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Section 14. Structural materials (II), insulators (II) and others

Modeling of the cyclic ball indentation test for small specimens using the finite element method

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Abstract

Cyclic ball indentation tests for Fe–Mn–Cu–C alloys with and without annealing treatments were simulated by finite element method (FEM) calculation using a 2D-axisymmetric model with a rigid surface indenter. When the friction between the indenter and the specimen was taken into account (friction coefficient is 0.3), the calculation gave a good simulation of the plastic deformation and true stress–plastic strain curve obtained from the actual indentation tests except for the stress decrease in a higher strain region. The stress decrease was not observed in the stress–strain curve from the simulation of the indentation test. The decrease in the experimental curves was explained well by the existence of the higher tensile region that was found in the stress distribution map from the FEM calculation.

1. Introduction

It is necessary to establish the small specimen test technology for the heavy irradiation experiments to develop fusion reactor materials because of the limited irradiation volume. The most attractive technique from a viewpoint of specimen miniaturization is indentation tests including micro-hardness tests. Recently the authors developed the innovative indentation system which can be applied to the various kinds of indentation tests in a wide range of load, indentation depth and test temperature [1]. The system is designed to extract all the possible mechanical property data from one small specimen and was applied to the cyclic ball indentation test [1]. The stress–strain curve which should be obtained from a tensile test was evaluated from the indentation test for Fe–Mn–Cu–C alloys, though there are a few material dependent parameters, such as α and β, that can be obtained only by comparing the indentation test results with the tensile results [1,2]. It was also shown that fracture properties such as crack occurrence, fracture strain or uniform elongation could be estimated from the indentation test [1].

In order to understand the meaning of material dependent parameters and to establish the technique to evaluate fracture properties, the stress–strain distribution under the indenter should be examined in detail.

In this paper, finite element method (FEM) modelling to simulate the indentation test is developed for evaluating the procedure to get the true stress–plastic strain curve and for examining the stress–strain distribution.

2. Experimental procedure

A Fe–Mn–Cu–C alloy, which is a model alloy of A533B steel used for the pressure vessel of nuclear reactor, was prepared by vacuum melting, followed by normalizing at 1173 K for 1.8 ks and then tempering at 873 K for 7.2 ks. The alloy was machined to make miniature tensile test specimens of dimensions shown in Fig. 1, designated as-machined specimens. All specimen surfaces were polished mechanically with emery papers of #240–1500. Heat treatments were performed at 873 K for 0.5 h in a vacuum of 10^{-6} Torr for half of the specimens covered with a Zr foil.

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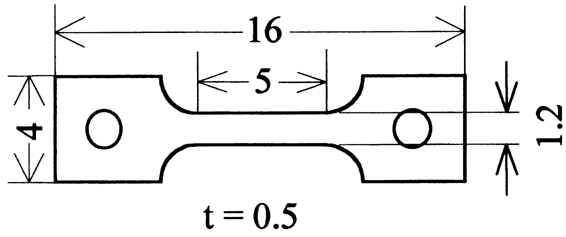

Fig. 1. Dimensions of tensile test specimen.

The cyclic ball indentation tests were conducted on the shoulder of the tensile test specimens prior to the tensile test. The effective strain rate of the indentation test was estimated to be 1.8×10^{-3} s^{-1} using the relation

$$\varepsilon_p = 2v/5d,$$

where v is the penetration rate and d is the final chordal diameter [3]. Tensile tests were conducted in the strain rate range covering the effective strain rate of the indentation test.

One indentation test includes 10 loading–unloading cycles where the peak load at each cycle was raised up to 20 kg by 2 kg step. A ball made of tungsten carbide with diameter of 0.4 mm was used as an indenter. The detailed testing procedure and analyzing equations are decribed in Ref. [1].

3. FEM modeling

FEM modeling calculations were conducted using finite element code, ABAQUS, from the HKS corporation. A SUN SPARC Station 10 workstation was used to run the code.

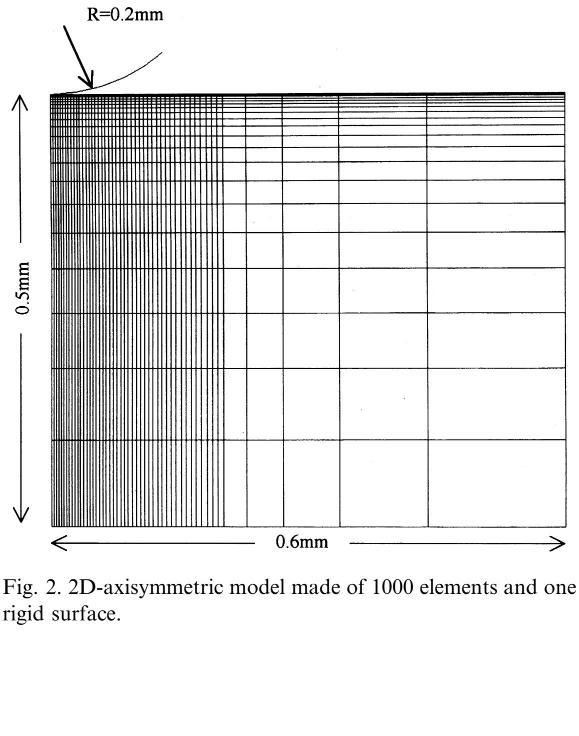

Fig. 2. 2D-axisymmetric model made of 1000 elements and one rigid surface.

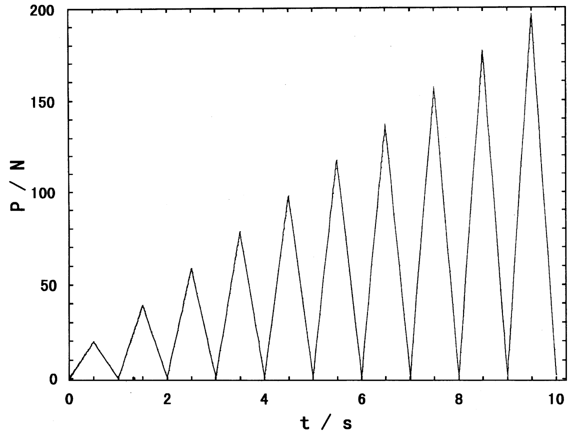

Fig. 3. Loading–unloading history in the simulation of the cyclic ball indentation test.

The 2-dimensional axisymmetric meshes of 1000 four-node first order elements shown in Fig. 2 was used for the modeling. The sufficiency of the mesh fineness was confirmed by testing the finer one which is made of 3000 elements. Material properties of the elements were defined to have elasticity of typical steel (the Young's modulus, E, is 2.09×10^5 MPa and the Poisson's ratio, ν, is 0.3) together with the plastic properties obtained experimentally from the tensile test. The plastic strain for stresses higher than the maximum tensile stress was obtained by extrapolating the actual curve assuming the power law. The ball indenter was described as a rigid spherical surface. A friction coefficient between the indenter and the specimen surfaces of 0 or 0.3 was used in the calculations. The cyclic indentation process was modeled by changing the point load on the rigid surface as shown in Fig. 3.

4. Results and discussion

4.1. Simulation of load–displacement and true stress–plastic strain curves

The tensile test results showed no significant effect of strain rate. Fig. 4 shows typical tensile test results for as-machined and 873 K-annealed specimens and the stress–strain relations inputted for the FEM calculation.

Fig. 5 shows the plastic deformation at each indentation cycle calculated on two different meshes. The difference between the values from the two meshes is no more than 2% except for the 2.9% at 8th cycle. It suggests that both meshes meet the requirements. In order to save calculation time and help with data storage limits, the coarse mesh was used in most cases.

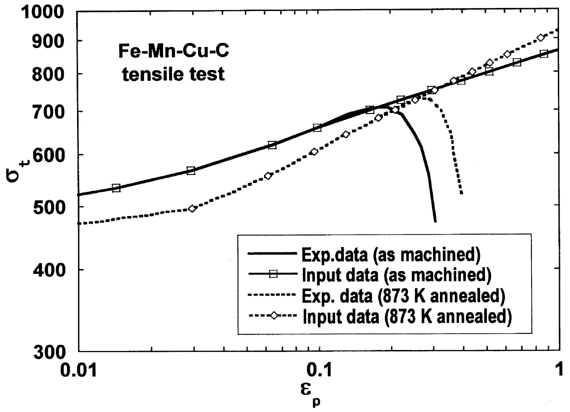

Fig. 4. Tensile test results and the stress–strain function included into the FEM calculations.

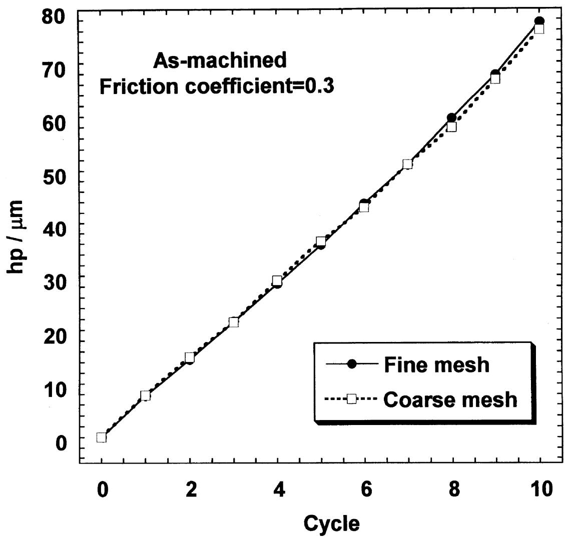

Fig. 5. Effect of mesh fineness on the FEM calculation results on plastic deformation.

Fig. 6 shows a typical load-displacement curve from the cyclic indentation test conducted for the as-machined specimen together with the FEM simulation of the tests. The experimental results showed much larger elastic deformations than any simulation result. The sources of the large elasticity are the deformation of a rod and a stage which are holding the tungsten carbide ball as well as that of the ball itself. Simulating all the elasticity is difficult but the plastic deformation measured after unloading should not be affected by the elasticity and should be simulated adequately. Actually the plastic deformation obtained from FEM calculation with a friction coefficient of 0.3 gave a good simulation of the actual deformation. The plastic deformation for

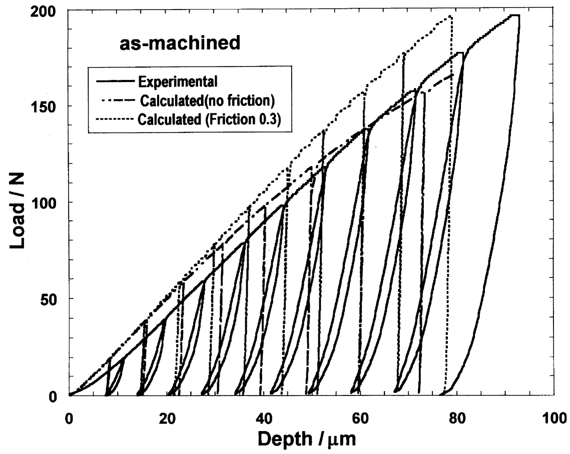

Fig. 6. The load–displacement curves obtained from the actual indentation test and from the FEM calculations with different interfacial friction coefficients, 0 and 0.3.

the no friction model was larger by 20% after 16 kg loading than that with the friction coefficient of 0.3. It suggests that the interfacial friction force exists and should be considered when the experimental data are analyzed. The model with the coefficient of 0.3 was used for all the calculations below.

The load–displacement curves for the as-machined and annealed specimens were analyzed and stress–strain curves were obtained as shown in Figs. 7 and 8. The material dependent parameter α was fixed to be 1 so that the difference between tensile and indentation test results shows the magnitude of α. The stress–strain curves obtained from the FEM simulation followed experimental results well for both specimens. The slight difference in

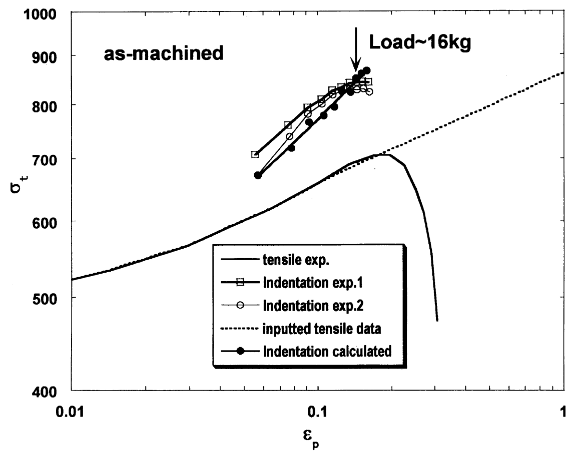

Fig. 7. The true stress–plastic strain curves of as-machined specimens evaluated from the indentation tests including FEM simulation and from the tensile test.

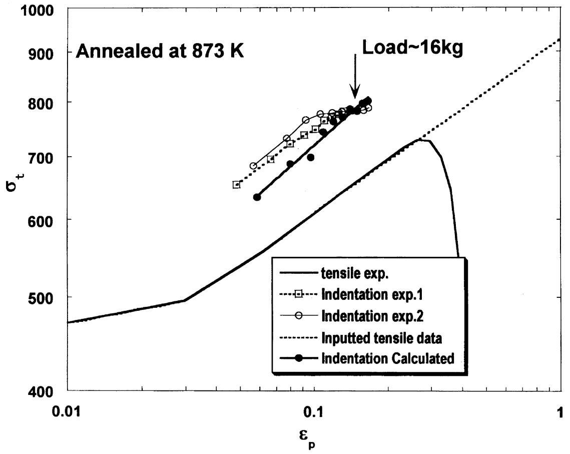

Fig. 8. The true stress–plastic strain curves of 873 K-annealed specimens evaluated from the indentation tests including FEM simulation and from the tensile test.

the stress suggests that the friction coefficient should be refined and to be higher than 0.3. The friction seems to explain partially the calculated stress values larger than the tensile test results [1].

4.2. Stress decrease in the true stress–plastic strain curve

The important feature which is common in the stress–strain curves is that the true stress obtained from the FEM simulated indentation test does not decrease in the higher strain region while the experimentally obtained stress decreased at around 15% plastic strain. Such a non decreasing stress–strain curve is resulted from using plastic properties with no fracturing feature such as necking. Hence, the stress decrease usually observed in the experimental stress–strain curve is most likely related to the fracture properties and should be some measure of fracture properties similar to the uniform elongation or fracture strain from the tensile tests.

The stress decrease mostly starts around the 8th cycle under a load of 16 kg. The stress and strain distributions in the FEM models at that cycle were examined. Fig. 9. shows the distribution of the maximum principal stress in the FEM model of the as-machined specimen under a load of 16 kg. Positive values of the stress means that the tensile principal stress is operating. The figure illustrates that the tri-axial high compression state exists beneath the indenter while a significant tensile stress is observed just outside the edge of the cavity. The ultimate tensile strength from the tensile tests for the specimen is close to

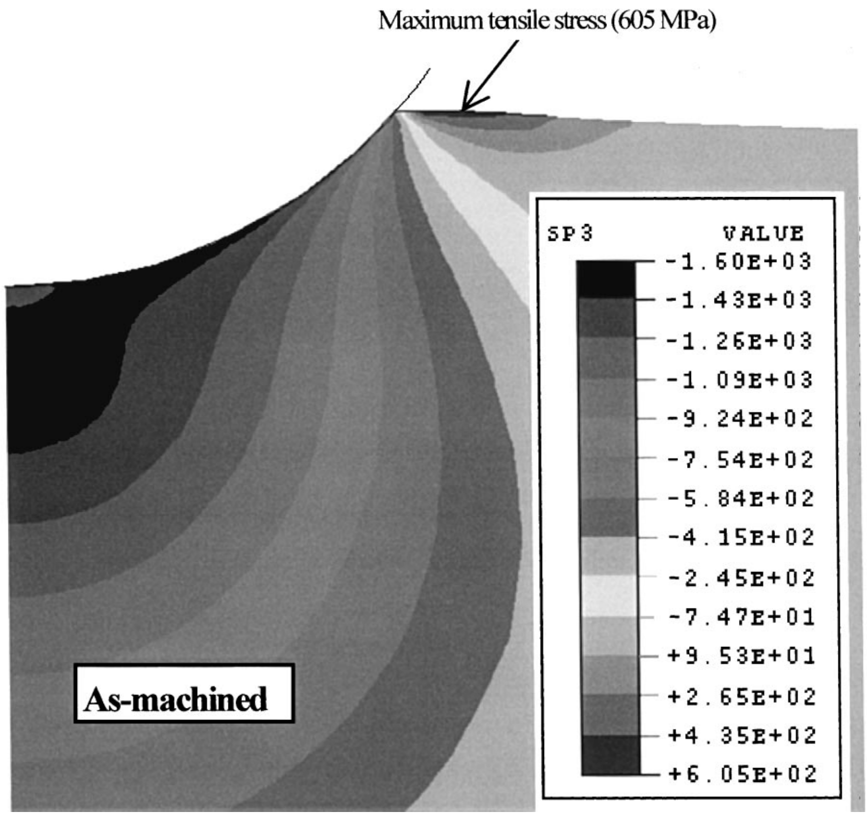

Fig. 9. Distribution of the maximum principal stress in the model of as-machined specimen loaded to 16 kg.

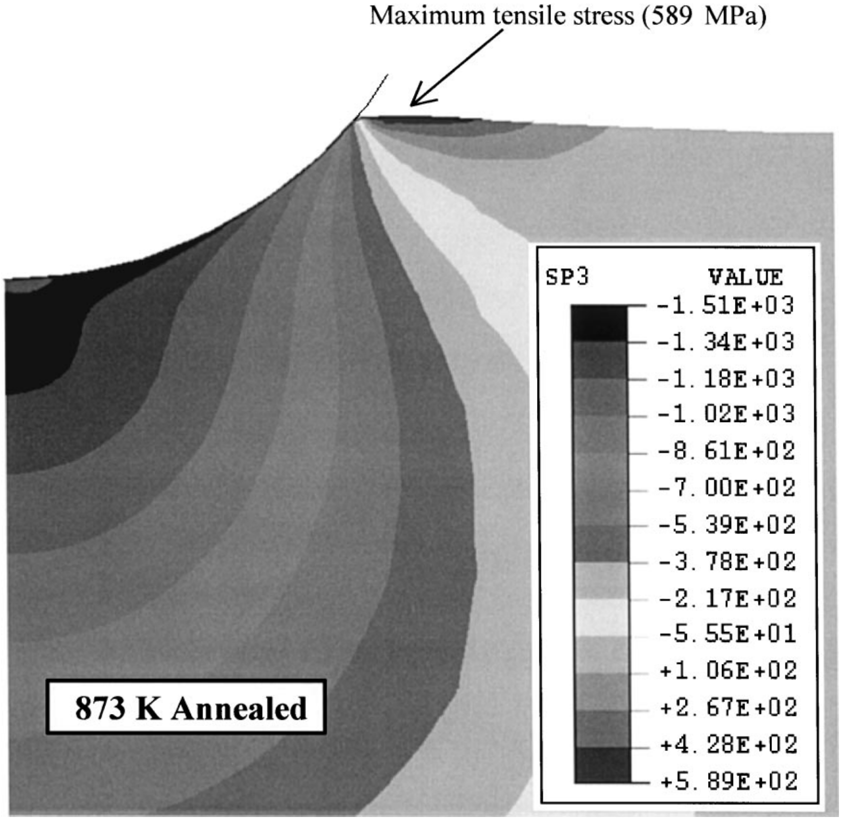

Fig. 10. Distribution of the maximum principal stress in the model of 873 K-annealed specimen loaded to 16 kg.

the highest tensile stress around the indents. The partial fracturing can occur at the most highly stressed point around the cavity, which can relieve the high tensile stress in that region. This idea seems also applicable to the case of the annealed specimen, the principal stress map of which is shown in Fig. 10.

5. Conclusion

The cyclic ball indentation tests for the Fe–Mn–Cu–C specimens with and without annealing and the simulation of the test by FEM calculation using the 2D-axisymmetric model were performed. The calculations suggested that the friction between the indenter and the specimen should be taken into account and gave a good simulation of plastic deformation and true stress–plastic strain curve except for the stress decrease.

The stress decrease was explained well by taking into account the high tensile stress region found in the FEM calculation of the stress distribution map.

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