Elastic-plastic fracture toughness and tearing instability characteristics of carbon steel for nuclear primary coolant systems

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1 INTRODUCTION

In the design of a typical piping system in light water reactor, the various service loads considered are the pressure, dead weight, thermal and seismic loads. However, the design is generally controlled by the load of seismic events, since the primary stresses during the normal operation are usually low. Therefore, the seismic analysis play a central role in the design of piping systems. Pipe cracking tolerance with respest to a seismic event is necessary to be clear for the purpose of the establishment of piping integrity.

One of the principal structural materials in primary and secondary coolant piping systems is carbon steel in light water reactors. The carbon steel employed in the reactors is tough, ductile and highest quality. Fracture behavior of carbon steel pipe is important for the leak before break concept to be applied to actual piping system design.

This paper presents an experimental investigation of instability behavior in ductile crack growth for carbon steel caused by cyclic loading.

2 DESCRIPTION OF EXPERIMENT

The material used in this experiment was JIS (Japanese Industrial Standard) STS 42 carbon steel which is commonly employed in nuclear piping systems in Japan. STS 42 is called Carbon Steel Pipe for High Pressure Service which corresponds to ASTM A 333 Gr.6. Compact tension specimens with a 1-inch wall thickness (1TCT) were taken from a large diameter pipe with the crack growth direction perpendicular to the pipe axis (Figure 1). All of the experiments were conducted at 100°C. The specimens were grouped into two different tests: a monotonic loading test and a cyclic loading test.

The cyclic loading test was performed using a low cycle fatigue

testing machine with a high compliance device. Figure 2 illustrates the loading apparatus and coil spring compliance device for inducing ductile crack instability. Various compliance values were obtained by exchanging various coil springs. Figure 3 shows the schematic representation of the load-load line displacement curve in the cyclic loading test. The stress ratio is 0.1 and crack instability occurs in the final cycle at point E in Figure 3.

The extent of crack growth in the 1TCT specimen was measured using an electronic indicator to monitor crack depth.

J integral value under the monotonic loading condition was calculated by the method of ASTM E 813 (1983). J_{max} value at maximum load under cyclic loading condition is calculated by the following equation (1980).

$$J^{n}_{max} = J^{n-1}_{max} \frac{W - a_n}{W - a_{n-1}} + \left(J^{*}_{n} - J^{*}_{n-1} \right) \frac{W - a_n}{W - a_{n-1}}$$

where

J^{n}_{max} and J^{n-1}_{max} : J_{max} at the cycle n and n-1, resectively,
a_n and a_{n-1} : crack length at the cycle n and n-1,
W : specimen width,
J^{*}_{n} and J^{*}_{n-1} : tentative J integral at the cycle n and n-1, respectively, which do not take into account the effect of crack growth and unloading.

3 TEST RESULTS AND DISCUSSION

3.1 Monotonic J-R curve

The J-R curve for STS 42 carbon steel was determined using the multiple specimens method. The monotonic J-R curve is shown in Figure 4. The experimental data were obtained from round robin test conducted by Tohiba(TOS), Nihon Kokan(NKK), Hitachi(HIT) and Yokohama National University(YNU).

In this study, the blunting line which fits the experimental data was determined to be $J = 2.37 \sigma_{fs} \Delta a$, rather than $J = 2\sigma_{fs} \Delta a$, which is generally used, where σ_{fs} is the flow stress of the STS 42 at 100°C and Δa is the extent of crack growth. In considering the amount of crack growth, the corrected J-R curve can be calculated from the monotonic J-R curve. The J integral value at ductile crack initiation, J_{in}, for STS 42 is thus determined to be 0.96 MJ/m^2 at 100°C.

3.2 Cyclic J-R curve

J_{max} at maximum load P_{max} for cyclic loading conditions is shown in Figure 5 for STS 42 as a function of the compliance value K_M, where the initial crack length a_o = 24 mm, P_{max}=43 kN and stress ratio R=0.1. The open symbols represent subcritical crack growth and corespond to the load from A to B in Figure 3. The semi-closed symbols correspond to the pre-final cycle load, which corresponds to point B in Figure 3. The closed symbols represent the J integral values at crack instability, which corresponds to point E on the final cycle in Figure 3.

The relationship between J_{max} and cycle numbers for the same load (P=43 kN), but with a stress ratio R=-1.0, is shown in Figure 6. The total number of cycles for the ductile crack instability are quite different for the different stress ratios R=0.1 and -1.0. The total

cycle number at instablity for R=0.1 is much larger than that for R=-1.0, even though the maximum loads were the same. However, the J_{max} values at instability are almost the same for both R=0.1 and -1.0.

The relationship between J_{max} and crack growth amount Δa is shown in Figure 7. This is the so-called cyclic or fatigue J-R curve. The cyclic J-R curves are compared with the monotonic corrected J-R curve of Figure 4. When Δa is small, J_{max} increases slightlly. However, when Δa increases, large scale yielding occurs in the cracked section of the specimen, and J_{max} increases rapidly. Ductile crack instability occurs in the vicinity of the monotonic J-R curve.

A simular result is seen in Figure 8 for the stress ratio of R=-1.0. In addition, the cyclic J-R curve for R=-1.0 is lower than that for R=0.1. The crack instablity also occurs in the vicinity of the monotonic J-R curve.

It shoud be emphasised that, beyond the crack blunting line, the cyclic J-R curve is lower than the monotonic J-R curve. This tendency is remarkable when the stress ratio is low. When large scale yielding occurs in the cracked section, the cyclic J-R curve rapidly approaches the monotonic curve.

A comparison of the J_{inst} (J_{max} at ductile crack instablity) under cyclic loading and J_{inst} under monotonic loading is illustrated in Figure 9 as a function of compliance K_M. There is little difference between the cyclic and monotonic instabilities. It should also be noted that tearing instability behavior for ductile cracks in cyclic loading can be estimated from the results of monotonic loading.

4 CONCLUSION

The cyclic J-R curve was determined for STS 42 carbon steel using a compliance loading system. It can be concluded that the J_{inst} value under cyclic loading is consistent with the J_{inst} value under monotonic loading.

REFERENCES

ASTM Standard E 813 1983. Standard test method for J_{ic}, a measure of fracture toughness.

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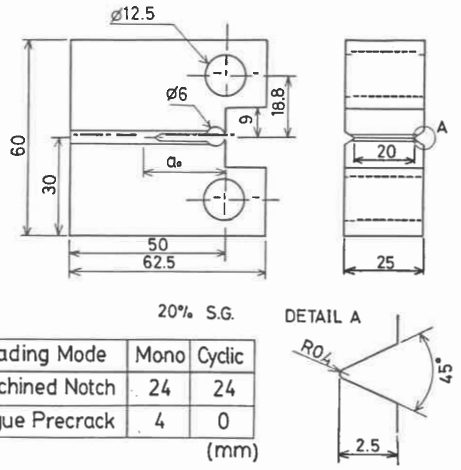
ACKNOWLEDGMENTS

This work has been conducted as part of the DF Subcommittee in Atomic Energy Research Committee in the Japan Welding Engineering Society sponsored by the Japan Atomic Energy Research Institute (JAERI). The authors wish to acknowlege and thank the members of the DF Subcommittee and JAERI for their important contributions.



Loading Mode	Mono	Cyclic
Machined Notch	24	24
Fatigue Precrack	4	0

(mm)

Figure 1 Test specimen

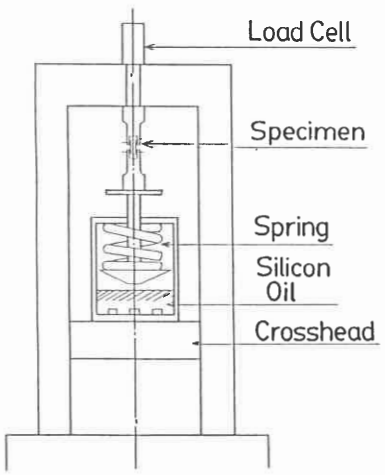


Figure 2 High compliance test apparatus

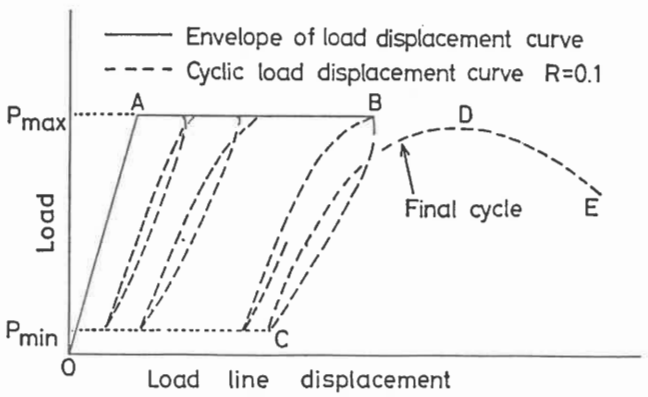


Figure 3 Schematic load - load line displacement curve (R=0.1)

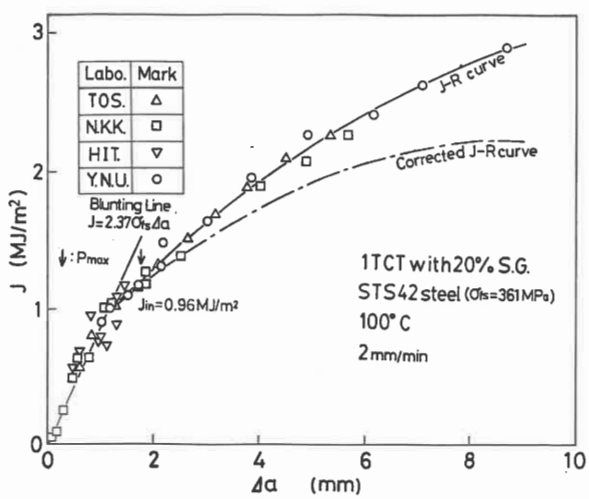


Figure 4 Monotonic J-R curve for STS 42 at 100°C

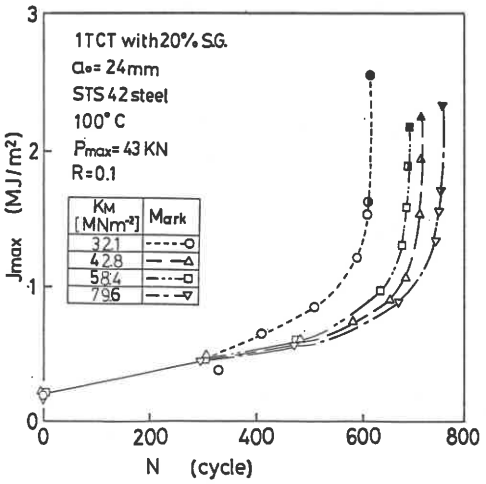


Figure 5 J_{max} - cycle curve of R=0.1 for STS 42

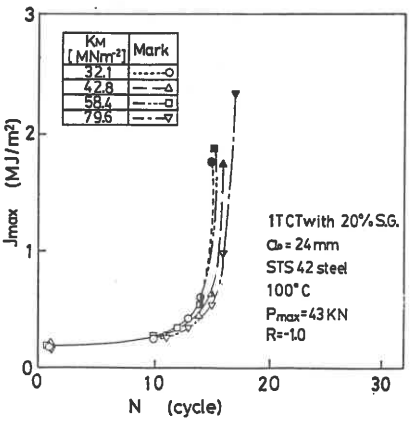


Figure 6 J_{max} - cycle curve of R=-1.0 for STS 42

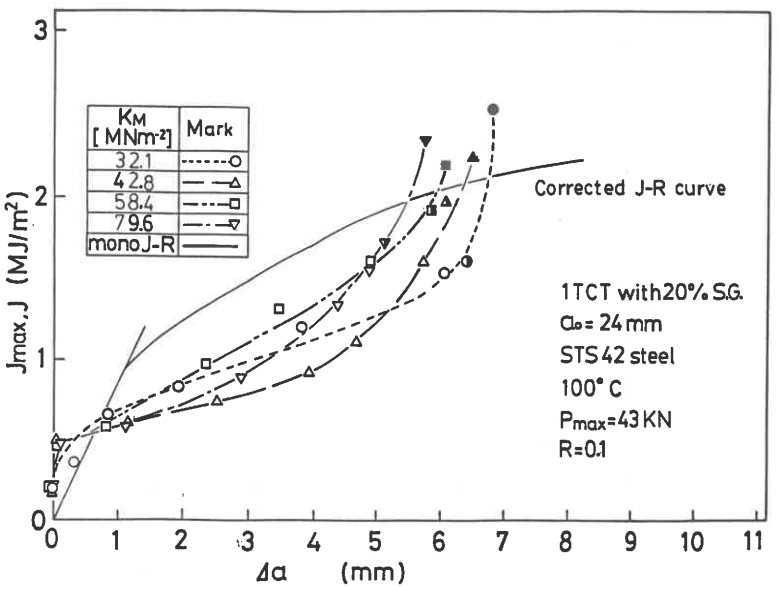


Figure 7 Cyclic J_{max}-R curve of R=0.1

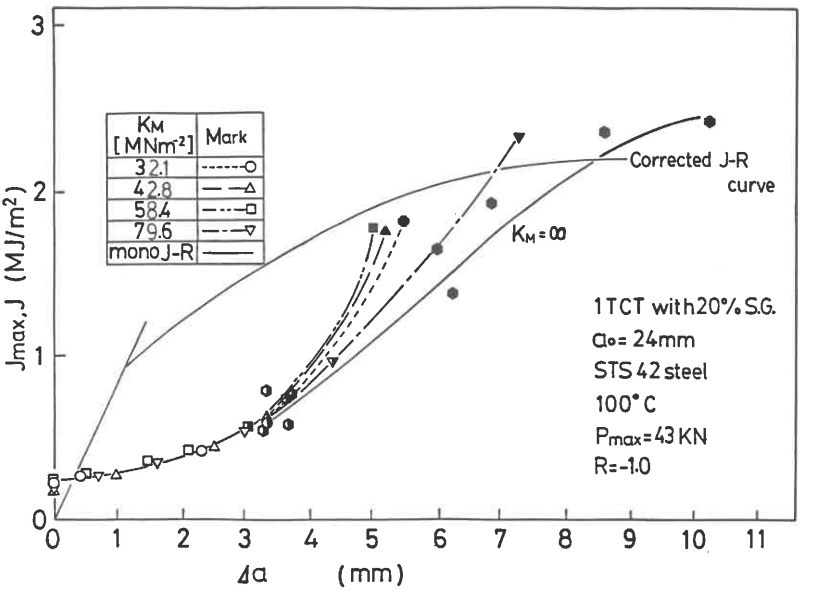


Figure 8 Cyclic J_{max}-R curve of R=-1.0

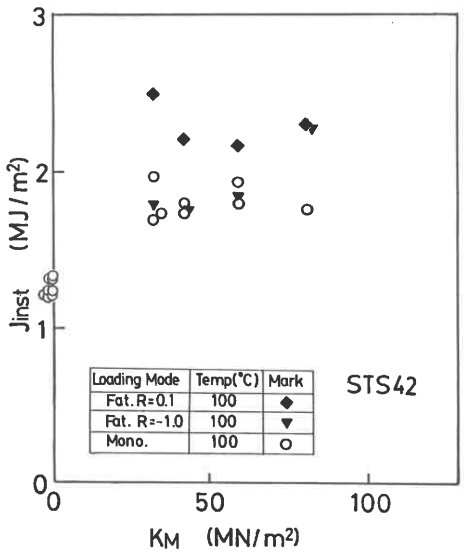


Figure 9 Relationship between J_{inst} and compliance K_M