Effects of Microstructural Inhomogeneity on Charpy Impact Properties for Reactor Pressure Vessel.

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1. Introduction

Commercial reactor pressure vessel (RPV) steels, SA 508 Gr.3 Mn-Mo-Ni low alloy steels, are manufactured more than thickness of 250 mm in order to show enough strength and toughness for safety. RPV steels are fabricated by vacuum carbon deoxidation (VCD), and then heat treatment of quenching and tempering is conducted after forging. The through-the-thickness variation of microstructure in RPV can occur due to the cooling rate gradient during quenching and inhomogeneous deformation during forging process [1,2].

The variation of microstructure in RPV affects the mechanical properties, and inhomogeneity in mechanical properties can occur. The evaluation of mechanical properties of RPV is conducted at thickness of 1/4T. In order to evaluate the safety of RPV more correctly, the research about the through-the-thickness variation of microstructure and mechanical properties in RPV is need.

2. Methods and Results

2.1 Fabrication and Microstructural Inhomogeneity

In this study, the archive RPV material, same to the materials used in Korea nuclear power plant reactor, is used. The archive RPV is produced by vacuum carbon deoxidation (VCD), forged, quenched, and tempered. For the analysis of microstructure and Charpy impact properties, specimens are machined from the normalized location in thickness direction of the archive RPV: 0T (inner surface), 1/4T, 1/2T (center). The longitudinal-thickness plane of the steels were polished and etched by a 2% nital solution, and microstructures (0T, 1/4T, and 1/2T) were observed by an optical microscope, as shown in Fig. 1a-c. For convenience, the martensite, fine lower bainite, fine upper bainite, and coarse upper bainite phases are referred to as M, LB, B, and UB, respectively. Microstructure at 0T consists of mainly lower bainite with small amount of fine upper bainite and martensite. Microstructure at 1/2T consists of almost coarse upper bainite.

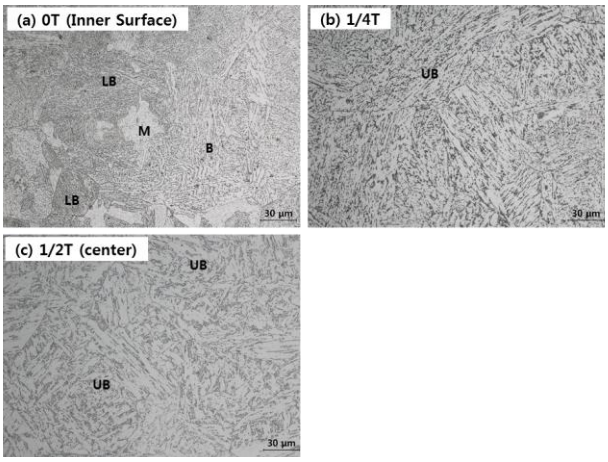

Fig. 1 Optical microscope images at the normalized location (a) 0T, (b) 1/4T, and (c) 1/2T. The martensite, fine lower bainite, fine upper bainite, and coarse upper bainite phases are referred to as M, LB, B, and UB, respectively.

2.2 Charpy Impact Properties

Charpy impact tests were performed on standard Charpy V-notch specimens (size; 10×10×55 mm, orientation; transverse-longitudinal (T-L)) in the temperature range from -100 ℃ to 300 ℃. In order to reduce errors in the data interpretation, a regression analysis for absorbed impact energy vs test temperature was conducted with a hyperbolic tangent curve fitting method [3,4]. Based on the regression analysis data, the upper shelf energy (USE) and reference temperatures (T_{41J} and T_{68J}) were determined, and the results are shown in Table I. In the inner surface region (0T), The USE is highest and the reference temperatures are lowest. At the 1/4T location, the USE is lowest and reference temperatures are highest. That means the impact properties are best at 0T and are worst at 1/4T.

Table I: Charpy impact properties at the normalized location.

Normalized Location	0T	1/4T	1/2T
USE	343	266	300
T_{41J}	-61.9	-15.1	-24.1
T_{68J}	-45.2	-5.2	-14.2

3. Discussion

3.1 Fracture Initiation and Propagation

In order to examine the crack initiation behavior, the fracture surface and cross-sectional area beneath the fracture surface of the Charpy specimens fractured at -0℃ were observed by an SEM, and the results are shown in Fig. 2a-b. In ductile fracture mode (Fig. 2a), cracks are formed at lath boundaries, inside which carbides exist as indicated by yellow arrows. In cleavage fracture mode (Fig. 2b), cleavage fracture is initiated at the coarse carbide particles. Those results mean that coarse inter-lath carbide acts as fracture initiation site regardless of fracture mode.

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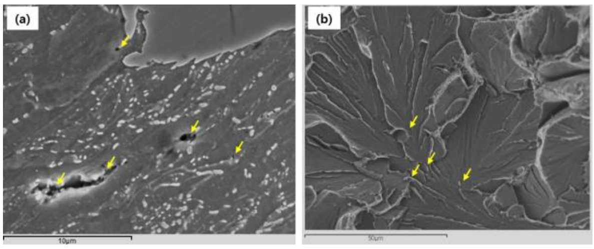

Fig. 2. (a) Cross-sectional area and (b) fracture surface of the Charpy specimens fractured at 0℃.

In order to examine the carbide size and shape, carbides were measured by an image analyzer, and then the area, aspect ratio, and mean diameter of carbide are measured. The average values of the top 10% of results are shown in Table II.

Table II: The average area, aspect ratio, and diameter of the top 10% carbides.

Normalized Location	Area (μm^2)	Aspect Ratio	Diameter (μm)
0T	0.25	3.89	0.61
1/4T	0.35	4.00	0.73
1/2T	0.32	3.79	0.68

Carbides at 1/4T location, which shows poor impact properties, are coarse and elongated shaped more than those in other location. However, carbides at 0T location, which shows good impact properties, are smaller than those in other location. Due to fine carbide formation and fine LB microstructure known as good for toughness [5], impact properties at 0T are best.

4. Conclusions

1. The fine low bainite (LB) is the dominant phase at the inner-surface (0T), but coarse upper bainite (UB) is the dominant phase at the center (1/2T). This is because cooling rate gradient from surface to center occurs during quenching.
2. Inter-lath carbides act as fracture initiation site, and it reduces impact toughness.
3. The upper shelf energy is low and the reference temperatures are high at the 1/4T. Impact properties are poor at 1/4T because of the formation of coarse upper bainite structure and coarse inter-lath carbides.
4. The upper shelf energy is high and the reference temperatures are low at the inner-surface (0T), and it means good impact properties. This is because the formation of fine carbide and fine low bainite structure, known as tough phase.

REFERENCES

[1] S.G. Druce, J.M. Titchmarsh, G. Jordan, and A. James, Metallurgical observations of a French SA508 Class 3 forging with respect to transition toughness behavior, Reserch Report of AERE Harwell: AERE R-11626, 1985
[2] H.W. Viehrig, J. Bohmert, and M. Grobe, Through-thickness characterization of mechanical properties of Russian VVER-Type and ASTM-Type reactor pressure vessel steel forgings, IAEA Symposium on Irradiation Embrittlement and Mitigation, Oct. 23-26, 1995, Espoo, Finland.
[3] "ASTM Standard E23-07ae1 Standard Test Method for Notched Bar Impact Testing of Metallic Materials," Annual Book of ASTM Standards, ASTM, West Conshohocken, PA, 2007.
[4] W. Oldfield, ASTM Standardization News, Vol. 11, pp. 24-29, (1975).
[5] H.K.D.H. Bhadeshia and S.R. Honeycombe, The bainite reaction, Steels, Elsevier, 2006.