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J-R Fracture Characteristics of Candidate Steels for Main Steam Line Piping of APR+ Nuclear Power Plants at Room Temperature

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1. Introduction

Leak Before Break (LBB) concept was applied to most primary high-energy piping system in domestic nuclear power plant (NPP) starting with design of Hanbit unit 3 and 4. Recently, efforts have been made to expand LBB concept to the secondary main steam line piping system for improving safety of NPPs. LBB characteristics studies have been performed on various kinds of low alloy steels such as SA508 Gr. 3, SA508 Gr. 1a, SA516 Gr. 70 and SA106 Gr. C [1-3]. Based on these studies, the required characteristics of the material for applying LBB concept to main steam line piping were analyzed. Essentially, in order to evaluate applicability of the LBB, mechanical properties are needed, and it is also required to derive the fracture resistance curve of the material through experiment and compare it with the crack driving force of the component. In this study, the experimental results of fracture resistance of each material which is considered as candidate materials of main steam line pipe such as SA508 Gr. 1a of reactor coolant system (RCS), SA508 Gr. 3 Cl. 1 of reactor vessel (RV) and SA508 Gr. 3 Cl. 2 of steam generator (SG) are provided to secure the LBB safety margin of structural integrity. Based on the results of LBB characterization for candidate materials, microstructural analysis and design of alloys for low alloy steel will be conducted to improve LBB characteristics by controlling alloying elements in the future.

2. J-R Tests and Results

This section describes the types of materials, preparation of specimens, *J*-R testing methods and its results for LBB evaluation.

2.1 Materials and Specimens

Test materials were SA508 Gr. 1a (RCS steel), SA508 Gr. 3 Cl. 1 (RV steel) and SA508 Gr. 3 Cl. 2 (SG steel) which were candidate forging materials of the APR+ main steam line pipe. Fracture toughness specimens for *J*-R curve testing were machined in 1-in. thick compact type (1T-CT). Chemical compositions are summarized in Table I. Two specimens were prepared per each material. The specimens were pre-cracked and then they were 20% side-grooved. The side groove had a root radius of 0.5 mm and an angle of 45°. The geometry of CT specimen for the *J*-R testing are shown in Fig. 1

2.2 Test Machine and condition

MTS 810 material test system with 50 kN loading capacity was used for the *J*-R testing as shown in Fig. 2. The tests were carried out at a constant rate of 0.5 mm/min at room temperature. Test conditions for each specimen are listed in Table 2. For the measurement of crack opening displacement, MTS 12 mm COD gage was used.

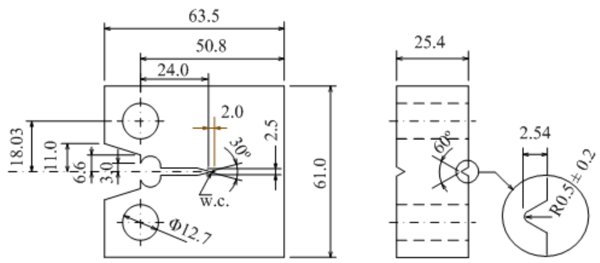

Fig. 1. Geometry of CT specimen for J-R testing.

Table I: Chemical composition

ID	Chemical Composition(wt%)				
	C	Mn	Ni	Cr	Mo
GD	0.21	1.20	0.28	0.23	0.05
GV	0.21	1.17	0.22	0.12	0.10
GI	0.25	1.11	0.32	0.15	0.06
C1	0.19	1.22	0.87	0.19	0.47
C2	0.21	1.36	0.96	0.17	0.5

(a) (b)

Fig. 2. (a) MTS material test system and (b) COD gage for the J-R testing.

Table II: Test condition

Material	Specimen ID	Manuf-acturer	Test Temp.	Loading Rate (mm/min)
SA508 Gr. 1a	GD01, GD02	D	Room Temp.	0.5
	GV01, GV02	V		
	GI01, GI02	I		
SA508 Gr. 3 Cl. 1	C101, C102	D		
SA508 Gr. 3 Cl. 2	C201,C202	D		

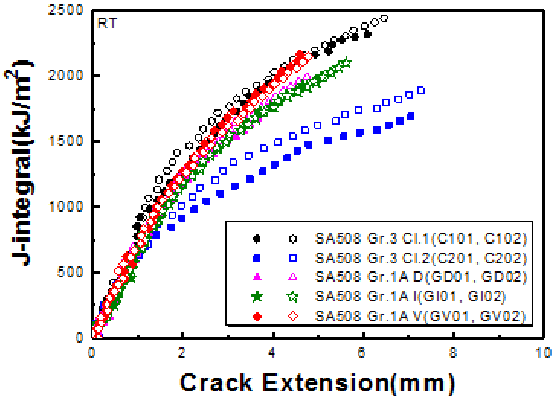

Fig. 3. *J*-R curves of candidate materials of main steam line pipes at room temperature.

2.3 Test Method

Fracture resistance tests were performed according to the unloading compliance method of ASTM E1820-16 [4]. From the test results, the *J*-R curve was derived using load-displacement data for each specimen. The specimens were thermally tinted at about 300°C for 30 minutes after the tests and then completely broken at low temperature using liquid nitrogen. The initial crack and final crack length were measured and compared with the test results interpreted by unloading compliance method.

2.4 J-R Test Results

The *J*-R curves for five candidate materials at room temperature are shown in Fig. 3. SA508 Gr. 1a steel did not show a large difference in *J*-R Curves depending on the manufacturer. *J*-R curves of SA508 Gr. 3 Cl. 1 steel showed a similar behavior to SA508 Gr. 3 1a steel. However, SA508 Gr. 3 Cl. 2 steel showed a relatively low *J*-R curve. Namely, the *J*-R characteristics at room temperature were higher in the order of C1>GV>GD, GI>C2, but SA508 Gr. 3 Cl. 2 steel showed a distinctly low *J*-R curve. The difference of *J*-R curve between the other candidate materials was insignificant. These results were in good agreement with the results of upper shelf energy (USE) tests as shown in Table 3. The impact test was carried out according to ASTM E23 using a standard size Charpy specimen taken in the T-L direction [5]. What is affected to the fracture toughness difference needs to be analyzed through microstructural analysis and other material properties tests and it is currently planned.

3. Conclusions

SA508 Gr. 1a is used for the APR+ main steam line piping in Korea. It is known that the difference in fracture resistance comes from steelmaking method and chemical composition of material, which is related to grain size and formation of carbide. In this study, fracture resistance characteristics were evaluated for five candidate materials of main steam line piping steels as a part of the study to improve the LBB characteristics. The results of fracture resistance test were compared with results of Chary impact test. As a result, SA508 Gr. 1a steel and SA508 Gr. 3 Cl. 1 steel showed a similar *J*-R curve, and difference in manufacturer (different steel making method and chemical composition) could not be found. However, SA508 Gr. 3 Cl. 2 steel showed a relatively lower *J*-R curve than the other materials. Based on the results of LBB characterization of candidate materials, microstructural analysis and design of alloys for low alloy steel to improve LBB characteristics by controlling alloying elements will be conducted.

Table III: Charpy impact characteristics of candidate materials for main steam line pipe

Specimen ID	USE(J)
GD (01, 02)	303
GV (01, 02)	320
GI (01, 02)	286
C1 (01, 02)	396
C2 (01, 02)	228

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