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Fracture Behavior of CW TP316L Stainless Steel under Dynamic and Cyclic Loads

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1. Introduction

Integrity assessment of systems, structures, and components (SSCs) under excessive seismic events is now required not only for newly designed nuclear power plants (NPPs) but also for long-term operated NPPs [1,2]. Thus, the reliability of integrity assessments under excessive seismic loading conditions has become an important issue. However, there are some uncertainties in the integrity assessment under excessive seismic loading conditions. One of them is consideration of material behaviors of SSCs under seismic loads. Thus, a number of experimental studies conducted cyclic stress–strain tests and dynamic and cyclic J-R fracture tests to clarify the deformation and fracture behaviors of structural materials of NPPs [3,4]. However, none of these studies has taken into account age-related material degradations, even though the materials of SSCs in long term operated NPPs are degraded by long-term exposure to high temperature, corrosive, and radiation environment.

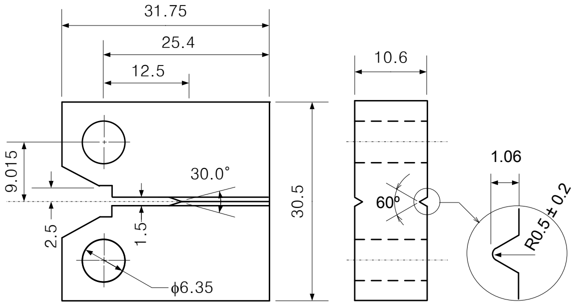
Therefore, the present study investigates the fracture behavior of cold-worked (CW) TP316L stainless steel (SS), which is simulated material for irradiation hardening and embrittlement of TP316L SS, under seismic loading condition. For this investigation, *J–R* fracture tests are performed on as-received (AR) and CW TP316L SSs under dynamic and cyclic loads. Also, tensile tests are conducted under quasi-static and dynamic loads to obtain reference mechanic properties for both materials.

2. Experiments

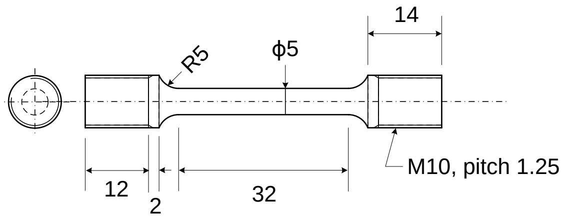
2.1 Materials and Specimen Design

AR and 33% CW TP316L SSs were used for the experiment. TP316L SS is commonly used as structural material in NPPs, especially it is used for reactor internal material. Some studies reported that the cold-working properly simulated the increase in strength and decrease in ductility and toughness of austenite SS due to neutron irradiation, even though it could not simulate the grain boundary segregation and formation of precipitations and voids induced by irradiation [5].

A compact tension (CT) specimen (thickness: 12.7 mm; width: 25.4 mm), in accordance with the ASTM E1820-15 [6], was used for monotonic and cyclic *J–R* fracture tests. A round-bar-type specimen (diameter: 5.0 mm; gage length: 25.0 mm), in accordance with the ASTM E8/E8M-09 [7], was used for the tensile test. Fig. 1 illustrates the CT specimen and tensile specimen used for the experiment.



(a) 0.5T- CT specimen



(b) Tensile specimen

Fig. 1 Specimens used for J-R fracture toughness and tensile tests

2.2 Experimental and Procedures

J-R fracture toughness tests were performed on both AR and CW TP316L SSs under monotonic and cyclic loading conditions at RT and 316°C. In the monotonic tests, two different displacement rates (V_{LL}) were considered: V_{LL} = 0.45 and 1,140 mm/min. The cyclic tests were conducted at V_{LL} = 0.45 mm/min. The displacement rate of 0.45 mm/min corresponds to a quasi-static loading rate, and V_{LL} = 1,140 mm/min is a dynamic loading rate corresponding to seismic load. 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 increment (d) of each step was 0.15 mm and the cyclic load ratio was $R = -1.0$.

In the monotonic *J–R* tests, crack extension was determined by the normalization method defined in the ASTM E1820-15 standard [6]. Crack extension in the cyclic tests was determined by a direct-current potential drop (d-c PD) method. *J*-integral in the cyclic *J–R* tests was calculated from the envelope area under the load versus load-line displacement (*LLD*) curve and above zero load, ignoring the compressive loading portion, in accordance with the ASTM standard procedure [6].

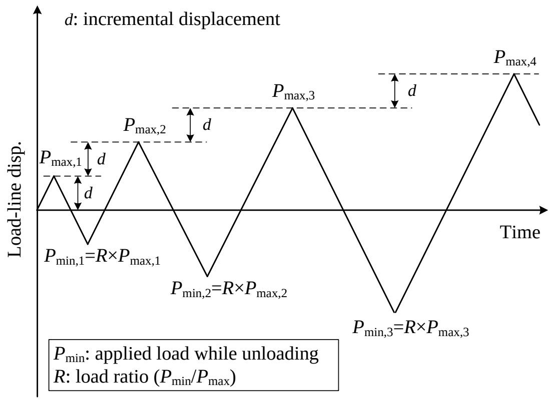


Fig. 2 Loading sequence applied to the cyclic J-R fracture toughness test

3. Results and Conclusions

The results of tensile tests show that, regardless of test temperature, CW TP316L SS has much higher strength and smaller elongation compared with AR TP316L SS. For CW TP316L SS, also, necking occurs immediately after elastic deformation; in particular, the uniform deformation is almost zero at 316°C. Such deformation behaviors are also observed from the results of dynamic tensile tests. At RT, the strength increases and the ductility decreases as the strain rate increases, while the effect of strain rate is negligible at 316°C. This strain rate dependency of CW TP316L SS is nearly the same as that of AR TP316L SS. Thus, it is indicated that the dynamic loading effect on deformation behavior of TP316L SS is not altered by cold-working, even though its strength and ductility are considerably changed due to cold-working.

Comparison of *J-R* curves of AR and CW TP316L SSs tested at RT and 316°C shows that the fracture resistance of TP316L SS is considerably reduced by cold-working regardless of displacement rates. In particular, the reduction in fracture resistance is significant at 316°C. The comparison of quasi-static and dynamic *J-R* curves of CW TP316L SS shows that the fracture resistance of CW TP316L SS is nearly independent of loading rate. This is consistent with that observed from AR TP316L SS.

The fracture resistance of AR TP316L SS is considerably reduced under cyclic load at both RT and 316°C. This cyclic loading effect on fracture resistance is a typical characteristic of material. Also, it is known that fully reversed cyclic load significantly reduces fracture resistance of materials and the reduction is associated with crack-tip sharpening developed during the compressive step of cyclic loading [4]. However, the cyclic loading effect on fracture resistance is negligible for CW TP316L SS. This is because the fracture resistance of CW TP316L SS is low enough so that the crack sharpening effect induced by cyclic load is relatively insignificant.

Acknowledgements

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