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Analyzing the Effects of Geometrical Discontinuity on Dynamic Strain Aging Behavior of Ferritic Steels

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1. Introduction

Low carbon ferritic steels, such as A106 Gr.B and A508 Gr.1a, are commonly used as piping material in nuclear power plants (NPPs). These ferritic steels are known to exhibit dynamic strain aging (DSA) when exposed to a certain range of elevated temperatures, including operating temperatures of NPPs, during deformation [1-4]. DSA in low carbon steels is related to the interactions between free carbon and nitrogen atoms and dislocations during plastic deformation [1,2], and it leads to abnormal increase in strength and decrease in ductility and fracture toughness [3,4]. Also, the DSA behavior is sensitive to the deformation rate. Therefore, DSA phenomenon has been considered to be a cause of uncertainty in the integrity evaluation of carbon steel components in NPPs, and a number of studies have been investigated the behavior of DSA under uni-axial tensile deformation. However, the behavior has not been clearly investigated under non-uniform stress and strain states induced by geometrical discontinuity. Our previous study only experimentally evaluated the effect of geometrical discontinuity on the DSA behavior via a series of tensile tests on the notched-bar and standard specimens [5].

Thus, the present study performed finite element (FE) simulations on tensile data given by our previous study and evaluated the stress and strain states for each type of specimen during deformation. A relationship between DSA behavior and stress and strain states was obtained by comparing the results of experiment and FE simulation, and it was confirmed by crack propagation tests using compact tension (CT) specimens with electro discharge machining (EDM) notch.

2. FE Simulation

2.1 Tensile data

This study used tensile data on standard and notched-bar specimens tested by our previous study [5]. The standard tensile data showed that the temperature region of DSA was elevated about 25~50℃ and 50~90℃, when the strain rate increased by 10 times and 100 times, respectively. Also, the characteristics of DSA observed from notched-bar specimens were the almost same as those observed from standard specimens. The temperature region of DSA indicated from notched-bar tensile tests, regardless of notch radius, was higher about 25℃ than that indicated by standard tensile specimen tests under the same displacement rate. Therefore, the existence of a notch in the specimen increases an apparent temperature region of DSA. The temperature increment is similar to or slightly smaller than that observed by increasing strain rate of 10 times.

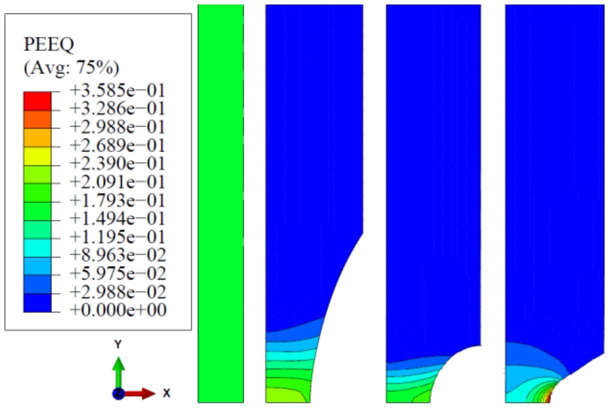

Fig. 1 Plastic strain contours for smooth and notched-bar specimens evaluated by FE simulations

2.2 FE simulation

To evaluate the stress and strain states during plastic deformation, detailed elastic–plastic FE analyses were conducted for each type of specimen, using the commercial finite element program ABAQUS [6]. Two-dimensional axi-symmetric models (CAX8R in ABAQUS) were used in the simulation, as shown in Fig. 1. A nonlinear geometry option was used to incorporate the effects of large geometry changes in the notched sections of the specimens. The material was modeled as an isotropic elastic–plastic material obeying the incremental plasticity theory.

3. Results and Discussion

3.1 Investigation of notch effects on DSA behavior

In order to quantitatively investigate the effects of notch on the DSA behavior of materials, the representative strain rate in the specimen was evaluated during plastic deformation. As a first approach the strain rate was averaged at the minimum section of specimens, and secondary it was averaged over the plastic deformed region in the specimens. The strain rates averaged at the minimum section of notched-bar specimens were higher about 10~15 times than those of smooth specimens. When averaged over the plastic deformed region, the strain rates of notched-bar specimens were higher about 3~5 times than those of smooth specimens (see Fig. 2). Thus, the higher temperature region of DSA at notched-bar specimen tests is associated with the higher strain rate at notched section of specimen. Also, it is indicated that the DSA behavior is represented by the strain rate averaged over the plastic deformed region of specimen rather than the strain rate averaged at the minimum section of specimen.

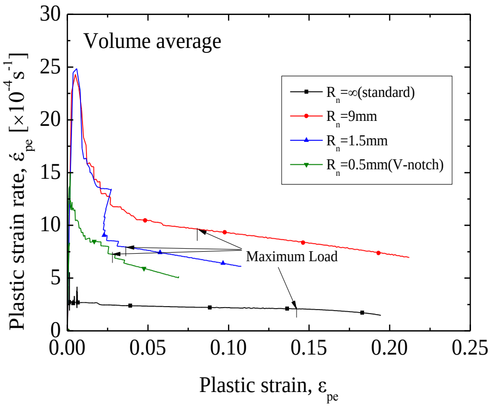

Fig. 2 Strain rates averaged over the plastic deformed region in the specimen

3.2 Confirmation tests

To confirm that the DSA behavior of material is governed by the strain rate averaged over the plastic deformed region of specimen, the crack propagation tests were conducted using CT specimens with EDM notch. The specimens were made of A508 Gr.1a piping material, which was revealed DSA behavior through tensile tests conducted at a displacement rate of 0.9mm/min. Prior to the the strain rate averaged over the plastic deformed region in the CT specimen during loading was evaluated by FE analyses using 2-D plane strain model. The strain rate and load-line displacement rate corresponding to the displacement rate of 0.9 mm/min in tensile test were determined from the results of analysis. The calculated load-line displacement rate was 0.5mm/min. Thus, the crack propagation tests were conducted at various temperature under a load-line displacement rate of 0.5mm/min, and the DSA behavior in the defective specimen was compared with that in the uni-axial tensile specimen. The DSA behavior in the defective specimen was measured by crack length at a given constant load-line displacement. In this tests, two different load-line displacements, 3mm and 6mm, were applied to the CT specimens.

Figure 3 presents the variations of the crack propagation length at load-line displacements of 3mm and 6mm with test temperatures. It showed that the maximum crack propagation lengths appeared at 250℃ and 288℃ for both load-line displacements. This means that the DSA effect on the crack propagation in the CT specimen was most significant in the temperature range 250~288℃, which exactly coincides with the DSA region indicated by appearance of serration and minimum ductility in tensile tests. Thus, it is confirmed that the temperature regions of DSA are the same when the strain rates averaged over the plastic deformed region coincide at different defective specimens.

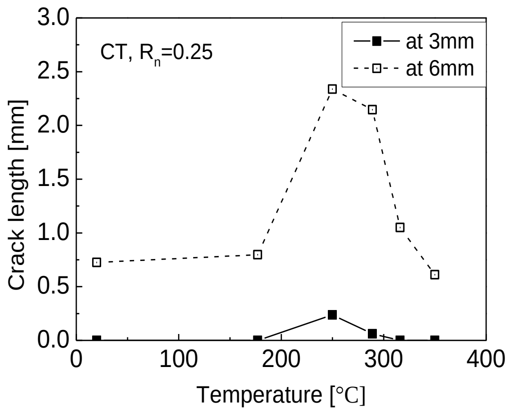

Fig. 3 Variation in crack propagation length with test temperatures

4. Conclusions

This study quantitatively investigated the effect of defect on the DSA behavior by comparing tensile data and stress and strain states at each type of specimen. From the results, it was found the DSA behavior is governed by the averaged strain rate over the plastic deformed region of specimen. This was confirmed by crack propagation tests on CT specimen conducted at various test temperatures.

Acknowledgements

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