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The evaluation of fracture toughness behavior of SA508 Gr. 4N low alloy steels in the transition temperature region

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1. Introduction

Nuclear reactor pressure vessels (RPVs) suffer increase of tensile strength and decrease of fracture toughness due to embrittlement of materials by neutron irradiation. Fracture toughness loss cause a increasing of ductile-brittle transition temperature, and then brittle fracture could be occurred. Therefore, for integritiy assessment of low alloy steels as RPVs, it is surely needed accurate evaluation of fracture toughness.

Generally, ferritic structural steels show significant decreasing of fracture toughness with decreasing temperature at which the fracture mode changes from ductile to brittle cleavage fracture. In this transition temperature region, fracture toughness of steels is changed rapidly with test temperature and shows large data scatter at same test temperature. In order to evaluate this transition behavior of fracture toughness, recently, a new standard test method of ASTM was developed by using Master Curve concept for the probabilistic and quantitative evaluation.

In this study, fracture toughness properties of several SA 508 Gr.4N low alloy steels, which have different Ni, Cr and impurities contents, was evaluated in transition region. Moreover, effects of alloying elements and impurities on the transition properties of Ni-Cr-Mo low alloy steels were investigated based on fractographs and micrographs.

2. Experimental Procedure

The materials used in this study were SA 508 Gr.4N model alloys with different Ni, Cr and impurities contents. Table 1 shows the chemical composition of the test 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 standard Charpy V-notched(PCVN, 10 x 10 x 55 mm^3) shape and then, fatigue pre-crack was inserted into these specimens. The samples were etched by 3 pct nital and then microstructure was observed by optical microscopy and scanning electron microscopy (SEM).

Fracture toughness tests were conducted following the ASTM standard E1921-03 procedure. Testes were performed by the displacement control in the static test machine equipped the MTS insight 50. The temperature was acquired in an isopentane fluid bath and an insulated chamber, which were both cooled by liquid nitrogen. The test temperature was controlled accurately within ± 1℃. For each model alloys, more than six valid toughness data were acquired in the transition temperature range and the micrographs of fracture surface were observed using SEM.

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

	Mn	P	Si	Ni	Cr	Fe
KL4-Ref.	0.30	0.002	0.24	3.59	1.79	Bal.
KL4-Ni1	0.33	0.002	0.25	2.66	1.81	Bal.
KL4-Ni2	0.32	0.002	0.24	4.82	1.83	Bal.
KL4-Cr1	0.33	0.002	0.25	3.65	1.04	Bal.
KL4-Cr2	0.32	0.002	0.26	3.63	2.47	Bal.
KL4-P	0.33	0.029	0.26	3.63	1.87	Bal.
KL4-SC	0.01	0.002	0.01	3.59	1.83	Bal.

3. Results and Discussion

Fig. 1 shows the fracture toughness test results from PCVN specimens for model alloys with different chemical composition 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 fracture toughness on the test temperature followed the Master Curve trend for all model alloys. Most of data points were included within 95%, 5% the theoretical tolerance bound lines. This results mean that reference temperature, T_0, is suitable for parameter characterized transition properties of fracture toughness.

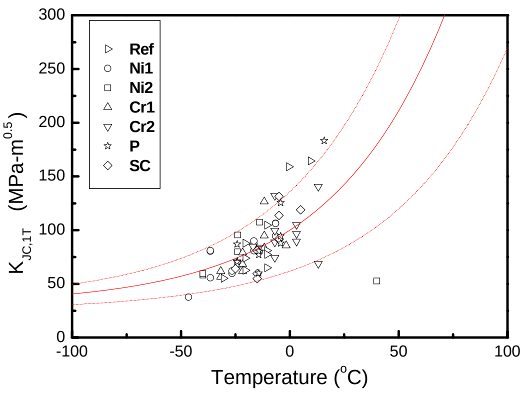

Fig. 1. Master curve for the fracture toughness test results of model alloys where test temperature were normalized by T_0 values determined on each material.

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

	KL4 -Ref	KL4 -Ni1	KL4 -Ni2	KL4 -Cr1	KL4 -Cr2	KL4 -P	KL4 -SC
T_0	-140	-104	-156	-78	-163	-106	-155

Table 2 summarizes the determined T_0 values from the fracture toughness test results. KL4-Ni1, which contained less Ni content than KL4-Ref, showed higher T_0 value compared with KL4-Ref. On the other hand, T_0 value of KL4-Ni2 is lower than that of KL4-Ref. This means that fracture toughness of alloys improved with a increasing of Ni content. In earlier researches, Ni has been known as effective alloying element for improvement of impact toughness of low alloy steels. It seems that positive effect of Ni on impact toughness has similar influence on fracture toughness, too.

The change of Cr content did its works similar effect of Ni content on fracture toughness of model alloys. That is to say that a increasing of Cr content results in improvement of fracture toughness of KL4 steel. This is because more fine-grained Cr-carbide was precipitated uniformly with a increasing of Cr contents.

A increasing of P content cause a high T_0 value which is 34℃ over that of KL4-Ref (-140℃), however, diminishment of impurities such as Mn, P and Si significantly lower T_0 value of model alloy. In general, it is well known that, grain boundaries of heat treated alloy steels are embrittled easily due to segregation of impurities such as P.

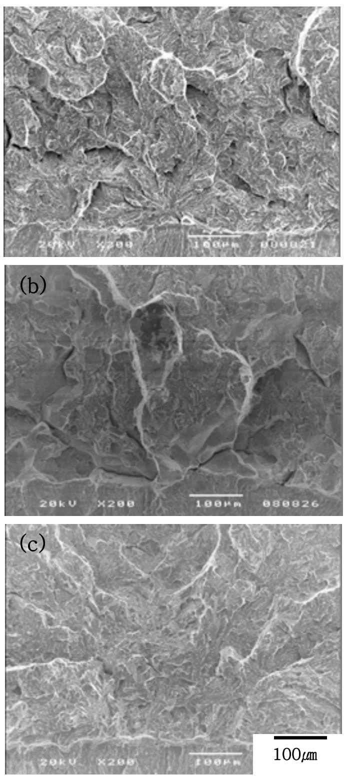

Fig. 2. SEM Fractographs of KL4 steels
(a) Ref, (b) P, (c) S-C

Fig. 2 displays fractographs of KL4-Ref, KL4-P and KL4-SC specimens. Fractograph of KL4-P(Fig. 2(b)) shows mixed fracture mode of grain boundary fracture and cleavage fracture. This suggests that grain boundaries were embrittled by P segregation with increased P content. On the other hand, in the case of KL4-SC which was decreased contents of impurities, tipical cleavage fracture occurred and crack initiation site was relatively far from crack tip.

4. Summary

Effects of alloying elements and impurities on the fracture toughness of KL4 steels in ductile-brittle transition region were investigated based on master curve method. The improvement of a transition property of KL4 steels was taken by increasing of Ni and Cr contents. This is due to characteristic toughness improvement property of Ni and Cr-carbide refinement with increasing of Cr, respectively. Addition of P made low fracture toughness of KL4 steel in transition temperature region due to segregation of P into grain boundaries. However, decreasing of impurities contents improved transition properties of KL4 steels. Additionally, the effects of Mo and Mn on fracture toughness of KL4 steels are underway.

Acknowledgement

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