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True stress–strain curve acquisition for irradiated stainless steel including the range exceeding necking strain

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ABSTRACT

True stress–strain curves were obtained for irradiated 316L stainless steel by a tensile test and by a curve estimation procedure. In the tensile test, the digital image correlation technique together with iterative finite element analysis was applied in order to identify curves for strain larger than the necking strain. The true stress–strain curves were successfully obtained for the strain of more than 0.4 whereas the necking strain was about 0.2 in the minimum case. The obtained true stress–strain curves were approximated well with the Swift-type equation including the post-necking strain even if the exponential constant n was fixed to 0.5. Then, the true stress–strain curves were estimated by a curve estimation procedure, which was referred to as the K-fit method. Material properties required for the K-fit method were the yield and ultimate strengths or only the yield strength. Some modifications were made for the K-fit method in order to improve estimation accuracy for irradiated stainless steels.

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1. Introduction

Neutron irradiation causes hardening and reduction in fracture toughness of materials [1–3]. The hardening is preferential from the viewpoint of component design because it increases the material strength. However, the reduced fracture toughness may decrease the load carrying capacity of a cracked component [4,5].

The stress–strain curve is an important material property to assess the load carrying capacity of a cracked component exposed to neutron irradiation. The finite element analysis (FEA) using a realistic stress–strain curve allows the deformation of the cracked component to be simulated and the maximum load to be derived. The critical condition for onset of the ductile crack initiation is determined using the J-integral value together with the fracture toughness. The stress–strain curve is also used to calculate the J-integral value [6–8].

Since the stress and strain become relatively large near the crack tip, the stress–strain curve used for the FEA should include a large range of strain values. However, the maximum strain obtained from the standardized tensile test is less than the strain for the tensile strength (hereafter, necking strain) because it is difficult to acquire the true stress and strain if the necking occurs [9–11]. The neutron irradiation reduces the necking strain and makes it difficult to identify the stress–strain curve for large strain. In a previous study by the current authors [12], the stress–strain curve including the post-necking strain was identified by the IFD method, which stands for Iteration FEA procedure based on DIC measurement method. In the IFD method, the digital image correlation (DIC) technique was applied to measure local strain at the necking portion root even after the necking occurred and then the stress–strain curve was determined by an inverse analysis through iterative FEA. The IFD method was successfully applied to obtain the stress–strain curves of carbon steel [12] and stainless steel [13] including the materials subjected to various degrees of cold working. In this study, this method was applied to an irradiated stainless steel.

One of the practical problems in a structural integrity assessment for actual plant components is how to obtain the material properties of the component. Particularly, it is difficult to get the stress–strain curve of the actual components. Several procedures have been proposed for estimating the stress–strain curve from the yield and ultimate strengths for structural integrity assessment of a cracked component [14,15]. However, these procedures did not focus on irradiated or hardened materials. It has been shown that the stress–strain curve of irradiated stainless steel was

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Nomenclature

S_y	0.2% proof strength (yield strength)
S_u	ultimate strength
T	temperature
ε_L	local strain at the necking portion root measured by the DIC technique
ε_p	true plastic strain
ε_u	true plastic strain at ultimate strength
σ	true stress
$\sigma_{n(exp)}$	nominal stress obtained by tensile test
$\sigma_{n(FEA)}$	nominal stress obtained by finite element analysis
A, ε_o n	constants for the Swift-type constitutive equation

approximated well with the Swift-type constitutive equation [16–18]. A curve estimation method (K-fit method) has been proposed for the Swift-type equation by one of the current authors and validated for cold worked stainless steels [19]. It is expected that the K-fit method is applicable to curve estimation for irradiated stainless steels including the post-necking strain.

In the current study, the authors tried to identify the stress–strain curve including the post-necking strain for a neutron-irradiated Type 316L stainless steel. First, the tensile test was performed in a hot cell. Although an hourglass type specimen has been used for the IFD method [12][13], plate specimens with a parallel gage section were used in order to attach an extensometer and to identify the yield and tensile strengths together with the stress–strain curve up to the necking strain. Then, the stress–strain curve was identified by the IFD method, for which some modifications were made in order to improve the accuracy of the stress–strain curve determination. Second, the applicability of the K-fit method for estimating the stress–strain curve of the irradiated stainless steel was discussed. Some improvements were made to apply the K-fit method to irradiated stainless steels.

2. Test material

The test material used was Type 316L stainless steel having the chemical composition shown in Table 1. Fig. 1 shows the configuration and dimensions of the tensile test plate specimen. The length, thickness and width of the parallel gage section of the specimen were 16 mm, 2 mm and 2 mm, respectively. Two specimens, which are referred to as specimen A and specimen B, were prepared and they were irradiated in the JMTR (Japan Materials Testing Reactor). The degree of irradiation was 3.7 dpa and 4.7 dpa for specimens A and B, respectively.

The tensile tests were conducted in a hot-cell in ambient air at room temperature. The cross-head speed of the tensile test machine was 2 mm per minute. An extensometer, which has been specially designed for tests in the hot-cell, was attached to the parallel gage section. The gage length of the extensometer was 16 mm. In order to apply the DIC technique, the surface of the specimen was observed by two 5M–pixel CCD cameras from the reverse side on which the extensometer was attached. The DIC technique identified the deformation of the specimen surface from the images obtained by the CCD cameras. The use of two cameras allowed identification of the three-dimensional displacement including the reduction in specimen thickness due to the necking. The commercial software, Vic-3D, was employed to analyze the obtained images and derive the strain in the loading direction.

Table 1
Chemical content of test material (wt %).

Fe	C	Si	Mn	P	Ni	Cr	Mo
Bal.	0.008	0.43	0.83	0.023	12.55	17.54	2.11

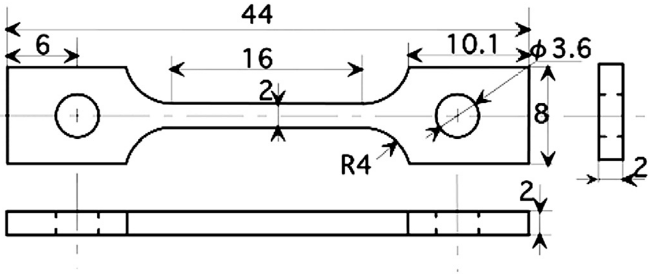
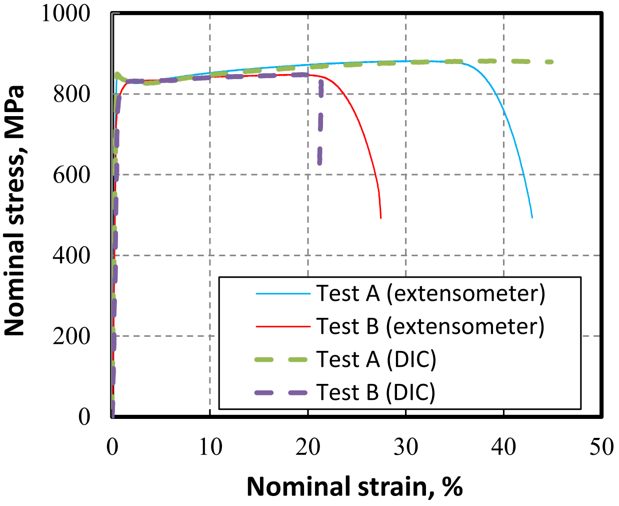


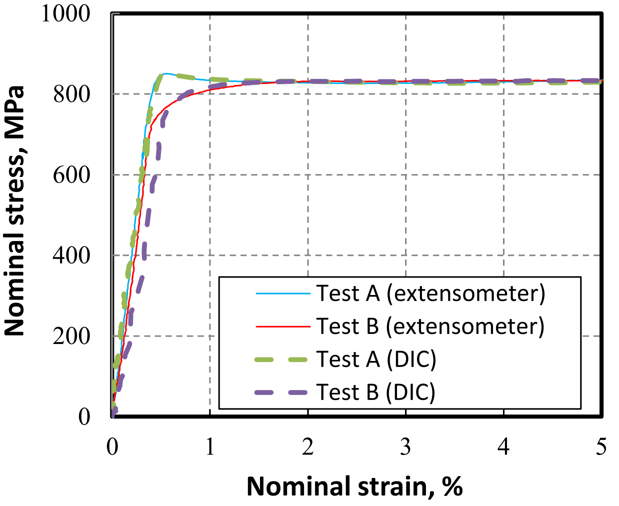
Fig. 1. Geometry and dimensions of tensile specimen (unit: mm).

3. Test results

Fig. 2 shows the nominal stress–strain curves obtained by the



(a) Whole curve until the specimen failure



(b) Magnified view forcing on relatively small strain

Fig. 2. Nominal stress–strain curve obtained by tensile tests. The nominal strain was measured by two ways: extensometer and the DIC technique.

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