Master curve analysis of the SA508 Gr. 4N Ni-Mo-Cr low alloy steels for reactor pressure vessels

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1. Introduction

Low alloy steels used as Reactor Pressure Vessels (RPVs) materials directly relate to the safety margin and the life span of reactors. Currently, SA508 Gr.3 low alloy steel is generally used for RPV material. But, for larger capacity and long-term durability of RPV, materials that have better properties including strength and toughness are needed. Therefore, tempered martensitic SA508 Gr.4N low alloy steel is considered as a candidate material due to excellent mechanical properties.

The fracture toughness loss caused by irradiation embrittlement during reactor operation is one of the important issues for ferritic RPV steels, because the decrease of fracture toughness is directly related to the integrity of RPVs. One reliable and efficient concept to evaluate the fracture toughness of ferritic steels is master curve method [1]. In ASTM E1921, it is clearly mentioned the universal shape of the median toughness-temperature curve for ferritic steels including tempered martensitic steels [2]. However, currently, concerns have arisen regarding the appropriateness of the universal shape in ASTM for the tempered martensitic steels such as Eurofer97 [3-5]. Therefore, it may be necessary to assess the master curve applicability for the tempered martensitic SA508 Gr.4N low alloy steel.

In this study, the fracture toughness behavior with temperature of the tempered martensitic SA508 Gr.4N low alloy steels was evaluated using the ASTM E1921 master curve method. And the results were compared with those of the bainitic SA508 Gr.3 low alloy steel. Furthermore, the way to define the fracture toughness behavior of Gr.4N steels well is discussed.

2. Experimental Procedure

The materials used in this work were commercial SA508 Gr.3 steel and model alloys of SA508 Gr.4N steel with various chemical compositions. Table 1 shows the chemical composition of Gr.3 steel and reference model alloy of Gr.4N steel. Test specimens were machined as a standard Charpy V-notched (10 x 10 x 55 mm^3) shape and then, a fatigue pre-crack was inserted into that.

Fracture toughness tests were carried out in 3-point bending by displacement controlled with MTS Insight 50. The test temperature was controlled within ±0.5^{o}C in an insulated chamber by PID controller equipped with a regulated liquid nitrogen flow.

Table 1. Chemical compositions of steels (wt%).

	C	Ni	Cr	Mo	Mn	P
H3	0.21	0.92	0.21	0.49	1.36	0.007
KL4-Ref	0.19	3.59	1.79	0.49	0.30	0.002

3. Results and Discussion

The measured K_{Jc} values of KL4-Ref in each test temperature were analyzed in terms of Weibull plotting. The slopes of lines fitted to data define the scatter of the K_{Jc} values. It was theoretically known that the slope should be over 4 [1]. The slope clearly tended to decrease from 8.99 to 3.71 with an increase of test temperature. So the scatters of the K_{Jc} values begin to be larger than prediction near -140^{o}C with occurrence of in-plane constraint loss. This tendency corresponded to the result in determination of invalid K_{Jc} values related to amounts of plastic deformation. The data set at -140^{o}C showed two invalid values among 10 values, while the data sets below -140^{o}C indicated all valid values. These results presented that in-plane constraint loss started from about -140^{o}C. Hence, the data sets including the data at -140^{o}C were used as reference data to assess the temperature dependency of fracture toughness.

Fig. 1 shows the standard master curves together with the K_{Jc} values of KL4-Ref (a) and H3 (b). As it can be seen, the data distribution of H3 was considerably fitted well to master curve through overall temperature range. However, the dependence of the K_{Jc} values on the temperature in KL4-Ref was steeper than that in the standard master curve shape. Moreover, in comparison between T_0 from all data sets and T_0 values from single-temperature determination procedure on the each temperature data sets, results of H3 showed that T_0 values did not deviate from T_0 from all data sets over about 7^{o}C. But differences between T_0 values from each data set and deviation from multi-temperature determined T_0 of KL4-Ref were extensively large. And T_0 values tended to decrease with a rise of test temperature. Hence, the adjustment of master curve expression was attempted for describing the K_{Jc} evolution well and determining more accurate T_0.

The adjustment was conducted by the exponential fitting for data of KL4-Ref:

$$K_{Jc(med)} = 30+70 \exp(0.031(T-T_0)) \qquad (1)$$

where exponential parameter related to curve shape was

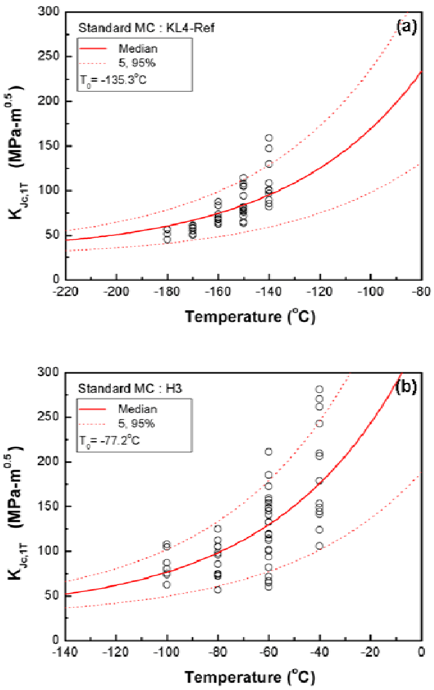

Fig. 1. Master curves of (a) KL4-Ref and (b) H3.

substituted for 0.031 instead of 0.019 in the standard curve expression. Fig. 2 shows the adjusted master curve of KL4-Ref. As it can be observed, the adjusted curve shape provided a better description for data sets through overall temperature. The shape of tolerance-bounds was also adjusted according to the new expression so that it reflected the distribution of data scatter more exactly. Moreover, T_0 values (-135.5 ~ -141.8°C) from single-temperature determination procedure at each data sets were almost same each other and were corresponded to -140.7°C, T_0 from the all data sets. Therefore, this adjusted master curve expression allowed considerably accurate T_0 determination.

The adjusted master curve concept was applied to other model alloys to confirm that the new expression represent the overall fracture toughness behaviors of tempered martensitic SA508 Gr.4N steels as well as that of KL4-Ref. Table 2 presents the number of data points above and below the median curve for the standard and adjusted master curve. In the case of the

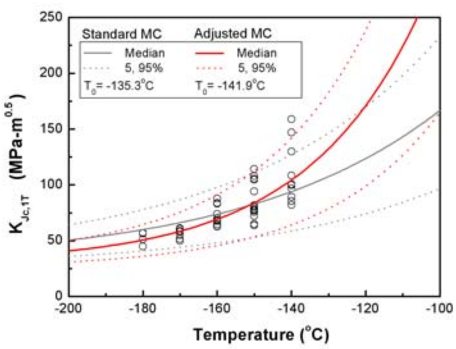

Fig. 2. The master curve with adjusted exponential parameter of KL4-Ref.

standard master curve plot, the proportions of data points below and above median curve were 60% and 40%, respectively. These results mean that the data distribution was asymmetric for the prediction of standard master curve. In contrast, a considerable agreement was found for the adjusted master curve in which the proportions of data below and above median were almost same (52% and 48%). As a result, the adjusted master curve expression derived experimental test result of KL4-Ref provided improvement of the description for the fracture toughness behavior of the tempered martensitic SA508 Gr.4N steels.

Table 2. Distribution of data points according to the standard and adjusted master curve.

	Number of K_{Jc} below median curve	Number of K_{Jc} above median curve
Standard MC	**148**	**99**
Adjusted MC	**129**	**118**

4. Summary

This work focused on characterization of the fracture toughness behavior of the tempered martensitic SA508 Gr.4N low alloy steels using a master curve concept. And the results were compared with that of bainitic SA508 Gr.3 low alloy steel. K_{Jc} evolution with temperature of Gr.3 steel were fitted to the standard master curve shape, but that of Gr.4N steel showed steeper behavior than the prediction of the standard master curve. The new master curve expression obtained from the adjustment of exponential parameter described well the steeper K_{Jc} evolution of reference alloy of Gr.4N steel through the overall transition region. And it allowed more accurate T_0 values to be determined compared with the standard master curve expression. In application of new expression to the data sets of model alloys with various chemical compositions, it was observed symmetrical distribution to the median curve of the adjusted master curve, but not to the median curve of the standard master curve. Based on the analysis results, it was considered that the adjusted master curve expression applied well to tempered martensitic SA508 Gr.4N Ni-Mo-Cr low alloy steels.

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