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Deformation Characteristics of Miniature Tensile Specimens of a SA 508 Cl.3 Reactor Pressure Vessel Steel

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Abstract

Deformation characteristics of miniature plate tensile specimens have been studied to develop the thickness requirement and a correlation to estimate the mechanical properties of bulk material from miniature specimen data. The material used was a SA 508 Cl.3 reactor pressure vessel steel and the thicknesses of miniature tensile specimens varied from 0.12 mm to 2 mm. The effects of thickness on the tensile deformation properties such as strength, ductility, and necking characteristics were analyzed. The yield and ultimate tensile strengths were independent of specimen thickness when the thickness was larger than about 0.2 mm. The uniform and total elongations decreased as the specimen thickness decreased. It was also observed that the uniform strain component in the width direction decreased with decrease in the specimen thickness, however, that in the thickness direction was rather constant in total thickness range studied. Based on this observation and a relationship between the necking angle and the ratio between strain components, a correlation between the uniform elongations of miniature specimen and standard specimen was derived. The uniform elongations calculated by this new correlation agreed well with the measured values.

1. Introduction

Design and integrity assessment of nuclear reactor structural components require much information on degradation of mechanical properties due to irradiation. Specimen miniaturization has been needed in order to obtain sufficient data from limited material or to reduce irradiation volume. The miniature tensile specimens have been extensively used in the fusion material program for many years[1-4]. The specimen miniaturization is also desirable for light water reactor materials when the they decrease with decrease in the thickness. Flow stress at a strain was known to be independent of thickness, if the thickness is larger than a critical thickness[2-4,6,7]. The critical thickness for the ferrous materials was known to be about 5 to 10 times the average grain size[6]. The strength variations in Fig. 2 indicate that the critical thickness is about 0.2 mm for the steel studied. This value is 5 times as large as the grain size (40 μm) of this material. Fig. 2 also shows that the yield strength and ultimate tensile strength of thick specimens are very close to those of standard specimens; 457 MPa and 602 MPa, respectively.

The thickness effect on the strength (or flow stress) of a specimen having a finite number of through-thickness grains was well described by a long-range interaction model; the reduction in the flow stress has been explained by the absent of constraints near the specimen surfaces[6]. When a polycrystalline specimen is subjected to an external load, the degree and direction of the deformation of a grain are different from those of adjacent grains, therefore the grains constrain each other to accommodate the misfit between them[6,9]. If the interaction between grains is not exerted by an elastic anisotropy, the constraint stress (or interaction stress) is directly related to the back stress due to the accumulated dislocations[9,10]. However, at specimen surface the constraint stress component which is normal to the surface would be relaxed by a plastic relaxation mechanism to satisfy the 'plane stress condition'. Resultantly, the relaxation of the constraint stresses at the surfaces reduces the yield strength and ultimate tensile strength of the thin specimens.

Fig. 3 shows the variations of the uniform and total elongations with the specimen thickness. The thickness effect on the ductility of the miniature specimens appears in the total thickness ranges tested. The Fig. 3 also shows that the elongation increment after initiation of plastic instability was largely reduced in the thin specimens because of the highly localized necking. As seen in the Fig. 3, the highest total elongation is 28.9 %. This value is very similar to that of the standard specimens; 29 %.

Fig. 4 shows the strain components in the thickness and width directions, which are measured at the uniform deformation region of the broken specimens. The strain in the thickness direction seems not to depend on the thickness, however, the strain in the width direction decreases as the thickness decreases. This preferred deformation to the thickness direction accounts for the decreases in the uniform and total elongations with decrease in thickness; if the strain component in the thickness direction reaches the critical strains for plastic instability or failure, then the specimen starts to reveal necking or to fail.

The necking angle, which is defined by the angle between loading line and fracture plane, is also affected by the directional deformation in the thin specimens. Fig. 5 shows the variation of necking angle with thickness. The necking angle increased from about 60° to nearly 90° as the thickness increases from 0.12 mm to 2 specimen multiplication is necessary in the post-irradiation tests[5].

Many studies for miniature tensile specimens have been focused on the effects of thickness on the strengths (or flow stresses)[2-4,6,7]. As the most important result, it has been known that the strengths were independent of the specimen thickness if the thickness was larger than a critical thickness and the strengths depended on the thickness in the thinner specimens. This strength variation with thickness has been well explained by a theory for long-range interaction among grains[6].

Main objectives of this study are to understand the characteristics of the deformation of miniature tensile specimens and to develop the thickness requirement and correlation to estimate the mechanical properties of the standard specimen. This paper includes the procedures and results of the tests using miniature tensile specimens. The discussion is focused on the thickness effects on various deformation characteristics such as strength, ductility, and necking property.

2. Experimental Procedure

The material used was a SA 508 Cl.3 reactor pressure vessel steel (RPV steel) manufactured by HANJUNG. The chemical composition of the steel is given in Table 1. Microstructure of the steel was tempered bainite and the mean prior austenite grain size was about 40 μm. The miniature plate tensile specimens used in the tests were machined by electric discharge machining(EDM)[8] and the drawing of the miniature tensile specimen is shown in Fig. 1. The thickness(t) of the tensile specimen varied from 0.12 mm to 2.0 mm.

Table 1. Chemical Composition (wt.%) of the SA 508 Cl.3 RPV Steel

Material	C	Mn	Si	Ni	Cr	Mo	V	Al	Cu	P	S
SA 508 Cl.3	0.21	1.36	0.24	0.92	0.21	0.49	0.005	0.022	0.03	0.007	0.002

A fixture was specially designed to protect the thin plate specimens from bending or torture and to fix the loading line during testing. Tension tests were carried out in an Instron static testing machine at strain rate of 1.67×10^{-3} sec^{-1} at room temperature.

3. Results and Discussion

Fig. 2 shows the yield and ultimate tensile strengths of the miniature specimens. Both the yield strength and the ultimate tensile strength are almost constant in the thickness range of 0.2 mm ~ 2 mm, but in the thickness range of below 0.2 mm mm; the aspect ratio (thickness/width) increases from 0.04 to 0.67. This result coincides with the result of Kohyama et. al[2].

By the constant volume condition and a Mohr's circle analysis, the necking angle θ was represented as a function of the strain ratio r; $r=\varepsilon_t/\varepsilon_w$, where ε_t is the strain component in the thickness direction and ε_w the strain component in the width direction [2]:

$$\cos 2\theta = -\frac{3}{1+2r} \qquad (1)$$

Fig. 6 compares the strain ratios calculated by this equation from the measured necking angles with the measured strain ratios.

As discussed above, the deformation becomes unstable when the strain in the direction of higher deformation, i.e., the thickness direction, reaches a critical strain. If the critical strain for instability in the direction of preferred deformation is defined as one half of the uniform elongation of bulk material; $\varepsilon^U/2$, and using equation (1), then the uniform elongation of the specimen of thickness t is given by

$$\varepsilon^U(t) = \frac{1}{2}[\ 1+\frac{1}{r(t)}]\ \varepsilon^U = \frac{1}{2}[\ 1-\frac{2\cos 2\theta(t)}{3+\cos 2\theta(t)}]\ \varepsilon^U \qquad (2)$$

The uniform elongations evaluated by this equation are given in Fig. 7, in which the calculated and measured values have a good agreement to each other.

4. Summary

Miniature plate tensile specimens were tested to investigate the thickness effects on tensile deformation. The analysis results of test data were summarized as follows:

(1) Reduction in the yield strength and ultimate tensile strength appeared when the specimen thickness was less than about 0.2 mm (a critical thickness). To obtain the valid strength data of bulk material with miniature specimen, the minimum thickness of about 0.2 mm is recommended for the SA 508 Cl.3 steel.

(2) The thickness effects were also appeared in the uniform elongation and total elongation. Especially, the total elongation depended largely on the specimen thickness.

(3) In the thin specimens, the deformation occurred preferentially in the thickness direction. The strain ratio between the thickness direction and the width direction was well correlated with the necking angle.

(4) A relationship to predict the uniform elongation of bulk material from that of a

miniature specimen was derived as:

$$\varepsilon^{U}(t) = \frac{1}{2}\left[\, 1-\frac{2\cos 2\theta(t)}{3+\cos 2\theta(t)}\,\right] \varepsilon_0^{U}$$

The values calculated by this equation were in a good agreement with the measured values.

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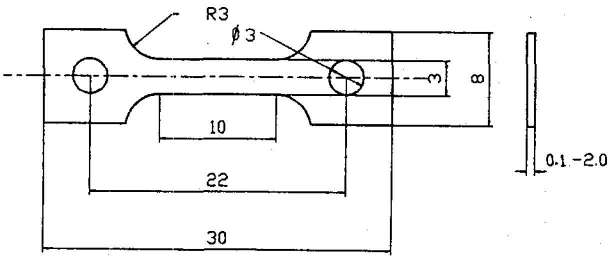

Fig. 1. Geometry and Dimension of Miniature Plate Tensile Specimen (Unit : mm)

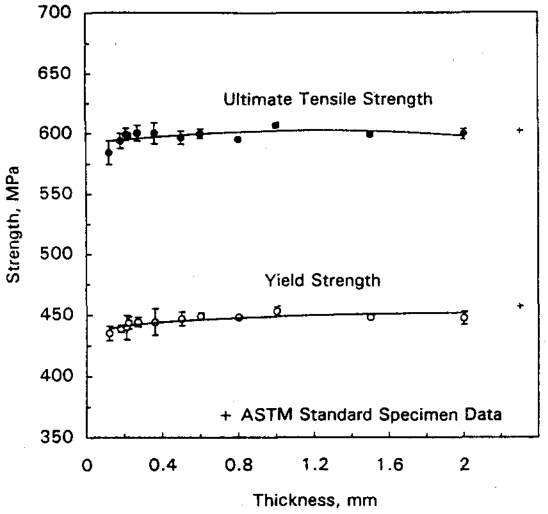

Fig. 2. Thickness Effect on Yield Strength and Ultimate Tensile Strength

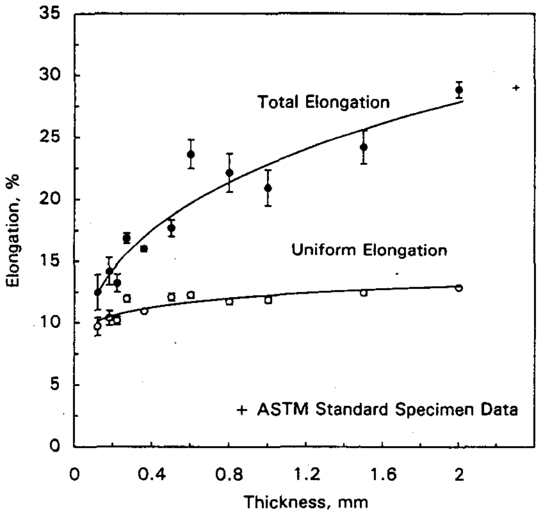

Fig. 3. Thickness Effect on Uniform Elongation and Total Elongation

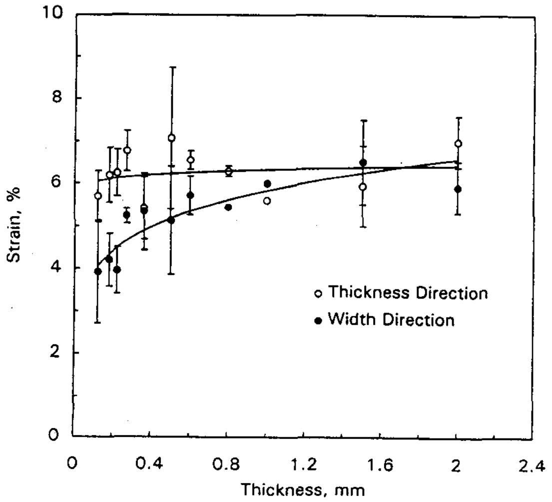

Fig. 4. Thickness Effect on Uniform Strain Components

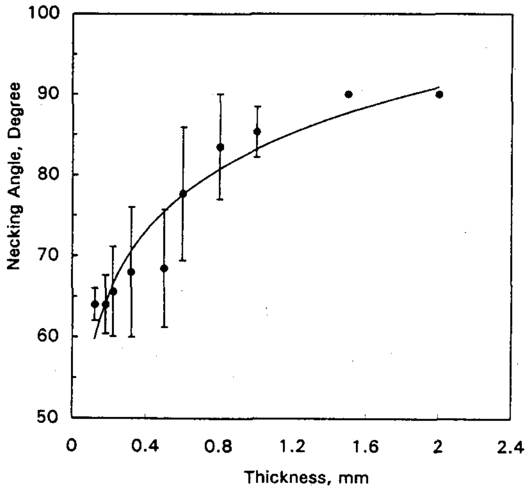

Fig. 5. Thickness Effect on Necking Angle

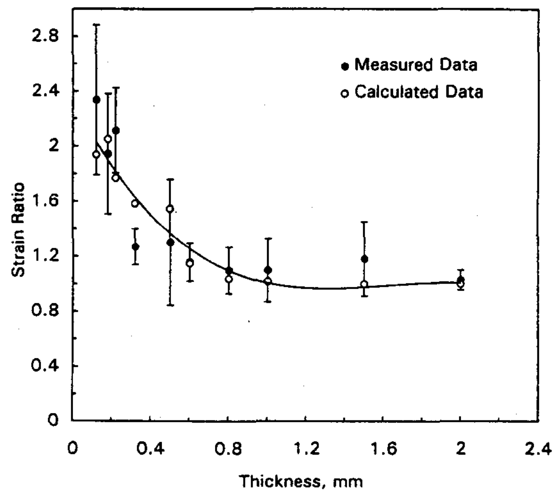

Fig. 6. Comparison of Calculated Strain Ratio and Measured Strain Ratio

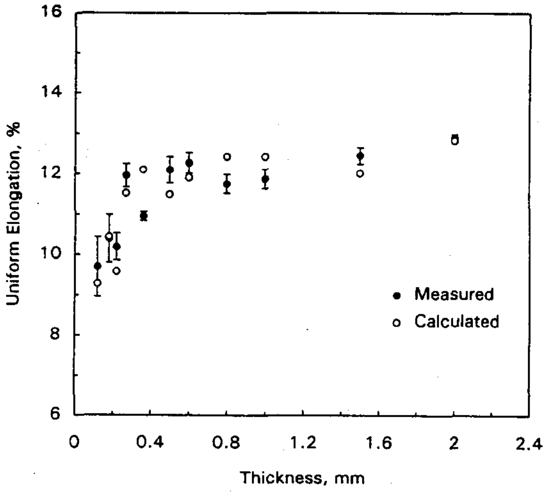

Fig. 7. Comparison of Calculated Uniform Strain and Measured Uniform Strain