The Effect of Alloying Elements of SA508 Gr. 1a Used for Main Steam Line Piping on *J*-R Fracture Characteristic

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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 apply LBB concept not only to the primary components but also 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, alloy design for SA508 Gr.1a steel was conducted to improve LBB characteristics by controlling alloying elements. And the *J*-R fracture toughness tests were carried out for SA508 Gr.1a material. It is known that improvement of toughness with high strength is a key factor to enhancement of the LBB safety margin. As a results of *J*-R fracture toughness tests, fracture toughness was improved when molybdenum and vanadium were added.

2. Design of Model Alloy

In this study, a total of 5 model alloys (1A, 1B, 1C, 1D, 1E) were considered, and a basic composition of commercial material, 1R (reference), was also manufactured for comparison with other model alloys. 1A is an alloy with molybdenum+vanadium added to the 1R alloy, and 1B is alloy with reduced carbon content. 1C is an alloy with copper added to the 1B alloy, and 1D is an alloy with boron added to the 1B alloy. 1E alloy is an alloy that have reduced carbon content to 0.10wt% and adds boron for strength improvement. Addition of Mo content can be expected to improve toughness and strength of material. In addition, copper and boron were added to compensate for the strength due to the reduction of carbon content. Table 1 summarized the nominal chemical composition of commercial GD (SA508 Gr. 1a) material and model alloys considered in this study.

3. *J*-R tests and Toughness Evaluation

Fracture toughness specimens for *J*-R curve testing were machined in 1-in. thick compact type (1T-CT). 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.

MTS 810 material test system with 50 ton 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 286°C. For the measurement of crack opening displacement, Epsilon 12 mm high temperature COD gage was used.

Table 1 Chemical composition of model alloy (wt%)

	C	Mo	V	Cu	B	Remarks
GD	0.2	0.06	0.005	0.05	·	Commercial
1R	0.2	0.06	0.005	0.05	·	Ref.
1A	0.2	0.1	0.05	0.05	·	Mo+V
1B	0.15	0.1	0.05	0.05	·	Low C, Mo+V
1C	0.15	0.1	0.05	0.15	·	Low C, Mo+V+Cu
1D	0.15	0.1	0.05	0.05	15ppm	Low C, Mo+V+B
1E	0.1	0.1	0.05	0.15	15ppm	Low C, Mo+V+Cu+B

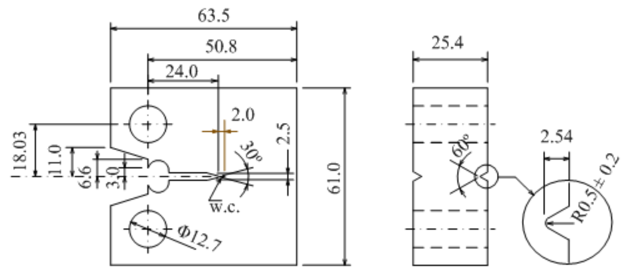

Fig. 1. Geometry of J-R specimen (1T-CT)

(a) (b)

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

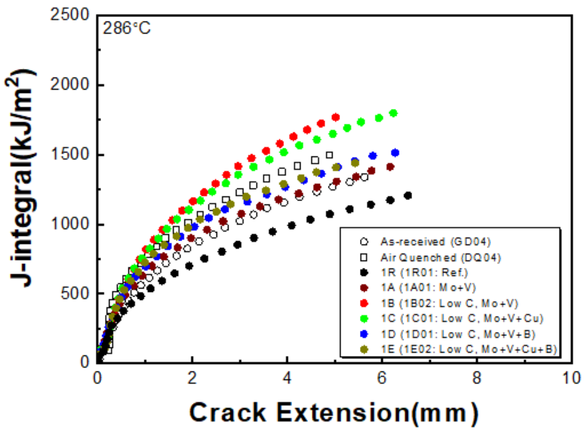

Fig. 3. *J*-R curves of model alloys

Fracture resistance tests were performed based on unloading compliance method according to ASTM E1820-16 [4]. From the test results, the *J*-R curve was derived using load-displacement data for each specimen. The initial crack length and crack extension were measured and compared with the test results interpreted by unloading compliance method. The *J*-R curves for all model alloys at 286°C are shown in Fig. 3.

Model alloy 1R which has same chemical composition as commercial material (GD04 in Fig. 3) has *J*-integral value of 716 kJ/m^2 and 997kJ/m^2 at a crack extension of 2mm and 4mm, respectively, which is lower value than commercial material (GD). Model alloy 1A with Mo+V showed more improved *J*-R characteristics than model alloy 1R and have similar *J*-integral values of commercial material (GD). Model alloy 1B with reduced carbon and higher content of Ni and Cr comparing with model alloy 1A was shown that 1144 kJ/m^2 and 1579 kJ/m^2 of *J*-integral values which was 428 kJ/m^2 and 582 kJ/m^2 higher values than model alloy 1R at crack extension of 2mm and 4mm. This is a 60% and 58% increase compared to model alloy 1R, indicating that the *J*-R characteristic was greatly improved. Model alloy 1C which have more Cu showed similar *J*-R characteristics to model alloy 1B, but *J*-integral value was slightly decreased, and model alloy 1D which has boron showed better toughness than model alloy 1A. However, toughness of model alloy 1D was reduced to 909 kJ/m^2 and 1263 kJ/m^2 of *J*-integral values at crack extension of 2mm and 4mm comparing with model alloy 1B. *J*-integral values of model alloy 1E were 950 kJ/m^2 and 1324 kJ/m^2 at crack extension of 2mm and 4mm, toughness of model alloy 1E was improved comparing with 1R, but lower than model alloy 1B.

4. 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, a total of 6 model alloys were manufactured to improve fracture toughness. The *J*-R characteristics of model alloys at 286°C were higher in the order of 1B>1C>1E=1D>1A>GD. Especially, model alloy 1B showed significant improvement of toughness when comparing to reference model alloy 1R. Based on these results, more detailed design of alloys for SA508 Gr. 1a will carried out to find the optimal alloying elements that can simultaneously improve the strength and toughness for the LBB safety margin.

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