Transactions of the Korean Nuclear Society Spring Meeting
Taebaek, Korea, May 26-27, 2011

Temperature Dependence of Dynamic Fracture Toughness for SA106 Gr.C Steel

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1. Introduction

Leak-before-break (LBB) concept is applied to design of high energy piping system of nuclear power plants (NPPs). Fracture resistance of piping material is one of the key parameters in applying LBB concept, and fracture toughness of piping material is required for LBB analysis [1]. It is known that dynamic strain aging (DSA) occurs in the range of operating temperature for ferritic steel and decreases fracture toughness of material [2]. Also, the temperature appearing DSA depends on loading rate. For LBB analysis of ferritic piping system, thus, J-R data tested under dynamic loading as well as quasi-static loading rate are required to regard the fracture resistance under seismic loading condition. A few studies conducted dynamic J-R tests for several ferritic steels [2,3]. In their tests, direct current potential drop (DCPD) method was used to measure the crack extension. However, DCPD method showed a significant uncertainty in the measurement of crack extension because of appearance of pulse signal at early stage of crack propagation caused by ferromagnetic effect of ferritic materials. Therefore, it was restricted to clearly understand the characteristics of fracture toughness for ferritic piping materials under dynamic loading condition.

This study conducted dynamic J-R tests for SA106 Gr.C ferritic steel at various temperatures using normalization method and compared the results with static J-R data. From the results, the temperature dependence of fracture toughness under dynamic loading condition was investigated.

2. Experiment

2.1 Test material and specimen

In this study J-R tests were conducted using SA106 Gr.C ferritic steel, which is commonly used for main steam line piping of NPPs. The specimens were machined as the standard 1T-C(T) specimens with L-C direction from the pipe specimen. The configurations of the specimen conformed to recommendations of ASTM E1820-08 [4]. The specimens were side-grooved to a depth of 10% of the specimen thickness on both sides after precracking whose length is about 0.59 W.

2.2 J-R tests

Static J-R tests were conducted by the unloading compliance method in accordance with ASTM E1820-08. Loading rate applied to static J-R tests was 0.6mm/min in cross-head speed. The crack extension of specimens in the dynamic J-R test was evaluated by normalization method, which is recommended for high loading rate J-R test by ASTM 1860-08. The test speed (V_{LL}) for dynamic J-R tests was determined based on the natural frequency of piping system [5]:

$$V_{LL} = 4 \times f(\#1) \times D_i$$

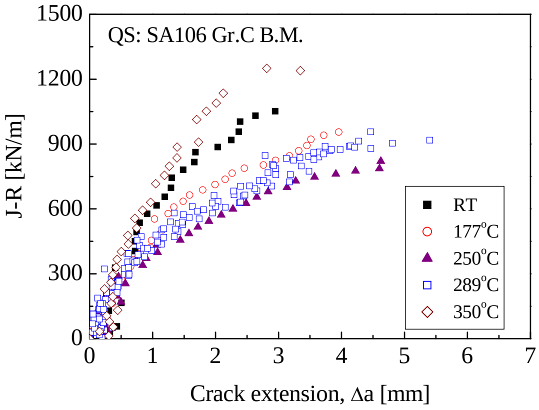
where D_i is the load-line displacement at crack initiation under quasi-static loading rate, and $f(\#1)$ is first mode natural frequency of piping system. The calculated test speed was 2100mm/min.

Both static and dynamic J-R tests were conducted at various temperatures in the range RT ~ 350°C in air. All tests were conducted on a servo-hydraulic test machine with high temperature furnace. The specimen temperature was controlled within ± 1°C. Load-line displacement of specimen was measured using a high temperature clip-on gage.

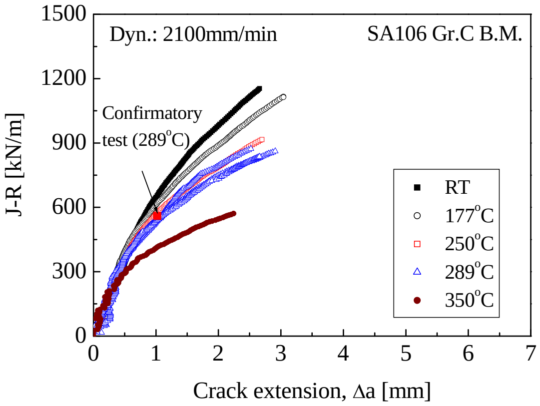
3. Results and Discussion

Figure 1 presents static and dynamic J-R curves as function of test temperature. As shown in Fig. 1(a), static J-R curve decreases with increase in test temperature and reaches the minimum at 250°C. Then, the curve increases again with increasing test temperature, and the J-R curve at 350°C is much higher than that at 250°C. However, dynamic J-R curve decreases with increasing test temperature up to 350°C, so the minimum appears at 350°C (Fig. 1(b)). Previous studies showed that the J-R curve of ferritic steels is reduced by DSA and the temperature region appearing DSA moves to higher temperature with increasing loading rate [ ]. Thus, it is shown that DSA effect on the fracture toughness of SA106 Gr.C piping steel is the most significant around 250°C for quasi-static loading condition and that it appears at higher temperature above 350°C for dynamic loading condition corresponding to seismic loading.

Comparison of J-R curves tested under quasi-static and dynamic loading rates at each temperature showed that dynamic J-R curves are higher than quasi-static J-R curves at temperatures below 289°C. But, the trend is reversed at 350°C; the dynamic J-R curve is much lower than quasi-static J-R curve. SA106 Gr.C ferritic steel is commonly used in the secondary piping systems of NPPs, whose operating temperature is less than 289°C. Thus, it is indicated that the static J-R data is conservatively applicable for LBB analysis of piping systems using SA106 Gr.C ferritic steel; in this case dynamic J-R data is unnecessary for LBB analysis.



(a) Quasi-static loading



(b) Dynamic loading

Fig. 1 J-R curves for SA106 Gr.C at various test temperatures

4. Conclusions

1) DSA effect on the fracture toughness of SA106 Gr.C piping steel was the most significant around 250°C for quasi-static loading condition, whereas the significant DSA effect appeared at higher temperature above 350°C for dynamic loading condition.
2) Dynamic J-R curves were higher than quasi-static J-R curves at the temperatures below 289°C, but the trend is reversed at 350°C.

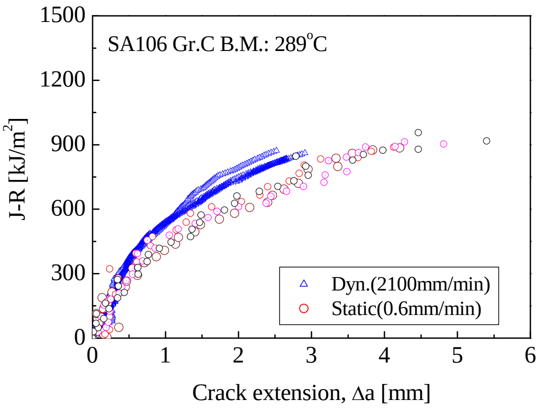


Fig. 2 Comparison of J-R curves tested under quasi-static and dynamic loading rates at 289°C

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