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A New Method for Nondestructive Evaluation of Mechanical Properties Using Instrumented Indentation Technique

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Abstract. The development of the instrumented indentation test (IIT), which gives accurate measurements of the continuous variation in indentation load as a function of depth, has paved the way to assessing tensile properties and residual stress in addition to hardness by analyzing the indentation load-depth curve. In this study, analytic models and procedures are presented for evaluating tensile flow properties and residual stress states using IIT. Tensile properties were obtained by defining representative stress and strain beneath the spherical indenter. The evaluation of residual stress is based on the concepts that the deviatoric stress part of the residual stress affects the indentation load-depth curve, and that analyzing the difference between the residual stress-induced indentation curve and the residual stress-free curve permits evaluation of the quantitative residual stress in a target region.

Introduction

Safety assessment of large structures such as power, petroleum, and chemical plants has attracted recent interest because of the frequent failure of structural components by time-dependent degradation in a severe operating environment. Safety assessment is generally done by conventional mechanical methods such as uniaxial tensile and fracture mechanical test, etc. However, these methods have many drawbacks: they are time-consuming and expensive, unsuitable for use in industrial conditions because they are destructive, and removal and testing of samples are difficult. Many kinds of nondestructive techniques, such as X-ray diffraction and ultrasonic tests, have been developed for this purpose, but they too have many drawbacks. For example, nondestructive methods are needed to determine properties in a specific parameter. In welded components, the problem is compounded by the fact that weldments contain a complex microstructure of many zones with varying material properties.

The instrumented indentation technique has been developed to overcome these limitations. This technique can nondestructively evaluate various mechanical properties such as residual stress, tensile properties, and fracture toughness by analysis of the indentation load-depth curve [1-3]. In the study, we adapt the residual stress model to a general biaxial stress state and use this model to characterize a friction stir-welded API X80 steel. The residual stresses estimated are compared with those obtained by ED-XRD. The tensile properties were determined from the indentation load-depth curve continuously measured by a spherical indenter based on a representative stress and strain approach. IIT results obtained by determining optimum representative stress and strain were compared to those obtained by uniaxial tensile testing for three metallic materials.

Tensile properties measurement using IIT

Tensile properties can be evaluated by defining representative stress and strain with parameters obtained from instrumented indentation tests using a spherical indenter. The mean pressure P_m obtained by dividing the maximum load L_{max} by the contact area is well known to be about three times the representative stress σ_R for fully plastic deformation of steels. In other words, the representative stress can be expressed as:

$$\sigma_R = \left(\frac{1}{\Psi}\right) P_m = \left(\frac{1}{\Psi}\right)\left(\frac{L_{max}}{\pi a_c^2}\right) \tag{1}$$

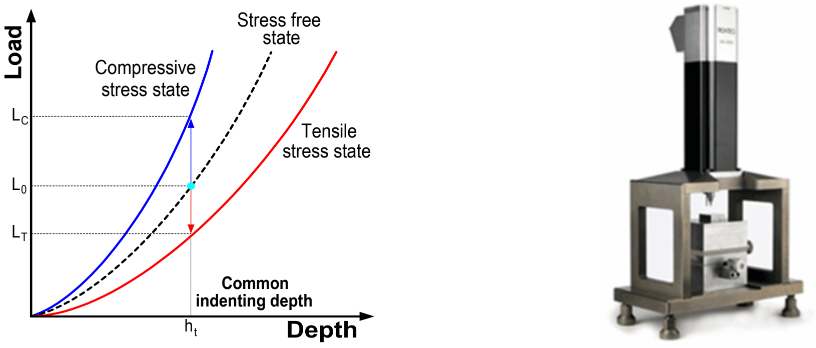
where Ψ is a plastic constraint factor, here taken as 3. On the basis of the deformation shape and strain distribution under a spherical indenter, Ahn and Kwon [1] proposed a new definition using the tangent function and a strain proportional constant, α:

$$\varepsilon_R = \left(\frac{\alpha}{\sqrt{1-(a_c/R)^2}}\right)\left(\frac{a_c}{R}\right) = \alpha \tan\gamma \tag{2}$$

where α was determined as 0.14 for various materials by FEA [4]. The true stress and strain points obtained from the indentation test are fitted to a constitutive equation (a simple power-law-type Hollmon equation, $\sigma = K\varepsilon^n$) and K, a material constant, and n, the work-hardening exponent, are determined. Since the elastic modulus is obtained by indentation testing, the yield strength can be measured from the intersection point of the flow curve and a line with a slope of the elastic modulus 0.2% offset from the origin. The ultimate tensile strain should be same as the work-hardening exponent, by the theory of instability in tension, and from this the tensile strength can be determined.

Residual stress evaluation using IIT

The change in indentation deformation caused by the residual stress was identified in the indentation loading curve in Fig. 1(a). A surface residual stress is assumed to be in an equibiaxial state ($\sigma_{res,x}=\sigma_{res,y}=\sigma_{res}$, $\sigma_{res,z}=0$) and uniform in the near-surface region (taken as about three times the indentation depth) [5]. If an arbitrary indentation state (h_t, L_0) is attained in an unstressed state and if the tensile in-plane stress σ_{res} is applied to the loading state at a fixed penetration depth h_t, the indentation load L_0 is reduced to a load L_T due to the decrease in surface penetration resistance. The load shift L_T-L_0 due to tensile stress is a clue for stress quantification. The surface-normal deviatoric stress σ_z^D is $-2\sigma_{res}/3$ by removing the hydrostatic stress $2\sigma_{res}/3$ from the surface residual stress σ_{res} and is added to the contact pressure. L_T-L_0 is defined as the product of the selected deviatoric stress component and its corresponding contact area A_c^T. Thus, an equation for the equibiaxial residual stress is derived in terms of the indentation load and contact area ($\sigma_{res}=3(L_0-L_T)/2\,A_c^T$).



(a) (b)

Figure 1. (a) Shift of indentation loading curve with changes in residual stress, (b) AIS (Advanced Indentation System) 3000, made by Frontics Inc.

Since the experiments and theoretical models described above treat only equibiaxial residual stress, the magnitude of the average stress effect can be determined by the instrumented indentation technique but the directionality and magnitude of an actual biaxial stress cannot. This impedes the wide application of the instrumented indentation technique to complex biaxial stress states in actual structures. If we denote one major stress component of the biaxial residual stress as $\sigma_{res,x}$ and the other as a minor stress component $\sigma_{res,y}$, $\sigma_{res,y}$ can be expressed as $p\sigma_{res,x}$ using the stress ratio p. The influence of biaxial stress on the indentation plasticity can also be analyzed through a similar hydrostatic-stress-removal method (Eq. 3):

$$\overset{\text{Biaxial stress}}{\begin{pmatrix} \sigma_{res,x} & 0 & 0 \\ 0 & \sigma_{res,y} & 0 \\ 0 & 0 & 0 \end{pmatrix} = \begin{pmatrix} \sigma_{res,x} & 0 & 0 \\ 0 & p\sigma_{res,x} & 0 \\ 0 & 0 & 0 \end{pmatrix}} = \overset{\text{Hydrostatic stress}}{\begin{pmatrix} \frac{(1+p)}{3}\sigma_{res,x} & 0 & 0 \\ 0 & \frac{(1+p)}{3}\sigma_{res,x} & 0 \\ 0 & 0 & \frac{(1+p)}{3}\sigma_{res,x} \end{pmatrix}} + \overset{\text{Deviatoric stress}}{\begin{pmatrix} \frac{(2-p)}{3}\sigma_{res,x} & 0 & 0 \\ 0 & \frac{(2-p)}{3}\sigma_{res,x} & 0 \\ 0 & 0 & -\frac{(1+p)}{3}\sigma_{res,x} \end{pmatrix}} \quad (3)$$

The deformation-sensitive deviatoric stress component is given as $\sigma_Z^D=-(1+p)\,\sigma_{res,x}/3$ in this case. Thus, if information on p is given, individual principal stresses can be calculated from the instrumented indentation test using Eq. 4.

$$\sigma_{res,x} = 3(L_0 - L_T)/((1+p)A_C^T)\,. \quad (4)$$

Experimental results and discussion

Indentation testing was performed using AIS 3000 equipment (Frontics Inc.; see Fig. 1(b)) with load resolution 5.6 gf and depth resolution 0.1 µm. The tensile properties measurement used a WC ball indenter (radius 250 µm). Residual stress evaluation used a Vickers indenter and the maximum applied load was 50 kgf. Testing speeds for both were 0.3 mm/min.

Figure 2 compares the flow curves obtained by IIT for three metallic materials (SUS304, SUS410, and SKD61) to tensile curves measured by uniaxial tensile test, and the values obtained are summarized in Table 1. The error range in yield and ultimate tensile strength obtained by IIT was within ±5% of those from tensile tests. In other words, these results mean that IIT can be an alternative to uniaxial tensile testing when tensile testing is impractical for whatever reason (e.g. small-size specimen, localized region such as heat-affected zone, etc.).

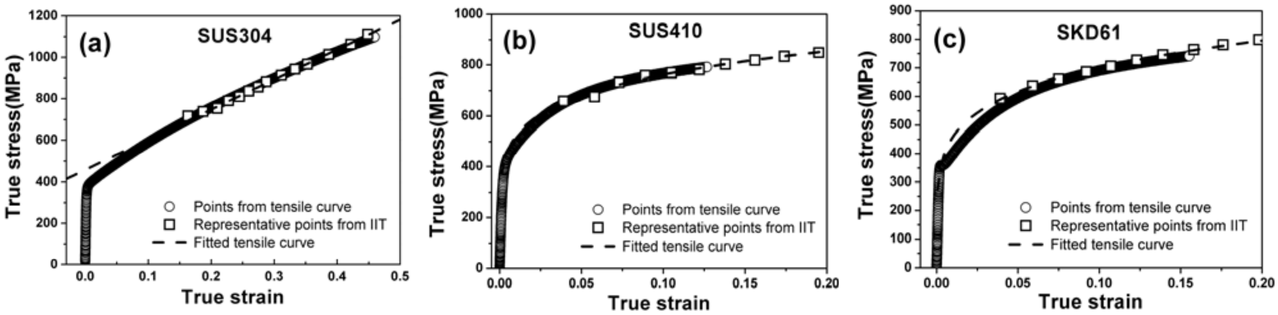


Figure 2. Comparisons of tensile curves obtained from uniaxial tensile test and IIT for (a) SUS304, (b) SUS410 and (c) SKD61.

Table 1 Tensile properties obtained from IIT and tensile tests

Material		SUS 304	SUS 410	SKD61
Yield strength (MPa)	Tensile	389.8	431.5	348.9
	IIT	396.6	471.9	361.8
	Error (%)	-1.7	-8.5	-3.7
Tensile strength (MPa)	Tensile	1085.2	792.1	896.5
	IIT	1110.2	836.6	882.2
	Error (%)	-2.3	-5.3	1.6

API X80 steel of thickness 20 mm as shown in Fig. 3(a) was used in the friction stir-welding (MegaStir Technology, UT, USA). Metallographic samples for optical observation, instrumented indentation testing, and ED-XRD observation were prepared from the welded joint followed by etching with 2% nital solution.

Residual stress distributions from the IIT and ED-XRD were consistent throughout the whole welded joint (see Fig. 3(b)). The discrepancy can be attributed to the indirectly calculated reference indentation curve and approximately determined stress ratio. The maximum tensile residual stress, about 150 MPa, was estimated near the BM-HAZ boundary, meaning that the BM-HAZ boundary is vulnerable to external loads. In addition, the high microhardness in the TMAZ-HZ region can be partly explained by the high compressive stress caused by the complex thermal cycle and phase transformation during friction stir-welding [6]. These experimental results suggest that the instrumented indentation technique is a promising nondestructive stress-measurement technique, especially for welded joints. However, the sparse indentation results, i.e. the 2-mm gap preventing the deformation field overlap, must be improved for more local welds by adopting such indentation techniques as zigzag probing.

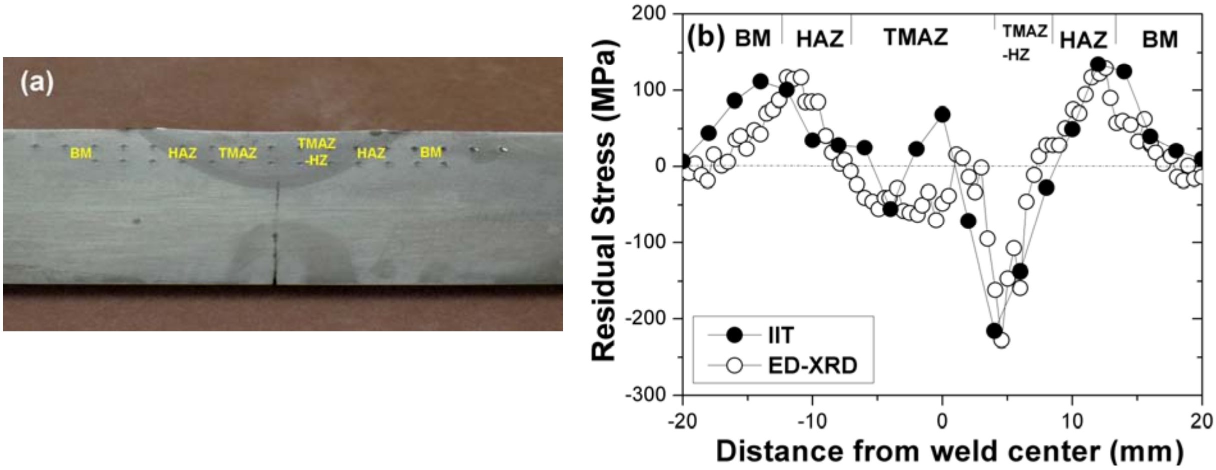


Figure 3. (a) Four distinctive microstructure regions within the friction stir-welded API X80, (b) Residual stress distributions measured from IIT and energy-dispersive X-ray diffraction.

Summary

Tensile properties of three metallic materials were obtained using IIT by applying the representative stress and strain approach. Comparison of tensile properties from IIT with those from uniaxial tensile test yielded an error range in the tensile strength of ±5%. The residual stress profile assessed from the instrumented indentation tests showed high tensile stress (or compressive stress) near the boundary between the base metal and heat-affected zone. The stress trend in instrumented indentation testing was completely consistent with the energy-dispersive X-ray diffraction results.

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