Assessing welding residual stress in A335 P12 steel welds before and after stress-relaxation annealing through instrumented indentation technique

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Abstract

Conventional nondestructive techniques for welding residual stress measurement have many disadvantages in the field because of poor repeatability, large scatter in data, complex procedures, inaccurate results, etc. To overcome these difficulties, an instrumented indentation technique was applied to evaluate the welding residual stress in A335 P12 steel welds in electric power-plant facilities before and after stress-relaxation annealing. Comparison of our results with stress values obtained from a destructive saw-cutting test showed that the instrumented indentation technique is very useful for quantitative/nondestructive evaluation of welding residual stresses in industrial facilities such as power-plants. © 2003 Acta Materialia Inc. Published by Elsevier Science Ltd. All rights reserved.

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1. Introduction

The welding thermal cycle generates inhomogeneous heating and cooling in the regions near the heat source, thus causing residual stress in the weldment. It is well known that welding residual stresses are detrimental to the integrity and fitness-for-service of welded industrial structures due to their susceptibility to fracture criterion, fatigue, hydrogen-induced cracking and stress-corrosion cracking [1]. Thus the quantitative measurement of welding residual stress is very important for the safe and economical operation of such industrial structures as power-plants, petrochemical plants, storage tanks and transmission pipelines. Conventional measurement techniques used to measure or predict the residual stress can be divided into two groups: mechanical stress-relaxation and physical methods. Mechanical stress-relaxation methods, also called strain-gauge methods, including hole-drilling and saw-cutting techniques, can generally be used to evaluate residual stress quantitatively without any reference sample, but they have limitations in industry because of their destructive characteristics. Physical methods including X-ray, ultrasonic methods, magnetic Barkhausen noise and neutron diffraction can

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analyze the residual stress nondestructively, and the former three methods among them have been partially used in fields. However, it is always difficult to separate microstructural effects on the physical parameters from the effects of residual stress, since the techniques are all highly sensitive to such metallurgical factors as grain size and texture [2]. From a similar viewpoint, it is almost impossible to use the nondestructive methods to assess residual stresses in weldments containing heat-affected zones (HAZs), since HAZs have very rapid microstructural gradients. Additionally, the nondestructive methods often show poor reproducibility and large scatter of testing results compared to the mechanical methods, since their physical properties can easily be affected by the electric or magnetic environment when performed in the field.

The present work is the first step in research on the development of a new technique that can be effectively and easily used for quantitative and nondestructive evaluation of welding residual stresses in fossil power-plants. To overcome the limitations of conventional methods including both destructive/mechanical and nondestructive/ physical methods, the instrumented indentation technique was adopted. Many studies have been conducted on the instrumented indentation technique by analyzing indentation load–depth curves to evaluate hardness, tensile properties, fracture toughness, and the like [3–5]. Also, an instrumented indentation testing procedure is being standardized [6]. However, little research has been done on indentation techniques for estimating macroscopic welding residual stress, although a few studies have used the nano-indentation technique to evaluate microscopic residual stresses such as would generate in thin-film applications [7–10]. In this study, the instrumented indentation technique is applied to the quantitative/nondestructive assessment of welding residual stress. The stresses in A335 P12 steel welds in fossil power-plant facilities were measured nondestructively by the indentation technique before and after stress-relaxation annealing, and the stress values obtained were compared with the results from the destructive saw-cutting technique to validate the indentation method.

2. Instrumented indentation for measurement of welding residual stress

Initial studies used indentation hardness as a parameter of the residual stress [7], but the apparent variations in hardness with change in the residual stress have been identified as an artifact of erroneous optical measurements of the indentation mark. Recently, studies using fine observations of the indentation mark [8,9] by scanning-electron or atomic-force microscopes have reported that the intrinsic hardness is invariant, regardless of the residual stress. Therefore, the change in contact morphologies with residual stress was modeled for constant maximum indentation depth assuming the independence of intrinsic hardness and residual stress [10].

The change in indentation deformation caused by the residual stress is identified in the indentation loading curve in Fig. 1: the applied load for the tensile-stressed state is lower than that for the stress-free state for the same maximum indentation depth [8–10]. In other words, the maximum indentation depth desired is reached at a smaller indentation load in a tensile-stressed state because a residual-stress-induced normal load acts as an additive load to the applied load. Therefore the residual stress can be evaluated by analyzing the residual-stress-induced normal load.

To evaluate the residual-stress-induced normal load from an indentation loading curve, the stress-
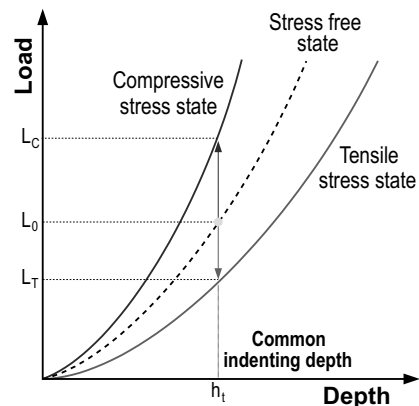

Fig. 1. Variation of indentation loading curves with changes in stress states [8–10].
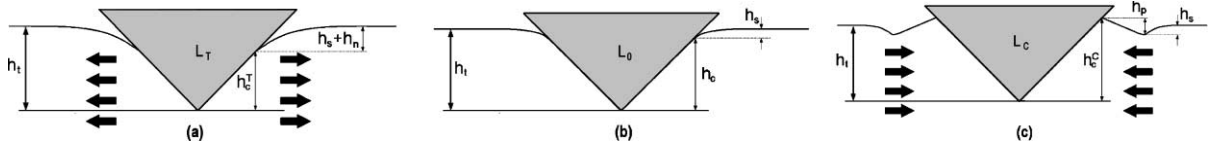
Fig. 2. Theoretical surface morphologies around the contact for (a) tensile stress, (b) stress-free and (c) compressive stress states.

sensitive contact morphologies are modeled as in Fig. 2. Tensile residual stress (Fig. 2(a)) is relaxed to the stress-free state (Fig. 2(b)) while maintaining a constant maximum depth, h_t as the stress relaxation pushes the indenter out from the surface. However, the pushing force is manifested as an increase in the applied load ($L_T \rightarrow L_0$) and the contact depth ($h_c^T \rightarrow h_c$) because the maximum depth is held constant. The indentation load and maximum depth for the tensile stressed state (L_T, h_t) are equivalent to those in the relaxed state (L_0, h_t). Thus, the relationship between the two states can be expressed as

$$L_0 = L_T + L_{res} \tag{1}$$

In the compressive-stress state (Fig. 2(c)), the applied load and contact depth decrease by stress relaxation under the maximum-depth-controlled path. Furthermore, this decreasing portion of the applied load is the residual-stress-induced normal load, L_{res}. Therefore, the residual stress in a welded joint can be evaluated by dividing L_{res} by the contact area A_c, regardless of the stress state [10]:

$$\sigma_{res} = \alpha L_{res}/A_c \tag{2}$$

where α is a constant reflecting the differences in direction between indentation loading and residual stresses. Although actual stress distribution near practical welded joint is not an equi-biaxial stress state, an averaged effect of the in-plane biaxial residual stresses is generally observed at the change in the indentation load. So, it is assumed for systematic understanding that the residual stress state under hard indenter behaves like an equi-biaxial stress state whose stress in an axis is the same with the average value of actual in-plane stresses. The equi-biaxial stress state assumed can be divided into mean stress term and plastic-deformation-sensitive, shear deviator term in Eq. (3): [11]

$$\underset{\text{Equi-biaxial stress}}{\begin{pmatrix} \sigma_{res} & 0 & 0 \\ 0 & \sigma_{res} & 0 \\ 0 & 0 & 0 \end{pmatrix}} = \underset{\text{Mean stress}}{\begin{pmatrix} \frac{2}{3}\sigma_{res} & 0 & 0 \\ 0 & \frac{2}{3}\sigma_{res} & 0 \\ 0 & 0 & \frac{2}{3}\sigma_{res} \end{pmatrix}}$$
$$+ \underset{\text{Deviator stress}}{\begin{pmatrix} \frac{1}{3}\sigma_{res} & 0 & 0 \\ 0 & \frac{1}{3}\sigma_{res} & 0 \\ 0 & 0 & -\frac{2}{3}\sigma_{res} \end{pmatrix}} \tag{3}$$

The stress component parallel to the indentation axis in the deviator stress term ($\sigma_{33} = -2\sigma_{res}/3$) directly affects the indenting plastic deformation. A residual-stress-induced normal load L_{res} can be defined from the selected deviator stress component in Eq. (4):

$$L_{res} = \frac{2}{3}\sigma_{res}A_c \tag{4}$$

Therefore, α of Eq. (2) can be assumed as ≈ 1.5.

To evaluate the stress values from several indentation load steps, we made multiple indentations and calculated the contact area directly from the partial unloading curve at each analyzed load. In the instrumented indentation test, the contact area is determined by analysis of the unloading curve rather than optical measurement. As shown in Fig. 3, the indentation load–depth curve can be obtained by *in situ* sensing of the load and depth signals during indentation. The initial slope of the unloading curve is defined as the stiffness S (see Fig. 2) obtained as follows: differentiation of the power-law-fitted unloading curve at maximum indentation depth yields the stiffness as shown in Eq. (5), where k and m are fitting parameters [3]:

$$S = \left(\frac{dL}{dh}\right)_{h=h_{max}} = km(h - h_f)^{m-1} \tag{5}$$

From Eq. (5) we can get the contact depth h_c:

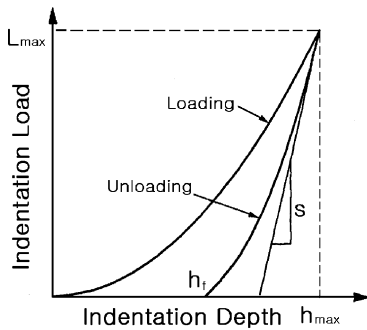$$h_c = h_{max} - 0.72\frac{L_{max}}{S} \tag{6}$$

Fig. 3. Schematic graph of the indentation load–depth curve [3].

The contact area A_c is calculated from the contact depth based on the geometry of the Vickers indenter:

$$A_c = 24.5h_c^2 \qquad (7)$$

It should be noted that the contact depth in Eq. (6) cannot consider the effect of material pile-up during indentation and thus the contact area in Eq. (7) can be underestimated by the large plastic deformation around the indenter. Since there is no established procedure for obtaining contact area accurately from load–displacement curve in consideration of pile-up, an optical measurement would be more precise way to estimate contact area. However, the purpose of this work is to develop a nondestructive testing method which can be easily used even at poor testing environment of industrial fields such as power-plant facilities, and so an optical measurement which can make testing procedure more complex was not considered in this study. Fortunately, a little difference in the contact area generates only small deviation of obtained residual stress value and not the abrupt change in the residual stress distribution. Consequently, the residual stress can be calculated from the analyzed contact area in Eq. (7) and the measured load change L_{res} by the effect of the residual stress shown in Eq. (1).

3. Experimental validation

To evaluate the applicability of the indentation technique to the measurement of welding residual stress, the welding residual stresses in a girth weld joint of cold reheater pipeline of a fossil power-plant were measured by the technique before and after stress-relaxation annealing. Samples of 17.9-mm-thick A335 P12 steel, the base material of the pipe of chemical composition 0.08C–0.01P–0.45Mn–0.01S–0.31Si–1.15Cr–0.55Mo, were machined into an X-groove configuration and welded first by gas tungsten arc welding (GTAW) with AWS ER80S-G electrode and then by shielded metal arc welding (SMAW) with AWS E8016-G electrode. Welding was carried out under the same conditions as used during plant construction (see Table 1). In addition, no significant defects were found in the completed weldments by nondestructive X-ray examination. Annealing was conducted on part of the welded samples for residual stress relaxation. The samples were heated by electric resistance and then held at 998 K for 2 h, a heat-treatment condition that is the same as postweld heat treatment (PWHT) used during plant construction. The results from annealed specimens were compared with those from the as-welded specimens.

In order to evaluate the residual stress of the weldment, two kinds of testing methods were used on both as-welded and annealed specimens: nondestructive indentation and destructive saw-cutting tests. Results of the indentation tests were compared with those of saw-cutting method to validate the indentation method. To measure the distribution of the longitudinal residual stress by the saw-cutting technique, strain gauges were attached along the distance from the weld centerline. The longitudinal stress, parallel to the welding direction, is known to be the largest of the welding residual stresses. The gauges, whose signals were obtained through a multichannel amplifier, provided information about relaxed residual stress values during cutting. Samples were

Table 1
Welding conditions used in this study

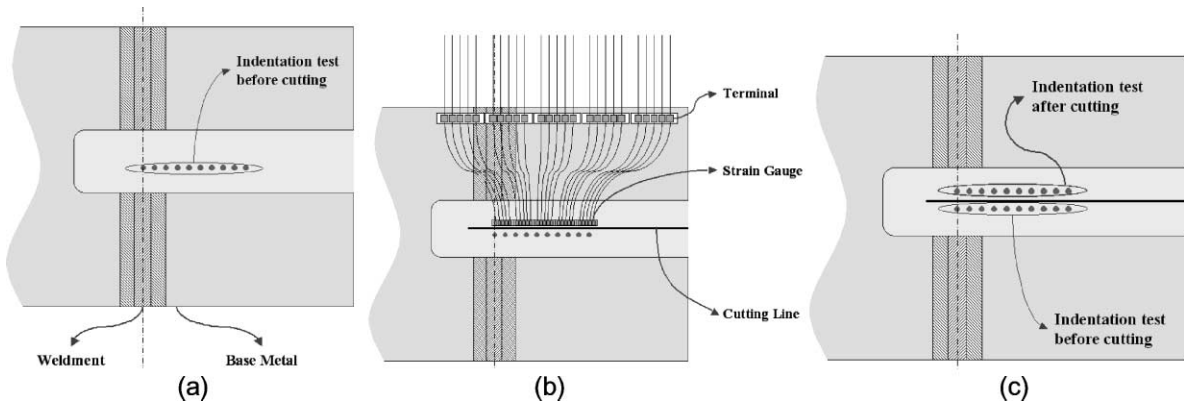| Welding method	Filler metal	Current (A)	Voltage (V)	Speed (cm/min)
GTAW	AWS ER80S-G	80–130	8–12	6–10
SMAW	AWS E8016-G	120–150	20–30	21–24

Fig. 4. Schematic diagram of experimental procedures: (a) indentation test before cutting, (b) stress measurement by saw-cutting, and (c) indentation test after cutting to determine the stress-free state.

cut manually using a cutting saw, since the heat generated by an auto-cutter can change material microstructures and damage the strain gauge. The relaxed strain values were easily converted to the residual stresses by multiplying by the elastic modulus.

The instrumented indentation tests were performed before and after cutting; schematic diagrams of experimental procedures are shown in Fig. 4. Indentation arrays using a Vickers indenter were made on the polished surface near the cutting line at 5-mm intervals. The testing machine was the Advanced Indentation System™ (Frontics, Inc., Seoul, Korea) and the maximum load and loading–unloading speed were 50 kgf and 0.5 mm/min, respectively. After cutting, indentation tests were also performed at the nearest location (3 mm) from the cut line, the results of which were used as reference or stress-free states. Residual stress is calculated by comparison of two indentation tests before and after cutting. Fig. 5 shows an example of the shape change in the indentation load–depth curve related to the existence of compressive welding residual stress in the base metal regions. Unlike HAZs and weld metal, the base metal has uniform microstructure and thus requires just one stress-free reference sample, so that the indentation curves are directly comparable with each other, as in Fig. 5.

The variations in residual stresses measured by indentation tests are directly compared with those
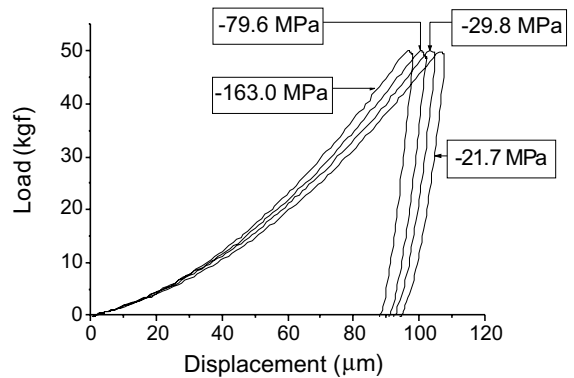

Fig. 5. An example of shape changes in indentation load–depth curves in the base metal regions according to welding residual stresses.

measured by saw-cutting methods in Fig. 6. It was assumed that there was no severe change in residual stress through thickness and no out-of-plane residual stress because the 17.9-mm-thick-specimens were too thin to have them. The results of saw-cutting tests show the distribution of longitudinal residual stresses in both as-welded and annealed specimens. In the as-welded specimen, i.e. the specimen before annealing, the maximum residual stress near the weld centerline is 250 MPa, above the minimum required yield strength (220 MPa) of the A335 P12 steel that is the pipe base metal. The high residual stress disappeared in the annealed specimen, as expected, showing
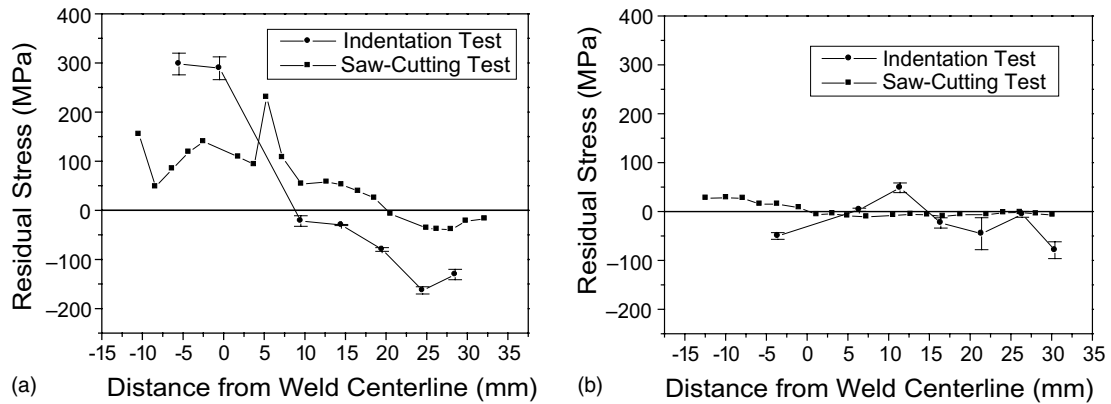
Fig. 6. Direct comparison of residual stresses measured by the indentation technique with those obtained from saw-cutting tests: (a) as-welded specimen and (b) annealed specimen.

that PWHT is very effective in relaxing residual stresses. For the indentation test results, scatter bands of the stress values are indicated instead of a deterministic value of residual stress, since multiple stress values can arise in a multiple loading–unloading indentation test, although the scatter is generally small. The high residual stresses observed in the as-welded specimen were clearly relaxed in the annealed specimen. The reason for the difference in obtained stress values between the indentation test and the saw-cutting test is the difference in the kind of residual stresses measured in the two tests: the stress measured by the indentation technique is affected by both longitudinal (σ_x) and transverse stress (σ_y), which are parallel and perpendicular to the weld line respectively, while residual stresses obtained from saw-cutting tests are longitudinal stress (σ_x) only. Additionally, as elaborated before, the assumption used in load–stress relationship and the contact area calculation without considering pile-up phenomena could partly contribute to the difference. Nevertheless, the differences shown in Fig. 6 is much smaller than ones between any other nondestructive/in-field test for residual stress measurement and a destructive test such as saw-cutting. From all the above results, it can be concluded that the instrumented indentation technique could be an useful in nondestructive evaluation of welding residual stress in industrial facilities.

4. Conclusions

The instrumented indentation technique was applied to the evaluation of welding residual stress in A335 P12 steel welds in fossil power-plant facilities. Comparison with the results of conventional saw-cutting tests showed that the indentation tests could be effectively and easily used for quantitative/nondestructive assessment of welding residual stresses in industrial structures.

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