Semi-destructive Method for Evaluation of Local Mechanical Properties in the Notch-Tip Region using an Indentation Technique*

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In the present study, a semi-destructive method for estimating the mechanical properties, including plastic strain, of materials was developed using the instrumental indentation technique (IIT). The formula for estimating plastic strain was derived using true stress-true strain curves that were measured by IIT. The developed method requires only one parameter, namely, the work hardening coefficient, for estimating the plastic strain of pre-strained materials. The usefulness of the developed method was evaluated using pre-strained specimens. The dimension of the plastic strain estimated using the developed method generally agrees with the dimension of the plastic strain of the pre-strained materials. The developed method was used to evaluate the distribution of plastic strain in the notched region of pre-strained materials. The distributions of plastic strain estimated by the developed method were validated by comparison with FE simulation results. The results indicate that the distribution of plastic strain can be estimated conveniently using the developed method.

Key Words: Instrumental indentation technique, Semi-destructive method, Plastic strain, True stress - true strain curve, Notch-tip region

1. Introduction

Evaluating structural damage from aging or large-scale accidents through non-destructive or semi-destructive procedures has become more important in order to more economically ensure structural the safety and reliability of industrial structures in service.

Although indentation techniques have been used to measure local mechanical properties, especially the hardness of materials1), the instrumental indentation technique (IIT) has recently attracted attention as a semi-destructive method for measuring the yield stress2), Young’s modulus3), the true stress-true strain relation4), or the residual stress5,6). Improvements in indentation machines and computers have enabled the measurement of load-depth curves by IIT. As such, IIT also has the potential to become a useful maintenance technique for evaluating structural damage, such as plastic strain, of industrial structures in service, which requires non-destructive or semi-destructive methods.

In the present study, a semi-destructive method for evaluating mechanical properties, including plastic strain, was developed using the true stress-true strain relations obtained from IIT. The developed method was validated experimentally and was used to evaluate the distribution of plastic strain in the notch-tip region of strained materials. The experimental results were compared with FE simulation results to verify the usefulness of the developed method.

2. True stress-true strain estimation using IIT

The true stress-true strain relation can be estimated from the load-depth curve obtained using IIT and a spherical indenter7). Figure 1 shows a schematic diagram of the load-depth curve obtained by IIT, and Fig. 2 shows a schematic diagram of spherical indentation and the relevant parameters.

Fig. 1  Schematic diagram of the load-depth curve.

Fig. 2  Schematic diagram of spherical indentation7).

The true stress is defined in terms of the indentation load, the contact area, and the plastic constraint factor, as follows:
\[ \sigma = \frac{1}{\Psi} \frac{P}{\pi a^2} \]  
(1)

where \( \sigma \) is the dimension of the true stress, \( P \) is the indentation load, \( \Psi \) is constraint factor, and \( a \) is the contact radius.

The true strain is defined as a function of ratio of the contact radius to the radius of the indenter, as follows:

\[ \varepsilon = \frac{0.14}{\sqrt{1 - (a/R)^2}} \frac{a}{R} \]  
(2)

where \( \varepsilon \) is the dimension of the true strain, and \( R \) is the radius of the indenter.

The contact radius is evaluated based on the contact depth. However, the contact depth must be calibrated by elastic deflection and the pile-up or sink-in effect, as shown in Fig. 3. Therefore, the contact depth is defined as follows:

\[ h_c = h_{\text{max}} - 0.75 \frac{P_{\text{max}}}{S} \]  
(3)

where \( S \) is the initial unloading stiffness and the contact radius considering the pile-up or sink-in effect is calculated as

\[ a' = \frac{5}{2} \frac{(2-n)}{(4+n)} a \]  
(4)

where \( a' \) is the actual contact radius and \( n \) is the work-hardening coefficient of the material.

Using the above-described technique, the actual contact radius considering pile-up or sink-in and the true stress-true strain relation are estimated to a high degree of accuracy.

3. Derivation of a formula to evaluate plastic strain

The formula used to evaluate the plastic strain is derived using true stress-true strain relations obtained by IIT. Figure 4 shows a schematic diagram of the true stress-true strain curves of the virgin material and the plastically pre-strained material. For a power-law hardening material, the true stress-true strain (\( \sigma-\varepsilon \)) curve of the virgin material is given as follows:

\[ \sigma = K \varepsilon^n \]  
(5)

and the true stress-true strain (\( \sigma-\varepsilon' \)) curve of plastically pre-strained material is defined as follows:

\[ \sigma = K' \varepsilon'^n \]  
(6)

where \( K \) and \( K' \) are the proportionality coefficients. The dimension of the true stress at the maximum nominal stress (\( \sigma_T \)) at \( \varepsilon = n \) is defined as follows:

\[ \sigma_T = Kn^n \]  
(7)

According to Fig. 4, the dimensions of the true stresses at the maximum stresses of the virgin material and the pre-strained material are the same. The dimension of the plastic strain can be derived by Eq. (5) through (7) and defined as follows:

\[ \varepsilon_{\text{pre}} = n - n' \]  
(8)

where \( \varepsilon_{\text{pre}} \) is the dimension of the plastic strain of pre-strained material.

In the present study, in order to simplify the method, we set \( K = K' \) so that only one parameter \( n' \) is required. Then, by evaluating \( n' \) of plastically strained material, the dimension of the plastic strain can be defined as follows:

\[ \varepsilon_{\text{pre}} = n - n' \]  
(9)

4. Experimental validation of the developed method

4.1 Experimental Conditions

The applicability of the developed method is validated experimentally using indentation specimens cut from tensile specimens pre-strained at several plastic strain levels. The material used in the experiment is a 490-MPa class high-tensile-strength steel, JIS SM490YB, the chemical composition of which is summarized in Table 1. The configuration of the tensile specimen is shown in Fig. 5. Tensile tests for obtaining the plastic pre-strain were performed at a crosshead speed of 0.5 mm/min and strains of 3% and 5%, respectively. The indentation specimen was cut from the tensile specimen, and the specimen surface was finally polished by diamond paste, as shown in Fig. 6. The indentation tests were
performed using an AIS2100 (FRONTICS, Inc.) with indenters having a radius $R$ of 250 μm. The loading rate was 0.1 mm/min, and the unloading ratio was 30%. The maximum depth was 100 μm.

Table 1  Chemical composition (mass%) of SM490YB.

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Fig. 5  Dimensions of the tensile specimen.

4.2 Experimental results

The indentation tests were performed at five measurement points for all three of specimens. It was confirmed based on the results that the variation of the load-depth curve obtained by IIT is negligibly small.

Figures 7(a) and 7(b) show the measured load-depth curves and the estimated true stress-true strain curves, respectively, with and without pre-strained materials. Both the load-depth and true stress-true strain curves shift to the upper side as the dimension of the plastic strain increases. In addition, the true stress-true strain curve obtained in the tensile test is in good agreement with that estimated by IIT without the pre-strained material.

For the virgin material, $K = 982.15$ and $n = 0.206$. When we use $K' = K$ for true stress-true strain curves of the pre-strained material, the values of $n'$ in 3% and 5% pre-strained materials are 0.188 and 0.176, respectively. Substituting these values into Eq. (9), the dimensions of the plastic strain are estimated to be 2.9% and 4.9%, respectively. These results generally agree with the dimension of the plastic pre-strain obtained in the tensile test. Thus, the validity of the method of evaluating the plastic strain using IIT and Eq. (9) is demonstrated.

Fig. 7  Indentation results for pre-strained materials.

5. Evaluation of the distribution of plastic strain in the notch-tip region

5.1 Procedures for experiments and simulations

The developed method is applied to the evaluation of the distribution of plastic strain in the notch-tip region. In same tensile specimen shown in Fig. 5, a notch was formed by means of electrical discharge. The length and radius at tip of the notch were 2 mm and 0.15 mm, respectively.

Tensile tests were conducted at a crosshead speed of 0.5 mm/min and strains of 3% and 5% in order to plastically pre-strain the specimens. Indentation specimens were obtained using the above-described process, as shown in Fig. 8. In the
indentation test, the loading rate was 0.1 mm/min, and the unloading ratio was 30%. In addition, the maximum depth was 100 μm. The plastic strain in the notch-tip region was estimated at 15 measurement positions, as shown in Fig. 9.

The experimentally estimated plastic strain in the notch-tip region was validated through comparison with numerical simulation results. Three-dimensional elastic plastic analysis was performed in order to evaluate the distribution of plastic strain in the notch-tip region using ABAQUS finite element code. A half symmetric model of the tensile specimen was used and the minimum size of the element side was 0.03 mm near the notch-tip, as shown in Fig. 10.

5.2 Results and discussion

Figure 11 shows the distribution of plastic strain in the notch-tip region estimated by IIT and FE simulations. The IIT results generally agree with the FEM results. The distribution of plastic strain in the notch-tip region can be evaluated accurately and easily by IIT. As such, the developed method using IIT is expected to be a useful semi-destructive method for evaluating local mechanical properties, including plastic damage of industrial structures in service.

6. Conclusions

The formula used to evaluate the plastic strain using IIT is...
derived and validated using pre-strained materials. In addition, the developed method is applied to the evaluation of the distribution of plastic strain around the notch-tip with pre-strain at several levels. The distributions of plastic strain estimated by IIT are in good agreement with the FE simulation results. Thus, the developed method using IIT can be used to accurately and easily evaluate local mechanical properties such as plastic strain.

Reference