracture toughness data from many different RPV steels revealed that the Charpy test estimations are generally conservative with the exception of a few cases [2]. Recent regulation codes in USA permit the master curve fracture toughness methodology in evaluating an irradiation embrittlement of commercial nuclear reactor vessels [3].

For the purpose of a long-term operation of Kori-1, the fracture toughness of RPV beltline weld has been investigated by the direct measurement of ASTM E1921-05 standard master curve procedure. The beltline circumferential weld, Linde-80/WF-233, is the only limiting material of irradiation embrittlement of Kori-1.

2. Fracture Toughness Test Procedure

Fracture toughness tests were carried out in accordance with ASTM E 1921-05 standard procedure [1]. Precracked Charpy sized specimens were used for three point bend tests in the transition temperature range. The load-line displacement rate was 0.15 mm/min to give a crack tip loading rate of 1 MPa√m/sec. All specimens were 20% side-grooved after fatigue pre-cracking. Unirradiated specimens were sampled from an archive weld block, Linde-80/WF-233, in accordance with the surveillance specimen orientation.

Irradiated samples were acquired from the broken halves of Charpy specimens reserved after conventional surveillance tests. Three different sets of specimens have different neutron fluence levels. PCVN(precracked Charpy) specimen can be made of a broken half of surveillance Charpy specimens according to the ASTM E 1253 standard procedure [4]. Only the central part of a reconstituted specimen represents the irradiated material and the side parts are made of a dummy material which will be welded to the central portion. The weld reconstitution was carried out at adequate conditions to minimize the effect of a weld heat, which may affect the deformation field and cause a recovery of an embrittlement on the specimen.

3. Fracture Toughness Test Results

Figure 1 shows the fracture toughness test results for un-irradiated material. The reference temperature, T_o was determined as -106.7°C from a total 23 specimen data points. The data set includes a total 8 reconstituted specimen data which showed the same data trend as the original specimens. It can support the credibility of the weld-reconstitution techniques for irradiated material testing. All data are well described by probabilistic bound lines.

Three sets of irradiated test results are plotted in Figure 2 with US database on Linde 80 welds. The neutron fluences of each data set are 1.2, 3.0 and 3.9 ($\times 10^{19}$ n/cm^2), respectively. Each data set has 15 specimen data and a total number of irradiated data points for Kori-1 are 45. The reference temperature, T_o values were determined as 13.4, 30.0 and 31.5 °C for three different fluence levels. The dashed line represents the ASME K_{IC} curve based on the highest fluence data set in accordance with the Code Case N-629 [3] procedure with an additional margin of 1σ (=28°F).

Irradiated data showed a one-to-one relationship between Charpy data and the master curve data for transition temperature shift of Kori-1 weld. Transition temperature shifts from both test data were practically the same for Kori-1 weld. It supports the current USNRC RG-1.99, Rev.2 procedure can be applied without modification for the evaluation of irradiation embrittlement of Kori-1 weld by using the master curve fracture toughness data.

4. Conservative application to integrity assessment

ASME Code Case N-629 defines a reference temperature for an equivalent nil-ductility transition as $RT_{To}=T_o+35^oF$. However, a margin on temperature shall be included in the above determination of RT_{To} to account for uncertainties associated with transferability of test specimen data to a specific structural evaluation. Determination of such a temperature margin shall be the responsibility of the Owner and subject to the approval of the regulatory authority.

USNRC RG-1.99, Rev.2 stipulates that $1\sigma(=28^oF)$ or 2σ shall be added to the measured RT_{NDT} value from Charpy tests. Recently [5], USNRC has approved a conservative margin $2\sigma(=65.8^oF)$ for application of the master curve test data to Linde 80 welds by considering both the initial and irradiated test data sets. In addition, a specimen size correction term was defined as 18^oF for PCVN specimens.

Figure 3 shows an RT_{PTS} evolution curve of Kori-1 beltline weld estimated by the rule of ASME Code Case N-629 and USNRC RG-1.99 Rev.2 by using the fracture toughness test results. Each curve contains the same additional safety margin of $2\sigma(=65.8^oF)$ and a bias margin of 18^oF as explained in the previous paragraph. The solid line is constructed from the best fit initial property of Kori-1 weld measured per ASTM E1921-05 standard procedure. The dashed line represents an extremely conservative reference property, which was based on the lower bound data set only. Since there are already uncertainty margins included in the code application process, use of only lower bound data must be unnecessarily conservative. Nevertheless, in any case, the maximum RT_{PTS} value could not reach a regulatory meaningful limit, 300^oF. Therefore, it is concluded that the fracture toughness of Kori-1 beltline weld would have a sufficient resistance to brittle fracture against a postulated PTS event.

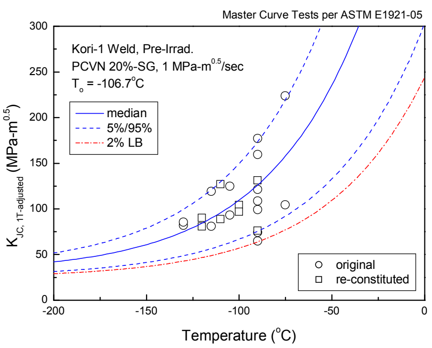

Fig. 1 Fracture toughness data of unirradiated weld

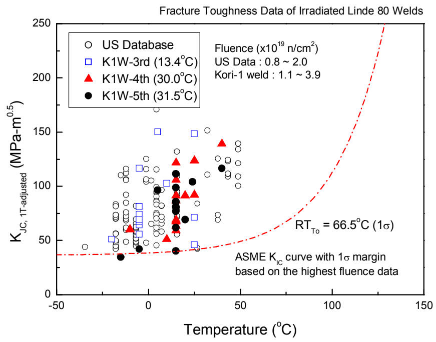

Fig. 2 Fracture toughness data of irradiated weld

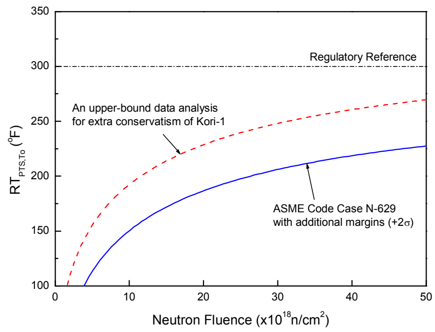

Fig. 3 RT_{PTS} evolution curve of Kori-1 based on fracture toughness test data

5. Conclusion

Fracture toughness measurements were carried out for Kori-1 beltline weld by using both unirradiated and irradiated precracked Charpy specimens in accordance with the ASTM E1921-05 master curve test procedure. The irradiation shifts of the reference temperature could be well predicted by USNRC RG-1.99, Rev.2 equation. Fracture toughness test data demonstrated that Kori-1 beltline weld would have a sufficient resistance to brittle fracture against a postulated PTS event with a sufficient amount of additional margins.

REFERENCES

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[4] ASTM Standard E 1253-99, "Standard Guide for Reconstitution of Irradiated Charpy-Sized Specimens," 1999

[5] USNRC, "Final Safety Evaluation for Topical Report BAW-2308, Revision 1, "Initial RT_{NDT} of Linde 80 Weld Materials" (TAC No. MB6636)," August 4, 2005