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Quantification of cold work pre-strain effect on fracture and application to irradiation problem

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1. Introduction

Materials in nuclear reactor systems can be irradiated during operating. Irradiation-embrittlement (IE) decreases ductility and fracture toughness of materials. Because of the limitation of preparation for irradiation-embrittled materials, the behavior of irradiation-embrittled material has been often studied using cold-worked materials.

This paper proposes a methodology of quantification of the pre-stain effect on fracture toughness and application to irradiation problems. The methodology is verified using tensile test of cold-worked stainless steel 316 and some irradiated steel data.

2. Analysis of tensile test for pre-strained SUS316

2.1. Experimental results

Figure 1 shows the engineering stress-strain curve for cold-worked SUS316 [1]. The strength increased and elongation decreased with increasing cold-work (CW). The specimen extracted from the cold-worked plate and it provided the different initial gauge area with respect to the amount of CW. As results, the tensile strength can increase with increasing CW as shown in Fig. 1.

2.2. Corrected tensile test results

Accepting that physically the tensile stress does not depend on the pre-strain, the engineering stress needs to be corrected using

$$S_{corr} = S \cdot \frac{(S_u)_{PS=0}}{(S_u)_{PS}} \tag{1}$$

where S_{corr} and S denotes the corrected and original engineering stress, respectively; S_u denotes tensile strength and the subscript, PS=0 and PS, indicates the material properties for un-strained and pre-strained material, respectively.

Figure 2 shows the corrected engineering stress-strain curves for cold-worked SUS316. The tensile strength was corrected by matching the strength to that for un-strained material, and the pre-strain (PS) ε_{PS} was determined by shifting the corrected curve to the engineering stress strain curve for un-strained material.

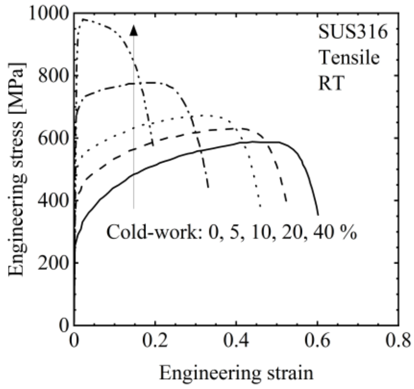

Fig. 1. Engineering stress-strain curve for cold-worked SUS 316 [1]

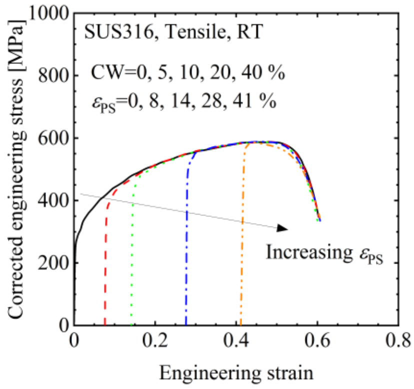

Fig. 2. Corrected engineering stress-strain curve for pre-strained SUS 316

3. Quantification of effect of pre-strain on fracture

3.1. Multi-axial fracture strain damage model

The fracture behaviour of pre-strained material can be quantified based on the multi-axial fracture strain damage model [2]. The model has two criteria: fracture locus (variation of fracture strain with stress-triaxiality) and critical damage value (criterion for accumulated damage). The fracture locus was determined using tensile test and fracture toughness test as follows [2]

$$\varepsilon_f = 3.757 \cdot \exp\left(-1.5 \cdot \frac{\sigma_m}{\sigma_e}\right) \tag{5}$$

where σ_e, σ_m denotes von-Mises equivalent stress and hydrostatic stress, respectively. The detailed information on determination procedure is given in [2].

3.2. Quantification the effect of pre-strain on fracture

The damage due to pre-strain is quantified using the critical damage value D_c. The pre-damage due to pre-strain was calculated using plastic strain energy density U_{fed} (the area under engineering stress-strain curve up to tensile strength) as follows

$$D_{c,\text{PS}} = D_{c,\text{PS}=0} \cdot \frac{U_{\text{fed,PS}}}{U_{\text{fed,PS}=0}} \tag{2}$$

where subscript PS=0 and PS indicates the property for the un-strained and pre-strained material, respectively.

The proposed quantification methodology is validated by simulating fracture toughness test for cold-worked SUS316. The true stress-plastic strain, obtained by shifting the curve for un-strained material as PS, fracture strain locus in Eq. (1), and D_C in Eq. (2) were used for simulation. The simulation was conducted using ABAQUS. The simulation result shows good agreement with experimental data as shown in Fig. 3.

4. Application to irradiated SUS 316

4.1. Application of proposed methodology to irradiation-embrittlement

Figure 4 shows the corrected engineering stress-strain curve for irradiated stainless steel 316, obtained from [3]. The strength increased and the elongation decreased with increasing dose [dpa]. The irradiated stainless steel shows very similar hardening behaviour with the cold-worked stainless steel. The application of cold-worked specimen to analyze the irradiated material was already proposed in [4-5]. Consequently, tensile properties for the irradiated material can be estimated by the proposed methodology.

Figure 5 shows the virtual fracture toughness test results for irradiated SUS316. It is noted that the material exposed to irradiation in reactor has radiation gradient but the preparation specimen having irradiation gradient is very difficult. The fracture behavior of sample having radiation gradient can be easily analyzed using proposed methodology.

5. Conclusion

This paper proposed a methodology to quantify the pre-strain effect of the cold-worked stainless steel on fracture toughness and application to irradiated materials. The effect of pre-strain on hardening and fracture is quantified by true stress-plastic strain curve and multi-axial fracture strain damage model, respectively.

Note that the hardening behavior of irradiated material shows similar results with that for pre-strained material. The fracture behaviour of irradiated material is analyzed using the proposed methodology.

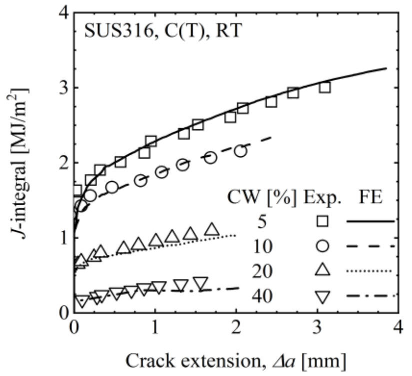

Fig. 3. Comparison of simulated *J*-resistance curve with the experimental data of pre-strained stainless steel 316 [1]

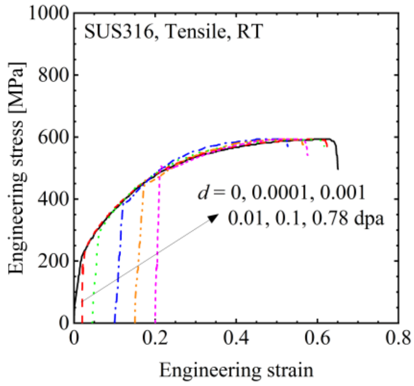

Fig. 4. Corrected engineering stress-strain curve for irradiated stainless steel 316 [2]

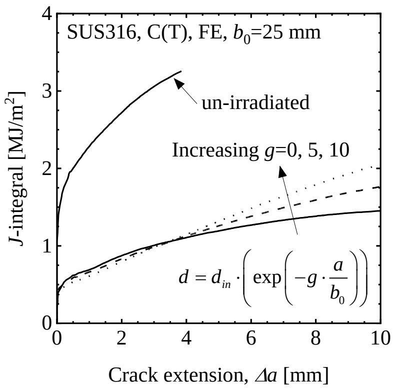

Fig. 5. Virtual fracture toughenss test results; where d and d_{in} denotes dose and dose at crack tip, respectively; g denotes shape of gradient; a and b_0 dentoes length of crack and ligament, respectively.

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