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J-R FRACTURE TOUGHNESS OF NUCLEAR PIPING MATERIALS UNDER EXCESSIVE SEISMIC LOADING CONDITION

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ABSTRACT
This study investigated the loading rate effect on the fracture resistance under cyclic loading conditions to clearly understand the fracture behavior of piping materials under excessive seismic conditions. J-R fracture toughness tests were conducted under monotonic and cyclic loading conditions at various displacement rates at room temperature (RT) and the operating temperature of nuclear power plants (NPPs), i.e., 316°C. SA508 Gr. 1a low-alloy steel (LAS) and SA312 TP316 stainless steel (SS) piping materials were used for the tests. The fracture resistance under a reversible cyclic load was considerably lower than that under monotonic load regardless of test temperature, material, and loading rate. Under both cyclic and monotonic loading conditions, the fracture behavior of SA312 TP316 SS was independent of the loading rate at both RT and 316°C. For SA508 Gr. 1a LAS, the loading rate effect on the fracture behavior was appreciable at 316°C under both cyclic and monotonic loading conditions. However, the loading rate effect diminished when the cyclic load ratio (R) was –1. Thus, it was recognized that the fracture behavior of piping materials, including seismic loading characteristics, can be evaluated when tested under a cyclic load of R = –1 at a quasi-static loading rate.

INTRODUCTION
The piping components of nuclear power plants (NPPs) should be designed and maintained to ensure their structural integrity under seismic condition as well as normal operation conditions [1-3]. After nuclear accident in Fukushima Daiichi NPPs, in particular, the interest in structural integrity of nuclear piping components during seismic event is greatly increased [4]. Thus, the reliability of integrity assessment for piping components under seismic loading condition is an important issue. In the current integrity assessment procedures [2,5], seismic load is treated as monotonic and applied once and the mechanical properties obtained from monotonic and quasi-static loading condition are used for the assessment. However, the seismic load has both dynamic and cyclic characteristics, and the mechanical properties under dynamic and cyclic loading conditions are different from those under monotonic and quasi-static loading conditions. Hence, ignoring the dynamic and cyclic loading characteristics in the mechanical properties of materials could cause an uncertainty in the integrity assessment under the seismic condition.

A number of studies have investigated the cyclic loading effect on the fracture behavior of materials [6-12]. All of these reported that the fracture resistance was significantly reduced by reversible cyclic load when compared to that under monotonic load, and the reduction depended on the unloading level and frequency of cyclic load. Also, they showed that such behavior under cyclic load was attributed to fatigue and fracture synergy that accelerated crack extension. However, most of investigations were based on cyclic tests at a quasi-static loading rate rather than at a dynamic loading rate [7-12]. Only a few studies performed cyclic fracture tests under the dynamic loading condition and they reported the interaction between cyclic and dynamic loading effects was negligible and both effects on the fracture behavior can be considered separately [6].

Table 1 Chemical compositions of SA508 Gr.1a LAS and SA312 TP316 SS piping materials (wt %)

Material	C	Mn	P	S	Si	Ni	Cr	Mo	V	Al	Cu
SA508 Gr.1a	0.223	1.27	0.009	0.0047	0.225	0.242	0.118	0.026	0.003	0.024	0.200
TP316SS	0.021	1.25	0.038	0.004	0.45	12.21	16.31	2.06	-	-	-

Table 2 Tensile properties of SA508 Gr.1a LAS and SA312 TP316 SS piping materials

Materials	Temp.	YS[MPa]	UTS[MPa]	TE[%]	RA[%]
SA508 Gr.1a	RT	359.9	543.6	35.9	74.8
	316ºC	232.4	537.4	32.8	71.8
TP316SS	RT	266.1	573.1	66.8	82.8
	316ºC	155.2	452.5	42.3	79.6

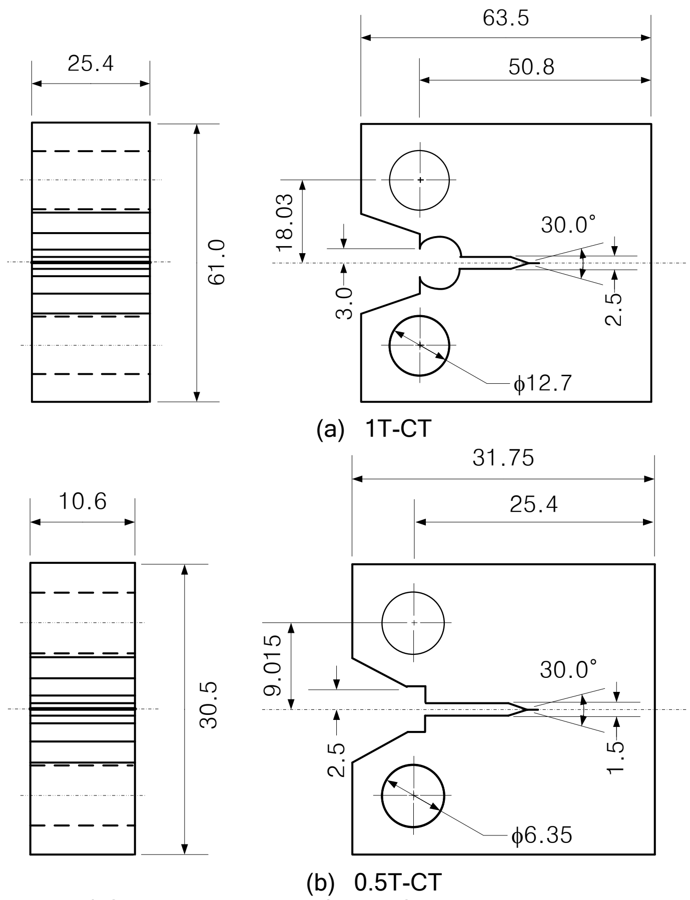


Fig. 1 CT specimens used for J-R fracture toughness tests

However, this conclusion was drawn from only a limited test condition, i.e., a single loading rate, although the loading rate under seismic condition is dependent on the routing of piping system and location within piping components. In particular, the deformation rate near crack-tip, which is closely related to loading rate and affects the fracture behavior of materials, is more difficult to quantify under the seismic condition because it depends on the geometry and location of the crack within the piping components. Considering such uncertainty in the loading rate under the seismic condition, the loading rate effect on fracture behavior under cyclic loading condition needs to be investigated to clearly understand the fracture behavior of piping components under the seismic loading condition.

Therefore, this study conducted J-R fracture toughness tests on two piping materials commonly used in NPPs under monotonic and cyclic loading conditions at various displacement rates at room temperature (RT) and operating temperature of NPPs (316ºC). The loading rate effect on the fracture behavior was investigated under monotonic and cyclic loading conditions by comparing J-R curves for different displacement rates. In addition, appropriate consideration of seismic loading characteristics in the evaluation of the fracture behavior of piping materials was discussed on the basis of these investigations.

EXPERIMENT

Test materials and specimens

The materials used for the experiments were SA508 Gr.1a low-alloy steel (LAS) and SA312 TP316 stainless steel (SS) piping materials. SA508 Gr.1a LAS is used for a main coolant pipe line in Korean Standard Nuclear Power Plant (KSNP) and its dimensions are 1075.4mm in outer diameter (D_o) and 102.6mm in thickness (t). SA312 TP316 SS is also commonly used for pipe lines in the primary system of NPPs and it is 4-inch, Sch.160 (D_o=114.3mm and t=13.5mm). The chemical compositions of both pipe materials are listed in Table 1 and their tensile properties at RT and 316ºC under quasi-static loading rate are summarized in Table 2.

In this study, the fracture toughness tests were conducted using compact tension (CT) specimen; a 1T-CT specimen with a thickness of 25.4mm was used for SA508 Gr.1a LAS and a 0.5T-CT specimen with a thickness of 10.6mm was used for SA312 TP316 SS. Both specimens were designed in accordance with ASTM E1820-15a [13] (Fig. 1), except that the thickness of 0.5T-CT specimen was thinner than that of ASTM standard, and were machined in L-C direction. All specimens were pre-cracked in fatigue and side-grooved on both sides of the specimen following the ASTM E1820-15a [13]. Length of pre-crack was 4.0mm for 1T-CT specimen and 2.5mm for 0.5T-CT specimen, so total length of crack (a) including machine notch became 0.59W, where W is width of specimen. The pre-crack was produced under several loading steps. At final loading step, the stress intensity factor range (ΔK) was maintained below 15MPa√m. For all steps the minimum to maximum load ratio and frequency of fatigue loading were 0.1 and 10Hz, respectively.

Experimental procedures

J-R fracture toughness tests were conducted under both monotonic and cyclic loading conditions at RT and 316ºC. Four different displacement rates (V_{LL}) were considered in the

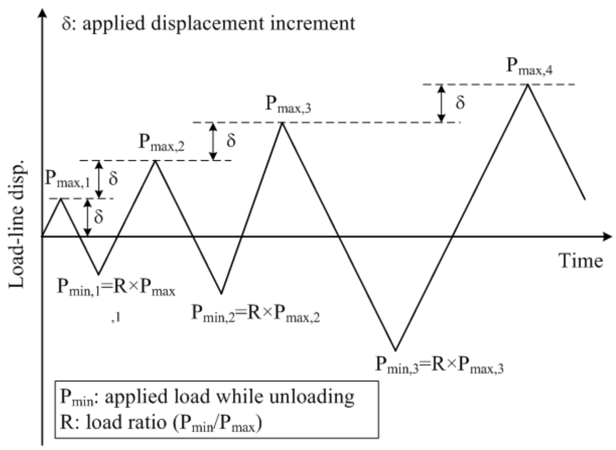
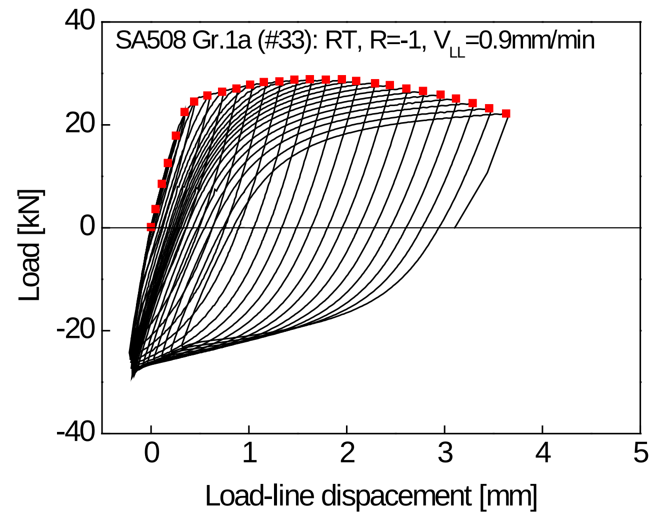


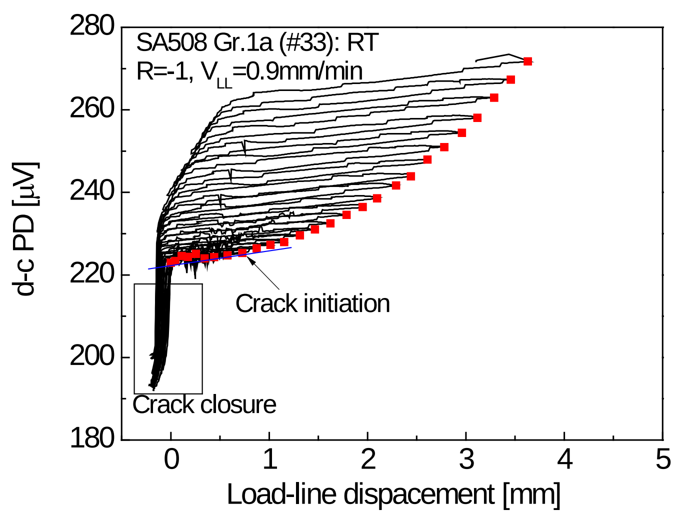
Fig. 2 Cyclic loading sequence used for cyclic J-R tests

monotonic tests; V_{LL}=0.9, 9.0, 90, and 2280mm/min for SA508 Gr.1a LAS and V_{LL}=0.45, 4.5, 45, and 1140mm/min for SA312 TP316 SS. In the cyclic tests, V_{LL}=0.9, 9.0, 90, and 2280mm/min were used for SA508 Gr.1a LAS and V_{LL}=0.45 and 45mm/min for SA312 TP316 SS. The displacement rates of V_{LL}=0.45 and 0.9mm/min corresponded to a quasi-static loading rate and V_{LL}=1140 and 2280mm/min corresponded to a typical dynamic loading rate recommended in the J-R tests for leak-before-break evaluation of ferritic pipelines of KSNP. For monotonic J-R tests, a tensile displacement was monotonically applied to the specimens without unloading. For cyclic J-R tests, an incremental displacement-controlled cyclic load was applied following the loading sequence shown in Fig. 2. In the cyclic loading sequence, the displacement was controlled during tensile loading step, while the load was controlled during the compressive unloading step to maintain a constant cyclic load ratio. In the tests, the constant displacement increment (δ) of 0.15mm was applied after each cycle and the cyclic load ratios ($R = P_{min}/P_{max}$) of –0.5 and –1.0 were used. Figure 3 shows a sample of load (P) vs. load-line displacement (LLD) curve and a direct-current potential drop (d-c PD) vs. LLD curve obtained from a cyclic J-R test.

In the monotonic J-R tests, crack extension was determined by normalization method defined in the ASTM E1820-15a [13], and the J-integral was calculated in accordance with the standard procedure [13]. Crack extension in the cyclic tests was determined by a d-c PD method incorporating Johnson's Equation [14]. Unlike the monotonic J-R test, a standard procedure for evaluating the fracture toughness under cyclic loading condition is not available. Some studies calculated J-integral from the area under the load vs. LLD curve and above the crack opening load [9,15,16]. Others calculated the J-integral from the envelope area under the load vs. LLD curve and above zero load, ignoring the compressive loading portion, in accordance with ASTM standard procedure [6-8,10-12]. In the present study, the second method was used to obtain the J-R curve under a cyclic loading condition, so that the J-integral at each cycle was calculated using the peak load at each cycle and the corresponding LLD, as indicated in Fig. 3(a). Also, the d-c



(a) Load vs. load-line displacement curve



(b) d-c PD vs. load-line displacement curve

Fig. 3 Sample data of cycle J-R fracture toughness test

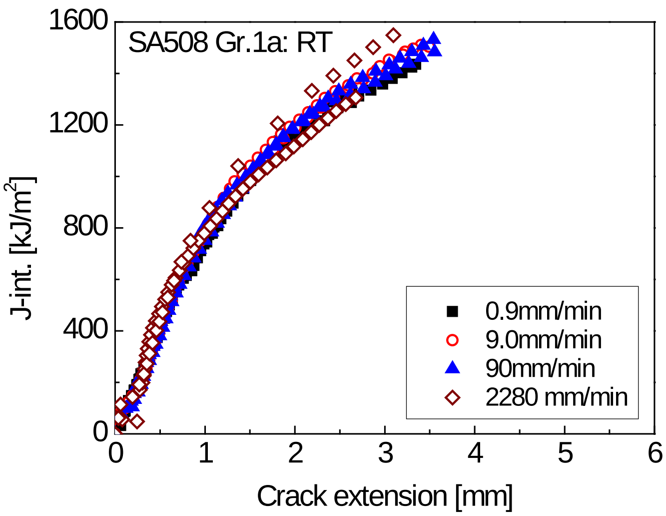
PD data indicated in Fig. 3(b) were used to determine the crack extension.

All of tests were conducted using a servo-hydraulic universal testing machine (UTM) with a 100kN load cell and a high-temperature furnace, and LLD was measured using a high-temperature COD gauge with a travel length of 10mm. In the tests at 316ºC, the temperature of the specimen was measured and controlled within ±2ºC using two K-type thermocouples attached both sides of the specimen.

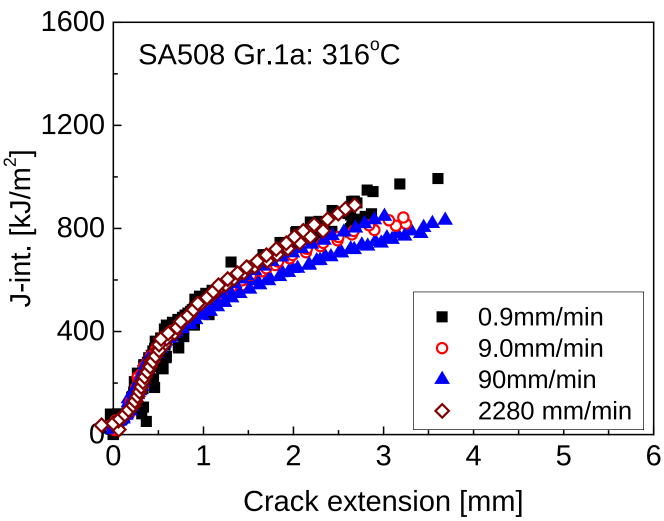
RESULTS AND DISCUSSION

Monotonic loading condition

Prior to cyclic J-R fracture tests, monotonic J-R tests were conducted at RT and 316ºC under various displacement rates to obtain reference J-R curves for each displacement rate and to investigate the loading rate effect on the fracture behaviour for both pipe materials under monotonic loading. Figure 4 exhibits

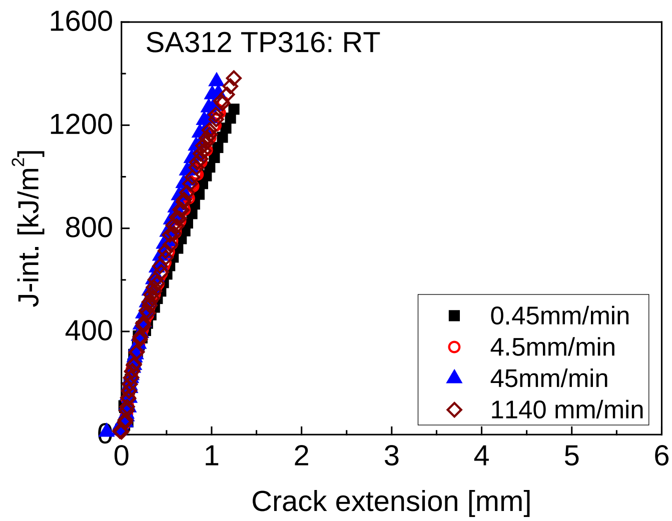


(a) RT

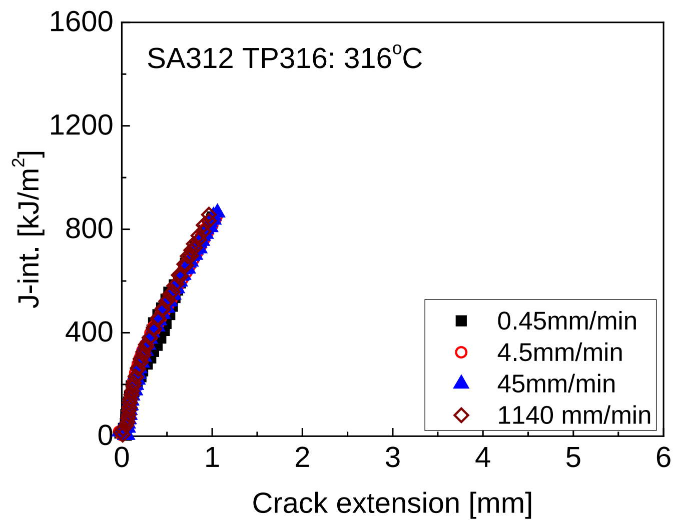


(b) 316°C

Fig. 4 Variation in monotonic J-R curves of SA508 Gr.1a LAS piping material with displacement rate



(a) RT



(b) 316°C

Fig. 5 Variation in monotonic J-R curves of SA312 TP316 SS piping material with displacement rate

the monotonic J-R curves of SA508 Gr.1a LAS piping material at different displacement rates at RT and 316°C. Figure 4(a) shows the J-R curves at RT are almost identical, although some scattering was observed at V_{LL}=2280mm/min. However, the variation in J-R curves with displacement rate was appreciable at 316°C (Fig. 4(b)); the J-R curve decreased with increasing displacement rate and reached a minimum at V_{LL}=9.0~90mm/min and then it increased with further increasing displacement rate. Thus, the J-R curve at the dynamic loading rate (V_{LL}=2280mm/min) was almost the same as that at quasi-static loading rate (V_{LL}=0.9mm/min). Our previous study showed that SA508 Gr.1a LAS piping material was susceptible to dynamic strain aging (DSA) at 316°C and the DSA effect on mechanical properties was most significant in the range of displacement rates of 9.0~90mm/min [17]. It is well-known that the occurrence of DSA in ferritic steels reduces their fracture resistance at elevated temperature [18-20]. Therefore, the appearance of a minimum J-R curve in the range of displacement rates of 9.0~90mm/min for SA508 Gr.1a LAS at 316°C is attributed to the occurrence of DSA.

The monotonic J-R curves of SA312 TP316 SS for different displacement rates are presented in Fig. 5. Figure 5(a) shows that the J-R curve of SA312 TP316 SS slightly increased with increasing displacement rate at RT. However, at 316°C, all of the J-R curves were nearly the same regardless of displacement rates, even though the displacement rates varied from 0.9mm/min to 1140mm/min (Fig. 5(b)). Past investigation showed that the fracture behaviour of austenitic SSs had only a slight loading rate dependency at the operating temperature of NPPs [6]. Hence, the present results showed the typical loading rate dependency of austenitic SSs.

It is clear that SA312 TP316 SS showed only a slight effect of loading rate on the fracture behaviour under monotonic loading condition, while SA508 Gr.1a LAS showed a more

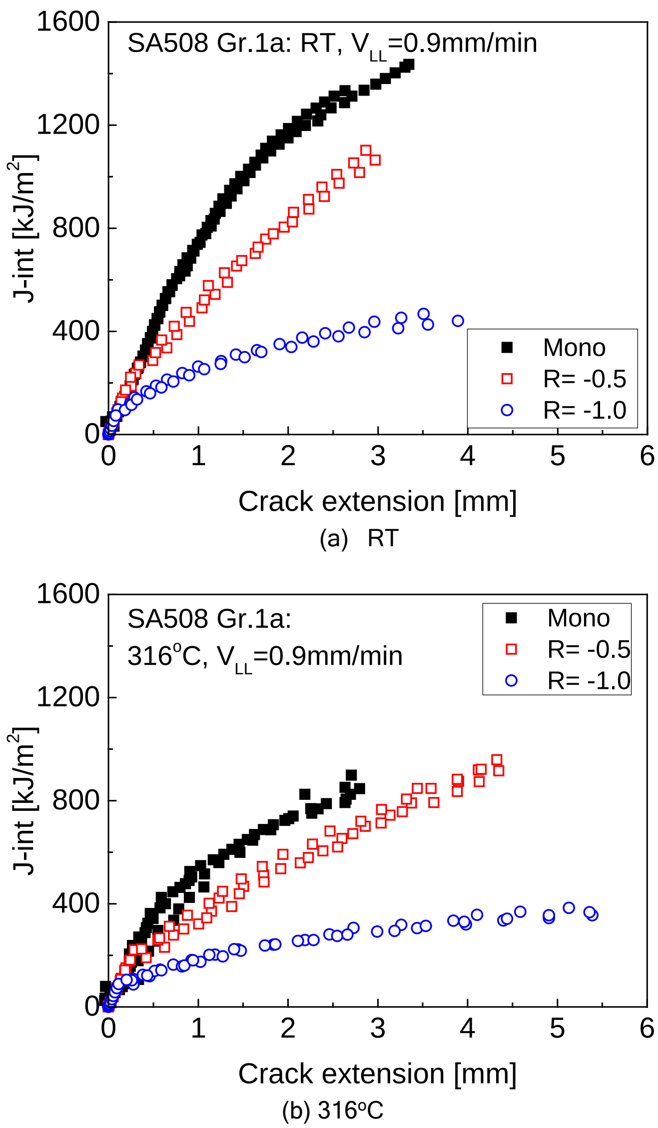


Fig. 6 Comparison of J-R curves of SA508 Gr.1a LAS piping material under monotonic and cyclic loading conditions

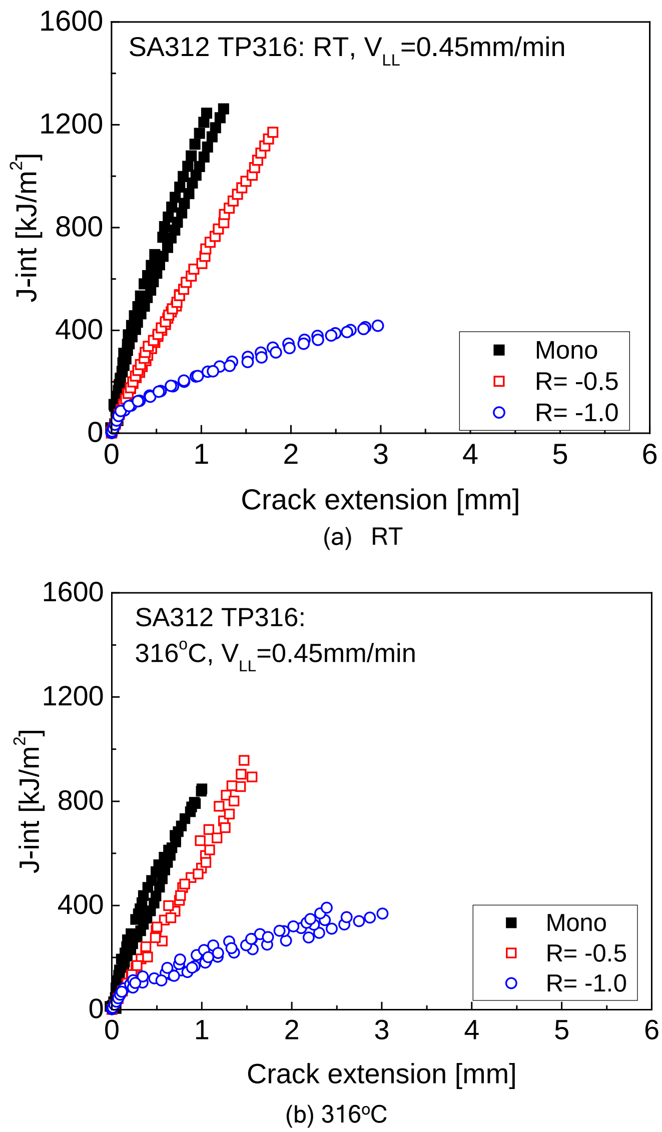


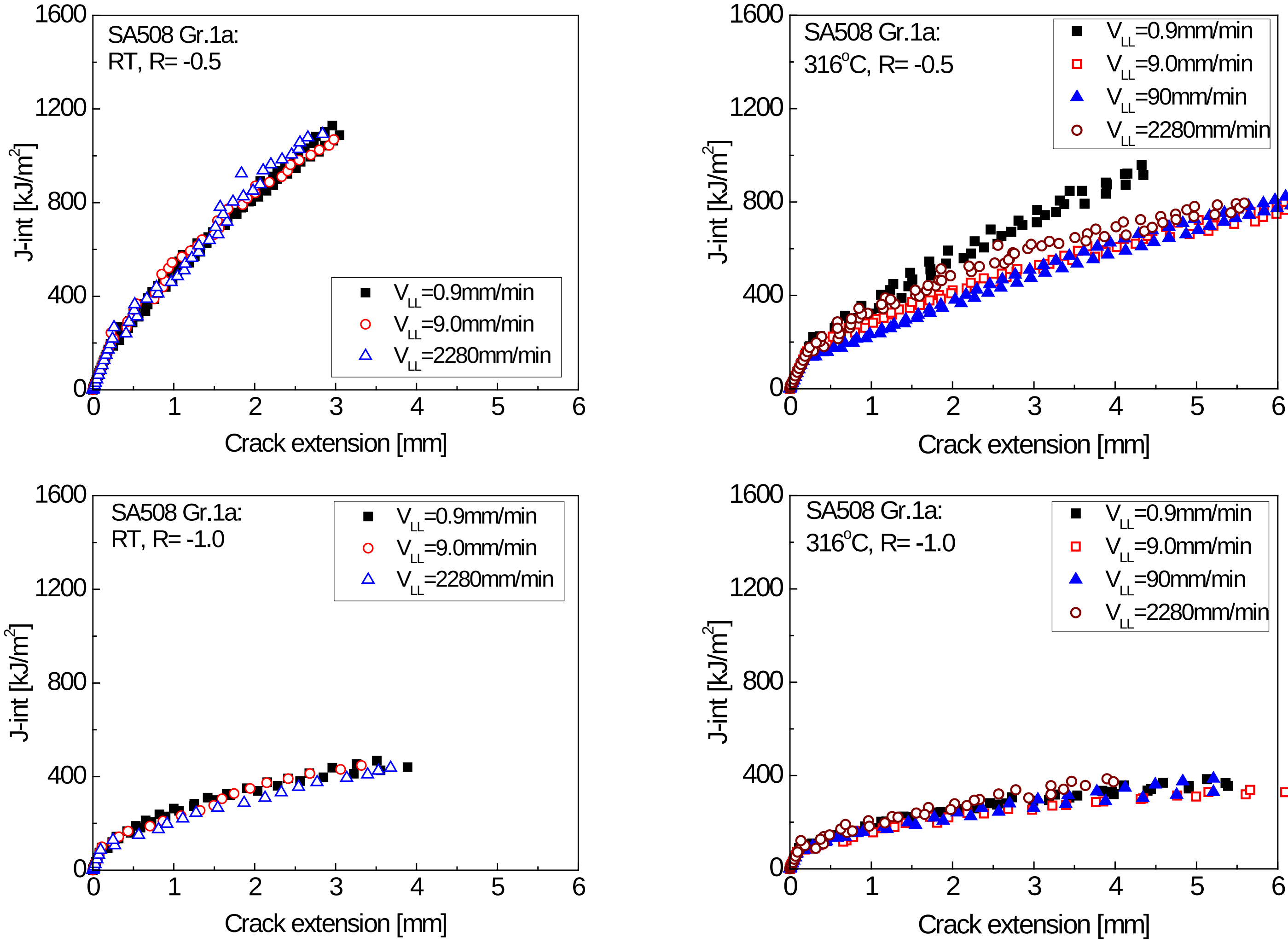
Fig. 7 Comparison of J-R curves of SA312 TP316 SS piping material under monotonic and cyclic loading conditions

pronounced loading rate effect at the operating temperature of NPPs. The fracture behaviour of SA508 Gr.1a LAS was nonlinearly varied with loading rate and the minimum fracture resistance appeared at an intermediate loading rate between quasi-static and dynamic loading rates. This specific loading rate dependency is related to the DSA characteristics of SA508 Gr.1a LAS at elevated temperatures.

Cyclic loading condition

Effect of compressive load level

The cyclic J-R fracture tests were conducted at RT and 316ºC under various displacement rates and cyclic load ratios. Figures 6 and 7 present the cyclic J-R curves of SA508 Gr.1a LAS and SA312 TP316 SS, respectively, tested under a quasi-static loading rate. The corresponding monotonic J-R curves are also exhibited in these figures for comparison. Regardless of test temperature and type of material, the cyclic J-R curves were much lower than their corresponding monotonic J-R curves. The decrease in the J-R curves was more significant when the cyclic load ratio was more negative. Such cyclic effects were also observed from the results of higher loading rates, although their J-R curves are not presented in the figures. Thus, it is evident that the reversible cyclic load considerably reduced the fracture resistance of the materials regardless of the loading rate, test temperature, and type of material. Several previous studies reported a similar adverse effect of reversible cyclic load on fracture resistance [6-8,10-12] and they showed the cyclic effect on fracture resistance saturated when the cyclic load ratio was lower than R=–1. Also, microscopic examination near the crack-tip during the tensile and compressive loading steps revealed that the crack extension under reversible cyclic



(a) RT (b) 316°C

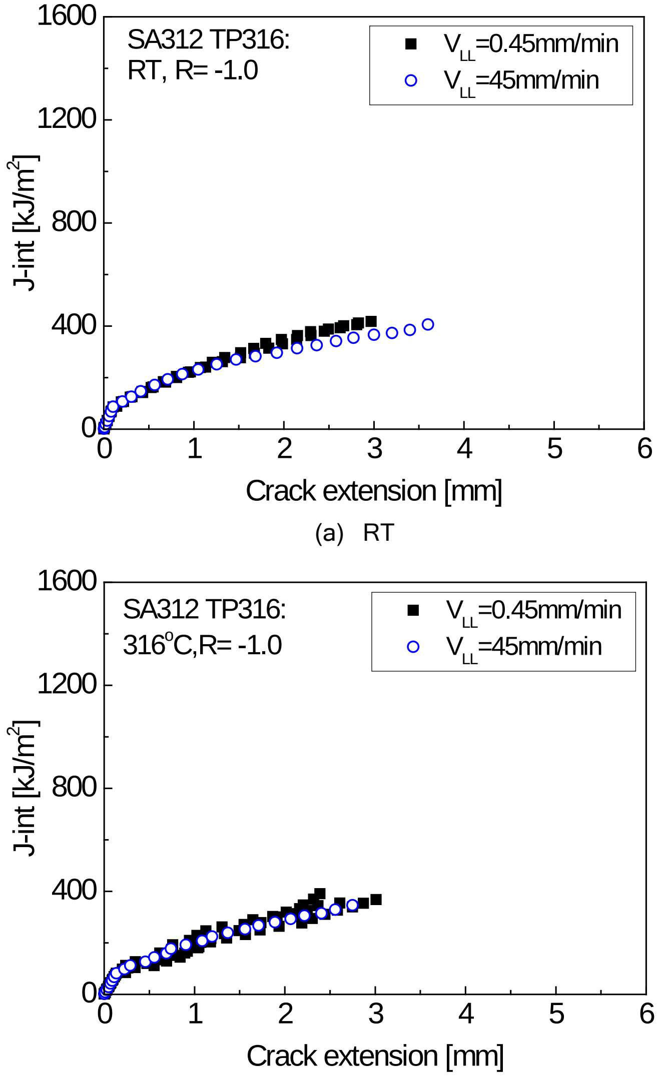
Fig. 8 Variation in cyclic J-R curves of SA508 Gr.1a LAS piping material with displacement rate

load was accelerated by crack-tip sharpening that developed during the compressive loading step [6,10]. Thus, the significant reduction in fracture resistance under cyclic loading with higher compressive load related to the enhancement of crack-tip sharpening and the saturation of the cyclic loading effect when R ≤ –1 was associated with crack faces contacting each other during the compressive loading.

Comparing J-R curves of each material at RT and 316°C, it is seen that, regardless of loading rate, the J-R curves at 316°C were clearly lower than those at RT when a monotonic load and a cyclic load of R=–0.5 were applied, but the difference of J-R curves at RT and 316°C was relatively small when a cyclic load of R=–1.0 was applied. Also, comparison of J-R curves for both pipe materials showed that the J-R curves of SA508 Gr.1a LAS were much lower than those of SA312 TP316 under a monotonic load and cyclic load of R =–0.5. However, the J-R curves for both pipe materials were almost identical under the cyclic load of R=–1.0 at both test temperatures. Thus, the fracture behaviour was less sensitive to test temperature and type of material at the more negative cyclic load ratio. This is because the contribution to crack extension by the crack-tip sharpening effect under cyclic loading was predominant compared with other parameters when the compressive load level of the cyclic load was high enough to reach the saturated condition of the cyclic effect.

Effect of loading rate

The cyclic J-R curves were compared for different displacement rates to investigate the effect of loading rate on the fracture behaviour under the cyclic loading condition. Figure 8 exhibits the J-R curves of SA508 Gr.1a LAS tested under cyclic loads of R=–0.5 and –1.0 at various displacement rates. Figure 8(a) shows that the variation in the J-R curves was negligible at RT for both cyclic load ratios, even if the displacement rate was increased by about 2250-fold. At 316°C, however, the cyclic J-R curves varied with the displacement rates (Fig. 8(b)); in particular, the variation was pronounced for the cyclic load of R=–0.5. For R=–0.5, the cyclic J-R curve at



(b) 316°C

Fig. 9 Variation in cyclic J-R curves of SA312 TP316 SS piping material with displacement rate

316°C decreased with increasing displacement rate and showed a minimum in the range of the displacement rates of 9.0~90 mm/min. But, the cyclic J-R curve at V_{LL}=2280mm/min is still lower than that at V_{LL}=0.9mm/min. Then, it increased with further increasing displacement rate. For R=–1, also, the displacement rate dependency was similar to that for R=–0.5, but the variation in the J-R curves with displacement rate was insignificant when compared to that for R=–0.5. On the other hand, as shown in Fig. 9, the cyclic J-R curves of SA312 TP316 SS, tested under the cyclic load of R=–1 at displacement rates of 0.45 and 45 mm/min, indicated that the fracture resistance was nearly independent of the displacement rate at RT and 316°C. Thus, it was concluded that the effect of the loading rate on the fracture behaviour under the cyclic loading condition was negligible for SA312 TP316 SS, regardless of the test temperature. However, the effect was appreciable for SA508 Gr. 1a LAS at the operating temperature of NPPs and the minimum in the J-R curve appeared at an intermediate loading rate, i.e., V_{LL} = 9.0~90 mm/min. This indicated that the loading rate effect for both piping materials under the cyclic loading condition was basically the same as that observed under the monotonic loading condition. Also, it was evident that, for SA508 Gr. 1a LAS, the DSA phenomenon still influenced the loading rate dependency at the operating temperature of NPPs, even under a cyclic load.

Notably, the loading rate effect of SA508 Gr. 1a LAS was dependent on the cyclic load ratio; i.e., the loading rate effect diminished when the cyclic load ratio was –1.0. This was related to the specific crack extension mechanism under the reversible cyclic loading condition. As mentioned in the previous section, the crack extension under a cyclic load is governed by both ductile tearing and crack-tip sharpening mechanisms. It is known that the occurrence of DSA promotes ductile tearing by decreasing the fracture strain near the crack-tip, thereby resulting in degradation of the fracture resistance of ferritic materials [18–20]. Therefore, the influence of DSA clearly appeared for monotonic loading and cyclic loading at R=–0.5, where the ductile tearing dominated the crack extension and thus the loading rate effect on fracture behaviour was pronounced. However, as the cyclic load ratio became more negative, crack-tip sharpening dominated crack extension. Therefore, the crack-tip sharpening effect overshadowed the DSA effect on ductile tearing, so that the loading rate effect inducing DSA phenomena was less at R=–1.0.

Consideration of seismic loading characteristics in the evaluation of facture behaviour

Because the seismic load has cyclic and dynamic characteristics, these loading characteristics should be properly considered in the evaluation of the fracture behaviour of pipe material to reliably assess the integrity of piping components under a seismic condition. The present results indicated that a reversible cyclic load significantly reduced the fracture resistance of the materials and the cyclic effect was dependent on the compressive load level of the cyclic load. However, the adverse cyclic effect on the fracture behaviour saturated when the cyclic load ratio reached R=–1, regardless of the loading rate, temperature, and type of material. The loading rate effect on the fracture behaviour under the cyclic loading condition was negligible for SA312 TP316 SS, while the effect was considerable for SA508 Gr. 1a LAS at the operating temperature of NPPs. The fracture resistance of SA508 Gr. 1a LAS at 316°C varied nonlinearly with loading rate, and a minimum appeared at an intermediate loading rate. This loading rate effect for SA508 Gr. 1a LAS under the cyclic loading condition was diminished when the cyclic load ratio was R=–1.

Based on these results, therefore, it is suggested that the fracture behaviour of pipe materials, which conservatively takes into account seismic loading characteristics, can be evaluated when testing is done under the reversible cyclic load of R=–1 with a quasi-static loading rate, although the seismic load has cyclic characteristic with random amplitude and various loading rates.

CONCLUSIONS

The effect of loading rate on the fracture behaviour under cyclic loading conditions was investigated to clearly understand the fracture behaviour of piping materials under seismic conditions. Monotonic and cyclic J-R fracture toughness testing of SA508 Gr. 1a LAS and SA312 TP316 SS pipe materials were conducted under various displacement rates at RT and 316°C. The conclusions are as follows:

1) Regardless of the loading rate, temperature and type of material, the fracture resistance of the pipe materials under cyclic loading conditions was considerably lower than that under the corresponding monotonic loading condition.
2) The fracture behaviour of SA312 TP316 SS was nearly independent of the loading rate under both cyclic and monotonic loading conditions, regardless of the test temperature.
3) The loading rate effect was appreciable at 316°C for SA508 Gr. 1a LAS. Its fracture resistance decreased with increasing loading rate and reached a minimum at an intermediate loading rate. It then increased with further increasing loading rate. However, this loading rate dependency was diminished when the cyclic load ratio was $R = -1$.
4) The fracture behaviour of the pipe materials, which includes the seismic loading characteristics, can be evaluated when testing is done under the cyclic load of $R = -1$ at a quasi-static loading rate.

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