Advanced Indentation Technique for Non-destructive Evaluation on Flow Properties and Residual Stresses of Nuclear Power Plant Facilities

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1. Introduction

An advanced indentation technique has been developed as a potential method for non-destructive testing of in-field structures. This technique measures indentation load-depth curve during indentation and analyzes such mechanical properties related to deformation as yield strength, tensile strength and work-hardening index. Also the advanced indentation technique can evaluate residual stresses based on the concept that indentation load-depth curves are shifted with the direction and the magnitude of residual stress applied to materials. In this study, we characterized the flow properties and residual stress of the materials used in nuclear power plants using advanced indentation technique.

2. Theory of advanced indentation technique

2.1 Evaluation of flow properties by indentation

Research for evaluating the flow properties from an indentation load-load depth curve shown in Fig. 1. was done as described below[1].

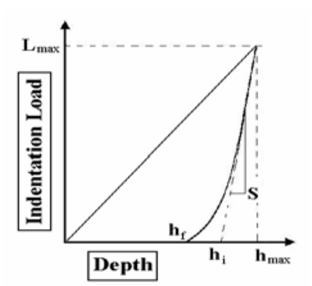

Figure. 1. A Schematic graph of the indentation load-depth curve.

The true stress and strain were defined in terms of the measured indentation contact parameters such as contact radius a, indenter radius R and the morphology of the deformed sample surface. And, real contact properties were determined by considering both the elastic deflection and the pile-up around the contacting indenter.

The true strain ε is defined in Eq. (1) at the position of the contact radius by multiplying a fitting constant α . The value of α is a universal constant, 0.14.

$$\varepsilon = \frac{\alpha}{\sqrt{1-(a/R)^2}}\frac{a}{R} \quad (1)$$

The true stress σ is defined using the relationship with contact mean pressure P_m as shown Eq.(2)

$$\sigma = \frac{1}{\psi}P_m = \frac{1}{\psi}\frac{L_{max}}{\pi a^2} \quad (2)$$

, where Ψ is a plastic constraint factor and is about 3 for fully plastic deformation of steels. Inputting them into a constitutive equation in Eq. (3), the flow curve is derived. The yield strength and the tensile strength are determined on the flow curve by indentation concept.

$$\sigma = k\varepsilon^n \quad (3)$$

2.2 Evaluation of residual stress by indentation

The change in indentation deformation caused by the residual stress was identified in the indentation loading curve shown in Fig. 2.

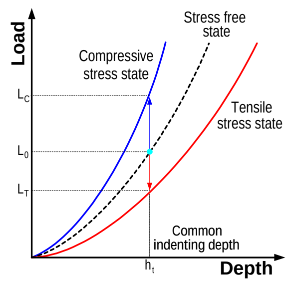

Figure. 2. Variation of the indentation loading curves with the changes in the stress states.

The applied load of the tensile stressed state is lower than that of a stress-free state for the same maximum indentation depth [2-3], because a residual-stress-induced normal load acts as an additive load to the applied load.
In the compressive stress state vice versa. This increasing or decreasing portion of the applied load can be named the residual-stress-induced normal load L_{res}. The residual stress can be evaluated by dividing L_{res} by the contact area A_c, regardless of the stress state[4].

$$\sigma_{res} = \beta L_{res} / A_c \quad (4)$$

, where β is a constant related to the stress directionality of biaxial residual stress. The biaxial stress state, in which $\sigma_y = \kappa\sigma_x$, can be divided into mean stress term and plastic-deformation-sensitive, shear deviatoric term in Eq. (5), where κ is -1.0 to 0.1(κ ≠ -1.0).

$$\begin{pmatrix} \frac{(2-\kappa)}{3}\sigma^x_{res} & 0 & 0 \\ 0 & \frac{(2-\kappa)}{3}\sigma^x_{res} & 0 \\ 0 & 0 & -\frac{(1+\kappa)}{3}\sigma^x_{res} \end{pmatrix} \quad (5)$$

The stress component parallel to the indentation axis in the deviatoric stress term is directly related to L_{res}. A residual-stress-induced normal load L_{res} can be defined from the selected deviator stress component in Eq. (6).

$$\frac{1}{\psi}\frac{L_{res}}{A_c} = \frac{(1+\kappa)}{3}\sigma_{res} \quad (6)$$

Consequently, the residual stress was calculated from the analyzed contact area A_c and the measured load change L_{res} in Eq. (4)

3. Experimental procedure

The testing machine was the Advanced Indentation System 2100, 3000™ made by Frontics, Inc. To confirm the results, the uniaxial tensile tests and saw-cutting, hole-drilling methods were also performed. The subject of materials were SA508, A335-P12, A335-P91 steel for the flow properties and the welded pipelines of API X65 for the residual stress.

4. Results and discussion

The flow curves obtained by advanced indentation test is compared to tensile curves measured by uniaxial tensile test in Fig. 3.

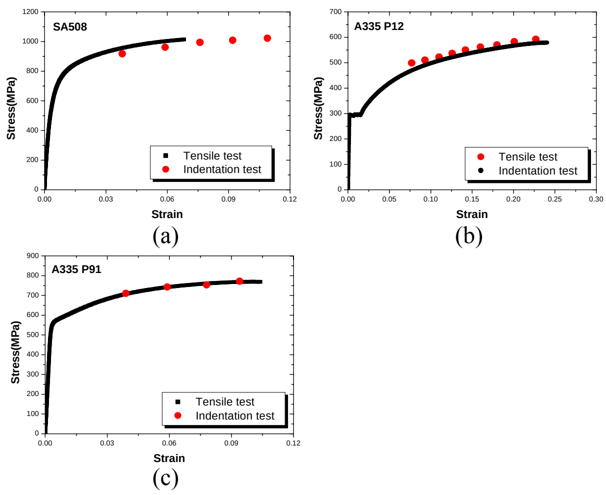

Figure. 3. Comparisons between flow properties calculated from advanced indentation test and those tensile test for (a) SA508, (b) A335-P12, (c) A335-P91

Flow properties of materials was nearly consistent with the results from the uniaxial tensile test.

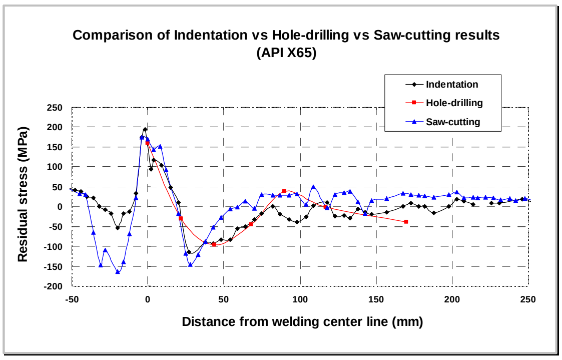

Figure. 4. Direct comparison of residual stresses measured by indentation test with those obtained from saw-cutting and hole-drilling tests for API X65.

The welding residual stresses were obtained in the welded pipelines of API X65 using indentation, saw-cutting and hole-drilling methods shown in Fig. (4). Their indentation results have good agreement with two kinds of reference test results. Especially, most important tensile residual stress was almost same that.

5. Conclusion

The advanced indentation test was used to evaluate the flow properties of various materials and residual stress in an API X65 steel. From all above results, it could be concluded that the advanced indentation technique can be applied to non-destructive evaluation of flow properties and residual stress in nuclear power plant facility .

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