Effects of alloying element contents on the toughness and transition behavior in the SA508 Gr. 4N Ni-Mo-Cr low alloy steels

Ki Hyoung Lee[a], Sang Gyu Park[a], Min Chul Kim[b], Bong Sang Lee[b], Dang Moon Wee[a]
a *KAIST, Advanced High Temperature Materials LAb., Guseoung-dong, Yuseong-gu,Daejeon, 305-701, Korea*
b *KAERI, Nuclear Material Research Div., 150 Deogjin-dong, Yuseong-gu, Daejeon, 305-353, Korea*
shirimp @ kaist.ac.kr

1. Introduction

Low alloy steels used as materials for reactor pressure vessels (RPVs) determine the safety and the life span of reactors. Currently, SA508 Gr.3 low alloy steel is generally used for RPV materials. But, for larger capacity and long-term durability of the next generation RPVs, materials that have much better properties are needed, such as strength, toughness and irradiation resistance. SA508 Gr.4N low alloy steel shows good mechanical properties due to high Ni and Cr contents in comparison with the currently used reactor pressure vessel steels.

Materials for RPVs suffer a decrease of toughness due to an embrittlement of the materials by neutron irradiation, especially in ferritic steels. This toughness loss causes an increase in the transition temperature, and then a brittle fracture could occur. Therefore, for an integritiy assessment of low alloy steels as RPVs, an accurate evaluation of the transition behavior is needed, such as fracture and impact toughness.

In this study, the toughness and transition behavior of SA 508 Gr.4N low alloy steels, which have different Ni, Cr and Mo, were evaluated in the transition region. And the applicability of the test results for Master-Curve method was assessed. Additionally, differences between influences of alloying elements contents on Charpy impact toughness and fracture toughness were discussed in terms of microstructural features.

2. Experimental Procedure

The materials used in this work were SA 508 Gr.4N model alloys with different Ni, Cr and Mo contents. Table 1 shows the chemical composition of the tested materials. Model alloys were austenitized at 880℃ for 2 hours followed by air cooling, and then tempered at 660℃ for 10 hours. 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.

Fracture toughness of steels was evaluated following the ASTM standard E1921-08 procedure based on Master-Curve concept for a probabilistic and quantitative assessment [1]. Tests were performed by the displacement controlled with MTS Insight 50. The temperature was controlled in an insulated chamber by PID controller equipped with a regulated liquid nitrogen flow. The samples were etched by 3% nital and then microstructure was observed by optical microscope and scanning electron microscope (SEM).

Table 1. Chemical composition of the steels. (wt%)

	Mn	P	Ni	Cr	Mo	Fe
KL4-Ref	0.30	0.002	3.59	1.79	0.50	Bal.
KL4-Ni1	0.33	0.002	2.66	1.81	0.53	Bal.
KL4-Ni2	0.32	0.002	4.82	1.83	0.54	Bal.
KL4-Cr1	0.33	0.002	3.65	1.04	0.54	Bal.
KL4-Cr2	0.32	0.002	3.63	2.47	0.53	Bal.
KL4-Mo1	0.33	0.002	3.57	1.87	0.1	Bal.
KL4-Mo2	0.33	0.002	3.70	1.86	1.0	Bal.

3. Results and Discussion

Fig. 1 shows the fracture toughness test results from the PCVN specimens for model alloys, where the temperature scale was normalized by the T_0 value of each steel. All toughness data were size-corrected corresponding to those of 1T specimens. As seen in Fig. 1, the dependence of the fracture toughness on the test temperature followed the Master Curve trend for all model alloys. Most of the data points were satisfied within 95%, 5% of the theoretical tolerance bound lines. In addition, the dependence of the fracture toughness on the failure probability was evaluated based on a 3-paramater Weibull plot for the overall data set. That result is plotted in Fig.2. The Weuibull exponents *m* of the model alloys were in the range of 3.33 to 4.25, which are nearly consistent with the theoretical value of the Weibull exponent according to the master curve approach (*m*=4). These results mean that reference temperature, T_0, is suitable for parameter characterized transition properties of SA508 Gr.4N model alloys.

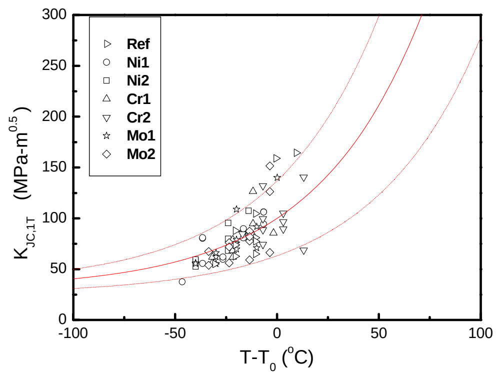

Fig. 1. Master curve for the fracture toughness test results of SA508 Gr.4N model alloys

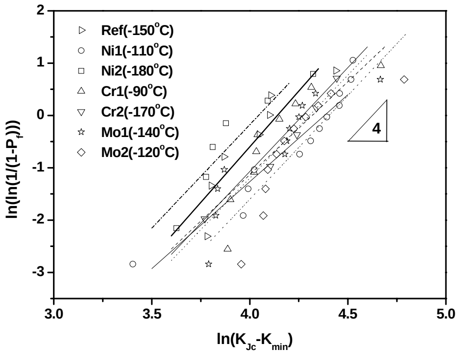

Fig. 2. Master curve for the fracture toughness test results of SA508 Gr.4N model allovs

Fig.3 shows the Charpy energy curves for the model alloys and Table 2 summarizes the T_0 values from the fracture toughness test results and the T_{28J} from the impact test results. The lower reference temperature (T_0) was presented in KL4-Ni2, Cr2 with higher alloying elements contents compared to KL4-Ref, especially in high Cr contents. However, in the result of the Charpy impact tests, the index temperatures, T_{28J}, decreased more extensively in KL4-Ni2 than in KL4-Cr2. On the other hand, KL4-Mo2, which contained more Mo content than KL4-Ref, was shown lower T_0 and T_{28J}, while a decrease of Mo contents had a little influence on toughness.

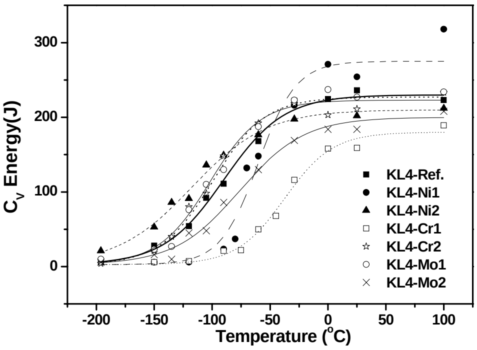

Fig.3. Variation of Charpy impact energy in the temperature range from -196°C to 100°C.

Table 2. Master curve reference temperature of model alloys with different chemical composition

	KL4-Ref	KL4-Ni1	KL4-Ni2	KL4-Cr1	KL4-Cr2	KL4-Mo1	KL4-Mo2
T_0	-142	-104	-156	-78	-164	-137	-120
T_{28J}	-140	-94	-175	-77	-149	-147	-126

To understand these effects of alloying elements contents on toughness of SA508 Gr.4N Ni-Cr-Mo low alloy steels, microstructural features of all specimens were observed. The grain and lath refinement occurred with an increase of Ni contents, while the behavior of carbide precipitation, such as distribution and sizes, was little altered [2]. Generally, Ni has been known as an effective alloying element for an improvement of the toughness of low alloy steels. But, It was reported that grain refinement induced by an increase of Ni content is less effective on the fracture toughness of steels, while it had extensive influence on the impact toughness[2].

It is reported that the carbide size was finer and the distribution was more uniform with an increase of Cr content in KL4 model alloys. This refinement of the carbides resulted in remarkable improvement on the toughness of steels, especially on the fracture toughness due to requirement of micro-crack growth up to critical size into carbide [3]. However, in former research, it is reported that refinement of carbides would not have any influence on the impact toughness.

The M_2C carbides, which have the fine needle-type, were observed in microstructure of KL4-Mo2 [4]. This needle-type carbides cause loss of the toughness of steels, because the micro-voids are nucleated preferentially between the needle-type carbides due to increases strain and stress localization by their alignment along a specific direction [5, 6].

4. Summary

The transition behavior including fracture toughness and impact toughness of SA508 Gr.4N low alloy steels with different Ni, Cr and Mo content were evaluated in the transition temperature region. In results of analysis in master curve concept, most of data sets were well fitted to a Weibull plot. The improvement of the transition behavior of steels was achieved by increasing of the Ni and Cr contents, especially in the case of Cr. On the other hand, Charpy impact toughness of steels was more greatly improved with an increasing of Ni contents compared with that of Cr contents. This is due to the differences between microstructural features of KL4-Ni2 with grain-refinement and KL4-Cr2 with carbide-refinement. Addition of Mo caused a low fracture toughness of steels due to a precipitation of the needle-type carbides which have specific directional feature.

Acknowledgement

This work is carried out under the Nuclear R&D program by the Ministry of Knowledge Economy.

REFERENCES

[1] E. Donald, An Introduction to the Development and Use of the Master Curve Method, ASTM International, 2005
[2] S. G. Park, J. Kor. Inst. Met & Mater., Vol. 46, 2008, 771
[3] W. J. Yang, J. Kor. Inst. Met. & Mater. 38, 2000, 675
[4] F. B. Pickering and T. Gladman, Iron and Steel Inst., Spec. Rep. No 93, 1963, 10
[5] Y. S. Ahn, J. Kor. Inst. Met & Mater., Vol. 38, 2000, 1309
[6] Y. S. Ahn, J. Nucl. Eng. & Desi., 194, 1999, 161