ORAL/POSTER REFERENCE: ICF100428OR

EFFECTS OF DYNAMIC STRAIN AGING IN J-R FRACTURE RESISTANCE OF SA516-Gr.70 PIPING STEELS

Ji Hyun Yoon, Bong Sang Lee and Jun Hwa Hong

Korea Atomic Energy Research Institute,
Dukjin-Dong 150, Yusung, Daejon 305-353, Republic of Korea

ABSTRACT

J-R fracture resistance tests have been performed on two heats of SA516-Gr.70 carbon steels used for the elbows of nuclear piping. The tests covered a wide temperature range of ambient to 500℃ with various loading rates ranging from 0.3 to 1000 mm/min. The steep drops in fracture resistance of the SA516-Gr.70 steels were observed at certain temperature ranges at all loading rates. The temperature for the minimum fracture resistance moved to the higher temperature region as loading rates increase. Tensile tests were also carried out at temperatures of 100 to 316℃ with a range of strain rates of 2.5×10^{-5} to 1.33×10^{0}/s. The serrated flows were observed on some of the stress-strain curves. All these features indicated that the test materials were susceptible to DSA. However, some differences were founded in fracture resistances and DSA sensitivity between the two test materials. From the metallurgical analysis performed on them, it was deduced that microstructural characteristics such as grain size and pearlite fraction made quite a larger gap between the fracture resistance levels of the two materials and that the chemical composition, especially the contents of free interstitial atoms, were a main controlling factor for DSA sensitivity in SA516-Gr.70 steels.

KEY WORDS

J-R fracture resistance, dynamic strain aging (DSA), SA516-Gr.70 steel, loading rate, LBB

INTRODUCTION

SA516-Gr.70 steel has been widely used for elbows of nuclear piping. The leak-before-break (LBB) design concept [1] that has been applied to nuclear piping recently requires confirming fracture resistance of the piping materials through J-R tests. However, the systematic J-R test data obtained under various test conditions are very rare while a large database has been built for another piping material, i.e. SA106 steel by the International Piping Integrity Research Group (IPIRG) program.

It is well known that the fracture resistances of ferritic steels like SA516-Gr.70 steel are deteriorated in dynamic strain aging (DSA) region. Although some researchers like Miglin et al. and Marengo et al. reported DSA effect in J-R fracture resistance [2,3], their investigations were limited to J-R tests under static loading condition. Therefore, J-R fracture resistances were investigated in the present study at various temperatures ranging from ambient to maximum reactor operating temperature and various loading rates for SA516-Gr.70 steels. DSA effects in of J-R fracture resistances of two heats of SA516-Gr.70 steels with loading rates and temperatures were analyzed. Furthermore, differences of DSA behaviors and fracture resistances between two test materials of same specification were described and discussed with respect to microstructure and chemical composition.

EXPERIMENTAL

Materials and Specimen

Two heats of SA516-Gr.70 steels for elbow are used in this study. The chemical compositions are shown in Table 1. The ASTM standard 1T-C(T) specimens with T-L orientation were used for J-R tests. The specimens were side-grooved to a depth of 10% of the specimen thickness on both sides after fatigue pre-cracking.

TABLE 1

CHEMICAL COMPOSITIONS OF SA516-Gr.70 STEELS

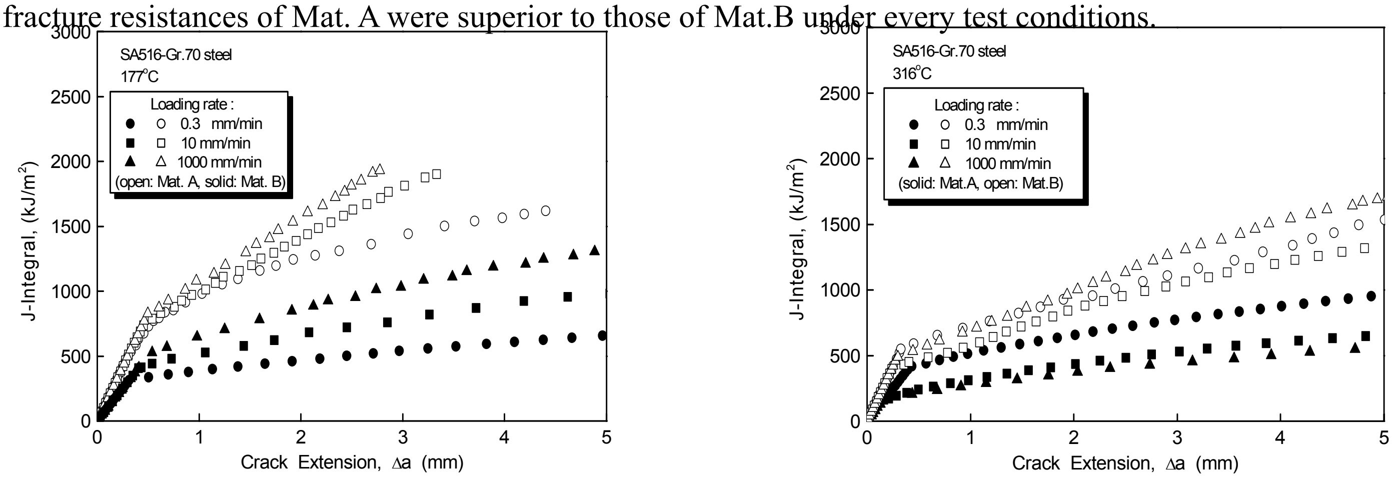
wt.% Material	C	Si	Mn	P	S	Cu	N	Ni	Cr	Mo	Al	V	Nb
Mat. A	0.22	0.31	1.14	0.005	0.002	0.10	0.0088	0.21	0.15	0.04	0.020	<0.005	<0.05
Mat. B	0.17	0.30	1.14	0.009	0.001	0.20	0.0024	0.36	0.03	0.10	0.031	0.028	0.016

J-R fracture resistance test

Direct current potential drop (DCPD) method that is applicable to the fast loading test was used for monitoring crack extension. The tests were conducted on a servo-hydraulic MTS 810 system. To insure signal integrity, the specimen and grip assembly was isolated from the rest of the load train. The details were reported elsewhere [4].

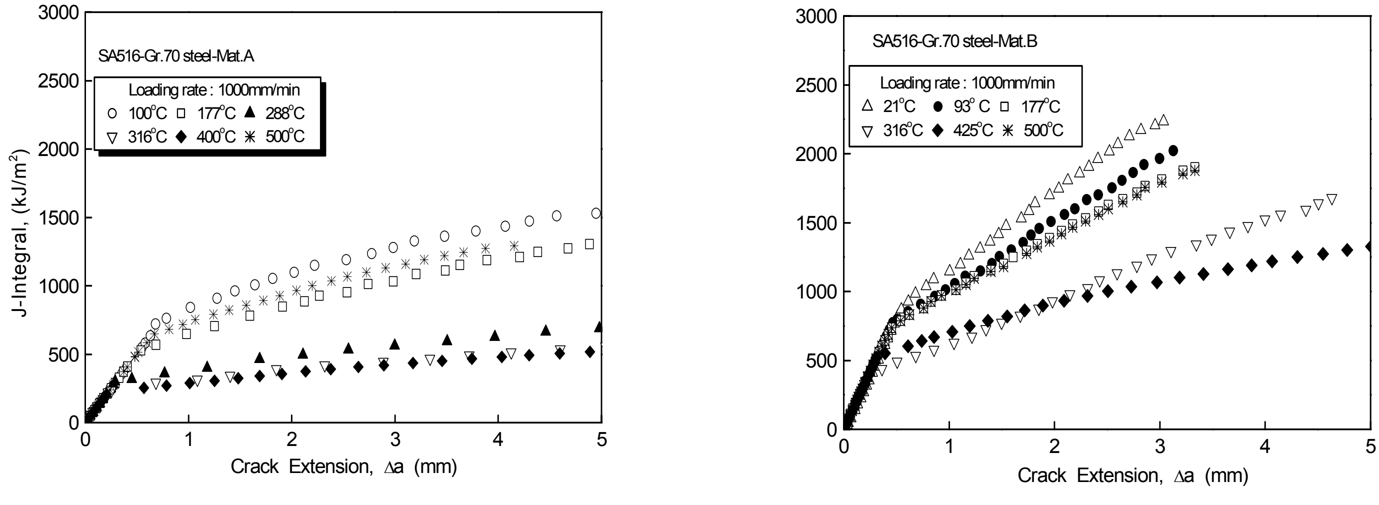
RESULTS AND DISCUSSION

Fig. 1 and Fig. 2 shows the J-R curves under various loading rates and temperatures. It was observed that the J-R fracture resistance of SA516-Gr.70 steels was very sensitive to the loading rate and temperature. The fracture resistances of Mat. A were superior to those of Mat.B under every test conditions.



(a) (b)

Fig. 1 : J-R Curves at various loading rates for Mat.A and Mat.B at (a) 177℃ and (b) 316℃.



(a) (b)

Fig. 2 : Variations of J-R curves with test temperature ; (a) Mat.A, (b) Mat.B.

J integral values named as $J_{0.1}$ were obtained at Δa=0.1 inch (2.54 mm) on J-R curves to appreciate the dependence of the fracture resistance on the temperature and loading rate quantitatively as shown in Fig. 3.

As the loading rate increased, the temperature at which the fracture resistance became minimum or each loading rate shifted to higher temperature region. On the basis of previous research, the occurrence of the abrupt drop in J-R fracture resistance at a specific temperature and loading rate range is due to DSA [2]. In case of Mat. B, the temperature range which DSA occurred in was shifted to a higher temperature region and was narrower compared to Mat. A.

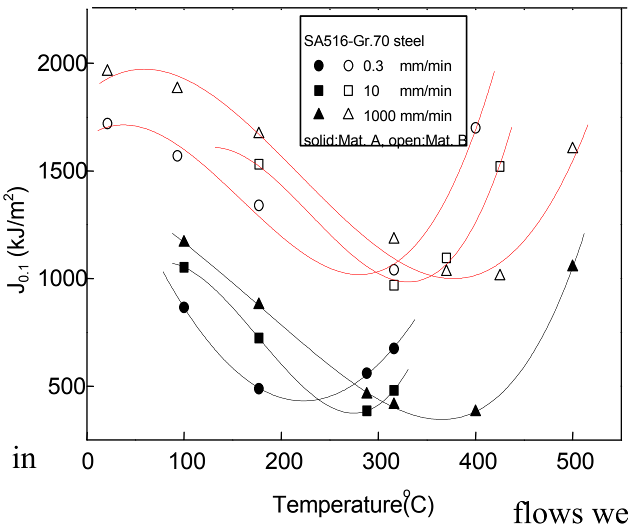
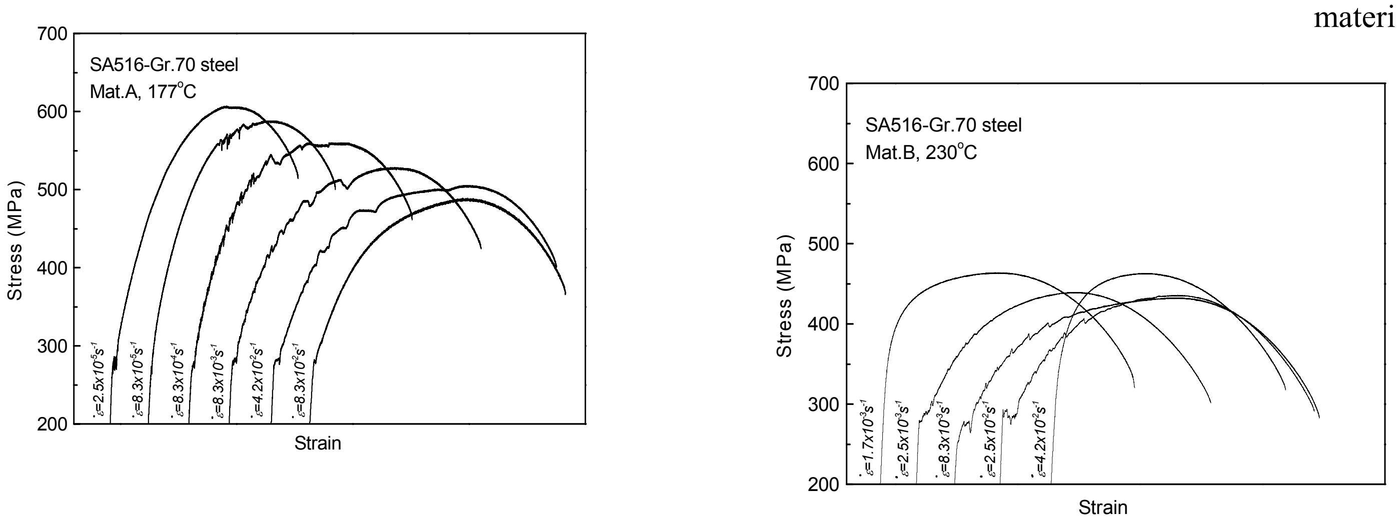


Fig. 3 : Variation of $J_{0.1}$ at various temperature and loading rate.

DSA phenomena was usually recognized by serrated flows in tensile stress-strain curve that is referred to Portevin-Le Chatelier effect [5]. Fig. 4 shows tensile test results for SA516-Gr.70 steels. The serrated flows were obviously observed in some test conditions. The serrations in Mat.A was more apparent than those in Mat.B. The conditions for the occurrence of serrated flows were expressed as a serration map in Fig. 5.

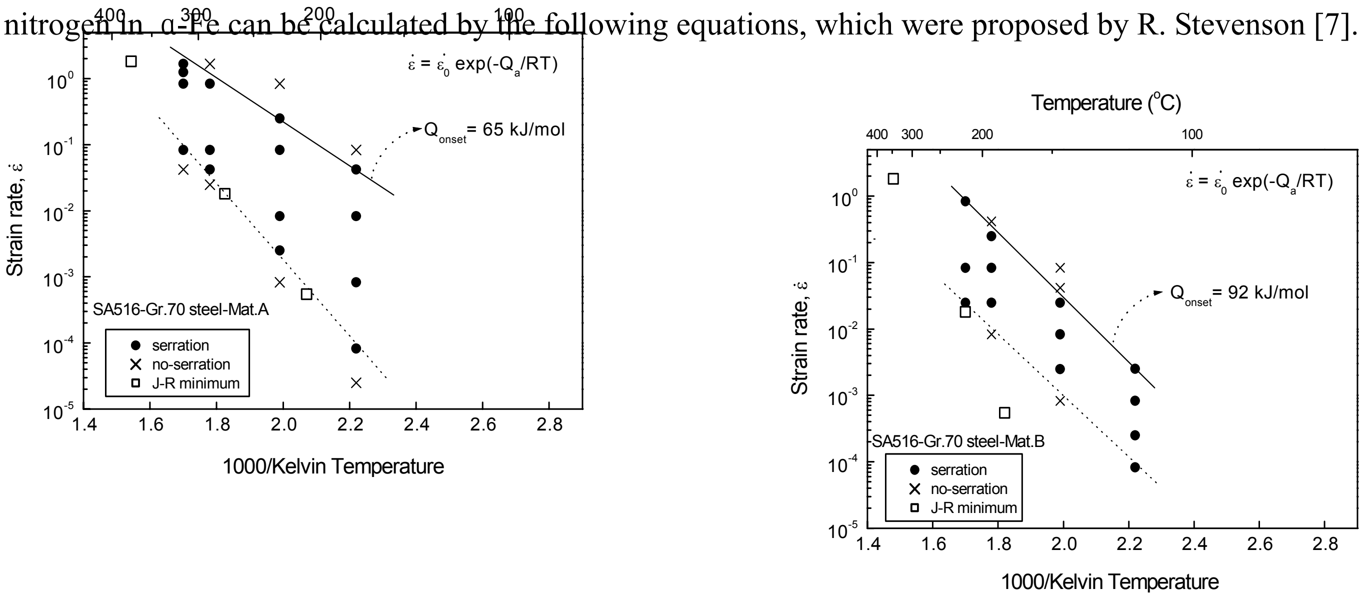
Since DSA is regarded as a thermally activated process, the activation energies of solute diffusion in test materials can be obtained from Arrhenius type plot.



(a) (b)

Fig. 4 : Stress-strain curves at various strain rates for (a) Mat.A and (b) Mat.B.

The activation energies were determined as 65 and 92 kJ/mol for Mat.A and Mat. B respectively as represented in Fig. 5. The differences of fracture resistance and DSA behaviors between two heats of SA516-Gr.70 steels were analyzed with respect to chemical composition and microstructural factors. It was found that the comparatively high fracture resistance of Mat. B under all test conditions due to smaller grain size and lower pearlite to ferrite ratio compared to Mat. A. The concentrations of interstitials and activation energy for diffusion are main factors that affect on DSA behavior in steel [6]. The concentrations of carbon and nitrogen in SA516-Gr.70 steels, in Mat A are higher than those of Mat. B. The solubilities of carbon and nitrogen in α-Fe can be calculated by the following equations, which were proposed by R. Stevenson [7].



(a) (b)

Fig. 5 : Serration map for SA516-Gr.70 steel ; (a) Mat.A, (b) Mat.B.

$$\text{wt\% C} = 2\exp(-38.07(\text{kJmol-1})/RT) \qquad (1)$$

$$\text{wt \% N} = 12.3\exp(-34.73(\text{kJmol-1})/RT) \quad (R : 8.314 \text{ J/mol/K}, T : \text{Kelvin temperature})$$

Table 2 summarized the solubilities of carbon and nitrogen in an iron matrix in the test temperature range. It is expected that the solubility of nitrogen is higher than that of carbon in SA516-Gr.70 steels in the test temperature range. The nitrogen concentrations of Mat. A and B are 88 and 24 ppm, respectively. These are within the solubility limit in the matrix. On the other hand, carbon concentrations of Mat. A and B exceed the solubility limit in the matrix. It means that the difference of DSA sensitivities between Mat. A and B is mainly due to the difference of nitrogen concentration.

TABLE 2

Solubility of C and N in α-Fe (in ppm)

	293 K	373 K	473 K	573 K	673 K	773 K
C (ppm)	0.003	0.09	1.3	6.8	22.2	53.5
N (ppm)	0.079	1.68	18.0	89.3	249.7	553.3

Baird and Jamieson reported that carbon and nitrogen are bound more strongly to the substitutional impurities like Mo, Co, Ni and Mn than to dislocations [8]. DSA will be extended to a higher temperature range than in pure Fe-C or Fe-N due to the reduced mobility of the carbon and nitrogen atoms in steel containing Mo, Co, Ni and Mn. Cr, V, Nb, Ti and Zr were also pointed as substitutional impurities which extend DSA to higher temperatures although they are less effective than Mo, Co, Ni and Mn. Chakravartty et al. reported that the nitride formers such as Al, Ti and V tie up a major fraction of nitrogen in the form of alloy nitrides and DSA is diminished in ferrictic-pearlitic steel [9]. As shown in Table 1, the concentrations of Mo, Ni, V, Al in Mat. B are even higher than those in Mat. A. From the previous studies, it is deduced that substitutional impurities such as Mo, Ni, V, Al also reduced DSA sensitivity in Mat. B.

CONCLUSIONS

J-R fracture resistance of SA516-Gr.70 steels is very sensitive to the loading rate and temperature due to dynamic strain aging.

The difference of J-R fracture resistance levels and DSA behaviors between two heats of SA516-Gr.70 steels are mainly due to differences of pearlite to ferrite ratio and chemical composition such as concentrations of interstitial solute atoms. It was presumed that substitutional solute concentrations also affected DSA behavior in SA516-Gr.70 steels.

ACKNOWLEDGEMENT

This work has been carried out as a part of Reactor Pressure Boundary Materials Project under the Nuclear R&D Program by MOST in Korea.

REFERENCES

1. USNRC (1987). *Leak Before Break Evaluation Procedure, USNRC Report NUREG-800, Standard Review Plan. 3.3.6.*
2. M. T., Migline et al. (1985). *Effects of Strain Aging in the Unloading Compliance J test, ASTM STP 856,* ASTM, Philadelphia,.
3. A. A., Marengo and J. E., Perez (1996). *Nucl Engng Des.* 167, 215-222.
4. J. H. Hong et al. (1997). *KAERI Report, KAERI/CR-35/97.*
5. A., Portein and F., Le Chatelier (1923). *Compt. Rend. Acad. Sci.*, 176, 507-512.
6. A. S., Keh et al., (1968). *Dislocation Dynamics*, McGraw-Hill, New York,.
7. R. Stevenson : *Metall. Trans.* 11A (1980) 1909
8. J. D. Baird, A. Jamieson (1966). *J. Iron Steel Inst.*, 204, 793.
9. J. K., Chakravartty et al. (1983). *J. Nucl. Mater.*,119, 51-58.