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J_{Ic} Prediction Model Based on Microstructure and Strength for SA508 Gr.1A Low-Alloy Steel

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1. Introduction

The main steam line (MSL) piping in nuclear power plants (NPPs) is a component that transfers high-temperature and high-pressure steam [1]. To improve the safety of piping in such an environment, it is necessary to apply a material with excellent leak-before-break (LBB) characteristics [2]. To apply the LBB concept to the MSL piping, the material's yield strength and fracture resistance must be improved to ensure sufficient LBB safety margin [3-4]. The microstructure of steel is generally influenced by changes in alloying elements and heat treatment processes, which in turn affect their mechanical properties. Therefore, to improve the mechanical properties, it is necessary to analyze the factors that influence them. In general, it is known that fine grains improve the fracture resistance due to impede the crack propagation [5].

In this study, various heat treatments were applied to improve the strength and fracture toughness of SA508 Gr.1A low-alloy steel. The key factors affecting the J-R fracture resistance behavior were then analyzed, and a simplified model was developed to predict the J-R fracture resistance based on these key factors.

2. Methods and Results

2.1 Materials and heat treatment

In this study, two types of SA508 Gr.1A low-alloy steel were used: a commercial and a high-strength SA508 Gr.1A low-alloy steel. Various heat treatments (control of cooling rate, control of austenitizing temperature & tempering time) were performed to analyze the changes in precipitates, grain size, and mechanical properties of the material. The small blocks with size of 130mm (L) ×150mm (W) ×38mm (T) were taken from the archive materials of reactor coolant system (RCS) piping.

2.2 Microstructure

The longitudinal - transverse (L-T) plane was mechanically polished and etched with a 3% nital solution for microstructural analysis. The microstructure of each specimen was investigated using an optical microscopy (OM, Eclipse-MA200, Nilon, Japan). Several SEM images were selected to analyze the precipitates. Then that size of the precipitates were quantified using an image analyzer.

The formation of low-temperature transformation microstructure increased with increasing cooling rate and austenitizing heat treatment temperature. The precipitates coarsen, which leads to an increase in the fraction of coarse precipitates that affect the fracture toughness as the tempering holding time increases.

2.3 Mechanical testing

Tensile tests were performed using a round tension test specimen (gauge length 25 mm, diameter 6.25 mm) prepared in the transverse (T) direction according to ASTM A370 standard [6]. The tensile tests were conducted at room temperature and 286 °C at a strain rate of 5.2×10-4/s using MTS universal testing machine (MTS 810.24 MTS Systems Corporation, USA). The tensile properties (yield strength, tensile strength, and total elongation) were determined from each stress-strain curve. The yield strength was determined by the 0.2% offset method. The yield strength at 288°C was significantly improved by more than 77% as the cooling rate increased. While the yield strength showed an increasing trend with increasing austenitizing heat treatment temperature, the difference was not significant. On the other hand, the tensile properties significantly decreased as the tempering holding time increased.

J-R fracture resistance test was performed using a compact tension (1T-CT) specimen ASTM E1820 guidelines [7]. The test was performed at the operating temperature of the MSL piping, 286 °C, at a test speed of 0.5 mm/min. A fatigue pre-crack was generated at room temperature. The J-R curve was derived using the load-displacement data for each specimen. The J_{Ic} value was significantly improved by more than 15% with increasing cooling rate and tempering holding time. On the other hand, despite the coarsening of precipitates with increasing tempering holding time, the J_{Ic} value was significantly improved by more than 15% from 647 to 735kJ/m^2. In generally, coarse precipitates and effective grain size affect fracture toughness [8,9]. Additionally, a plastic zone is formed at the crack tip when a load is applied. Therefore, a model was proposed to predict the J-R fracture resistance of SA508 Gr.1A low-alloy steel considering the effective grain size, tensile properties, and plastic zone size. The results of the predicted and tested J_{Ic} values are shown in figure 1. The prediction values of each material were well matched with the values of J_{Ic}.

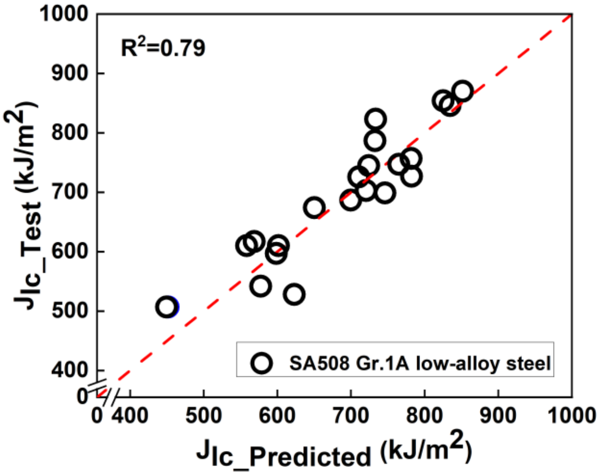

Fig. 1. Results of the predicted and tested J_{Ic} values.

3. Conclusions

1. The formation of low-temperature transformation microstructures, such as bainite and martensite, along with fine precipitates, enhances both strength and J-R fracture resistance.
2. The J-R fracture resistance exhibited a linear correlation with the number of effective grains within the crack-tip plastic zone, which is determined by the material's yield strength and effective grain size.
3. A model for predicting J_{Ic} value was developed by considering the effects of yield strength and tensile strength on the plastic zone, using test data from SA508 Gr.1A steels with varying microstructures and properties. The predicted J_{Ic} values showed good agreement with the experimental results.

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