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Nondestructive Evaluation of Welding Residual Stress in Power Plant Facilities Using Instrumented Indentation Technique

Yeol Choi[1,2,a], Yun Hee Lee[2,b], Jae Il Jang[1,c], Sang Ki Park[3,d],
Kwang Ho Kim[1,e], Yang Won Seo[1,f] and Don Gil Kwon[2,g]

[1]Frontics, Inc. Research Institute of Advanced materials, Seoul National University, Korea
[2]School of Materials Science and Engineering, Seoul National University, Korea
[3]Power Generation Research Lab., Korea Electric Power Research Institute, Korea
[a]ychoi@frontics.com (yariman@snu.ac.kr), [b]uni44@mmrl.snu.ac.kr, [c]jijang@frontics.com,
[d]skpak@kepri.re.kr, [e]khkim@frontics.com, [f]ywseo@frontics.com, [g]dongilk@snu.ac.kr

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Abstract. The weld joints in power-plant pipelines have long been considered important sites for safety and reliability assessment. In particular, the residual stress in pipeline weldments induced by the welding process must be evaluated accurately before and during service. This study reports an indentation technique for evaluating welding residual stress nondestructively. Indentation load-depth curves were found to shift with the magnitude and direction of the residual stress. Nevertheless, contact depths in the stress-free and stressed states were constant at a specific indentation load. This means that residual stress induces additional load to keep contact depth constant at the same load. By taking these phenomena into account, welding residual stress was obtained directly from the indentation load-depth curve. In addition, the results were compared with values from the conventional hole-drilling and saw-cutting methods.

Introduction

Operating conditions for power-plant pipelines are made more severe by their cryogenic contents and many inhomogeneous welded joints. Welded joints are fracture initiation points because of the effects of microstructural and mechanical inhomogeneities [1], and residual stress induced by welding is one of the most important factors in reliability diagnosis. Welding thermal cycles generate inhomogeneous heating and cooling in the regions near the heat source and thus cause residual stress in the weldment, sometimes so large as to surpass the yield strength of the welded material. It is widely recognized that welding residual stresses is detrimental to the performance of the weldment; the tensile-stressed region is particularly harmful because of its susceptibility to fatigue and stress corrosion cracking [2]. Thus the quantitative measurement of welding residual stress is very important for the safe and economical operation of industrial power-plant facilities.

Conventional techniques for measuring or predicting residual stress can be divided into two groups; mechanical stress-relaxation and physical methods. Mechanical stress-relaxation methods, including hole-drilling and saw-cutting techniques, can generally evaluate residual stress quantitatively without any reference sample, but their practical application is limited by their destructive characteristics. Physical methods such as X-ray, neutron diffraction, magnetic Barkhausen noise and ultrasonic methods can analyze residual stress nondestructively. However, they suffer from the difficulty of separating microstructural effects on physical parameters from the effects of residual stress, since all these techniques are highly sensitive to metallurgical factors such as grain size and texture [3]. They thus often show poor reproducibility and large scatter in results compared with mechanical methods. For similar reasons, it is almost impossible to use these nondestructive methods to assess residual stresses in weldments because the heat-affected zones (HAZs) have very rapid microstructural gradients. Hence a new mechanical testing method for residual stress evaluation is needed.

To overcome the limitations of both destructive/mechanical and nondestructive/physical methods, the new nondestructive/mechanical indentation technique described here was developed for the quantitative evaluation of residual stresses in weldments. The instrumented indentation technique, which measures load and depth continuously during indentation and analyzes load-depth curve, has been developed for evaluating hardness, elastic modulus, tensile properties and the like [5, 6]. In this study, we developed the indentation technique for residual stress of materials and evaluated the welding residual stresses of A335 P12, API X65 and SS400 pipelines used in power-plant facilities.

Evaluation of residual stress using advanced indentation technique

Indentation hardness as analyzed from the indentation L-h curve changes with the material residual stress: indentation L-h curves are shifted with the direction and magnitude of residual stress within the tested material. However, the variations in the apparent indentation hardness with change in residual stress have been identified as an artifact of erroneous optical measurements of the indentation imprint [7, 8]: in a study of the influence of in-plane stress on indentation plasticity that investigated both the shape of the indentation curve and the contact impressions, the contact hardness was found to be invariant regardless of the elastically applied stress (residual stress) [7, 8]. The FEA results showed the important role of sink-in or pile-up deformations around the contact in the stressed state in producing the stress-insensitive contact hardness [Bolshakov]. 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 [9].

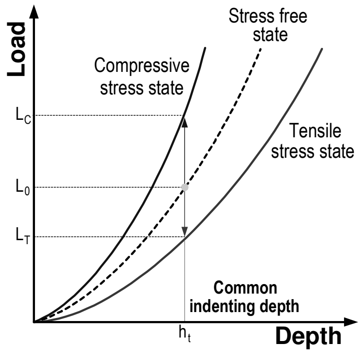


Fig. 1 Variation of indentation loading curves with changes in the stress state [13-15]

The change in indentation deformation caused by the residual stress was identified in the indentation loading curve in Fig. 1. The applied load in the tensile-stressed state is lower than that in the stress-free state for the same maximum indentation depth [7-9]. 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.

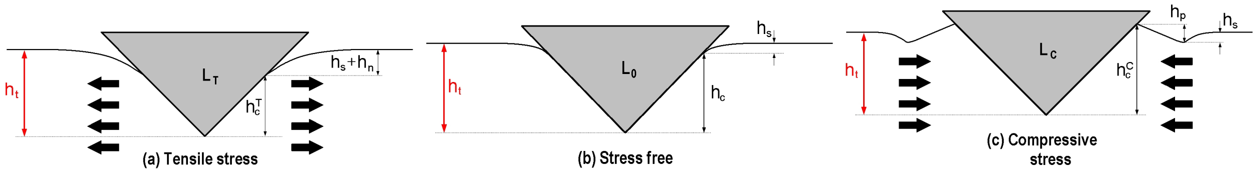


Fig. 2 Theoretical surface morphologies around the contact for
(a) tensile stress, (b) stress-free and (c) compressive stress states

The detailed changes in contact morphology can be seen in the schematic diagram in Fig. 2. The residual stress is relaxed from a tensile-stressed state to stress-free state while maintaining the constant maximum depth, h_t, as the stress relaxation pushes the indenter out from the surface. The pushing force appears 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, the applied load and contact depth decrease by stress relaxation under the maximum-depth-controlled path. Furthermore, this decreasing portion of the applied load was 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 related to the stress directionality of biaxial residual stress. The biaxial stress state, in which $\sigma_y = k\sigma_x$, can be divided into a mean stress term and plastic-deformation-sensitive shear deviator term [10]:

$$\overset{\underline{\text{Biaxial stress}}}{\begin{pmatrix} \sigma^x{}_{res} & 0 & 0 \\ 0 & \sigma^y{}_{res} & 0 \\ 0 & 0 & 0 \end{pmatrix} = \begin{pmatrix} \sigma_{res} & 0 & 0 \\ 0 & k\sigma_{res} & 0 \\ 0 & 0 & 0 \end{pmatrix}} = \overset{\underline{\text{Mean stress}}}{\begin{pmatrix} \frac{(1+k)}{3}\sigma^x{}_{res} & 0 & 0 \\ 0 & \frac{(1+k)}{3}\sigma^x{}_{res} & 0 \\ 0 & 0 & \frac{(1+k)}{3}\sigma^x{}_{res} \end{pmatrix}} + \overset{\underline{\text{Deviator stress}}}{\begin{pmatrix} \frac{(2-k)}{3}\sigma^x{}_{res} & 0 & 0 \\ 0 & \frac{(2-k)}{3}\sigma^x{}_{res} & 0 \\ 0 & 0 & -\frac{(1+k)}{3}\sigma^x{}_{res} \end{pmatrix}} \tag{3}$$

The stress component parallel to the indentation axis in the deviator stress term ($\sigma_{33} = -\frac{(1+k)}{3}\sigma^x{}_{res}$) directly affects the indenting plastic deformation. A residual-stress-induced normal load L_{res} can be defined from the selected deviator stress component as:

$$L_{res} = \frac{(1+k)}{3}\sigma_{res} A_C \, . \tag{4}$$

Therefore, α in Eq. (2) can be taken as approximately 1.5 in the equi-biaxial stress state. In the instrumented indentation test, the contact area is determined by unloading curve analysis. By differentiation of the power-law-fitted unloading curve at maximum indentation depth, the contact depth and contact area A_c can be calculated from the contact depth based on the geometry of the Vickers indenter [5].

$$\mathbf{A_c = 24.5 h_c{}^2} \tag{5}$$

Thus residual stress was calculated from the analyzed contact area in Eq. (4) and the measured load change L_{res} by the effect of residual stress shown in Eq. (1).

Experimental procedures

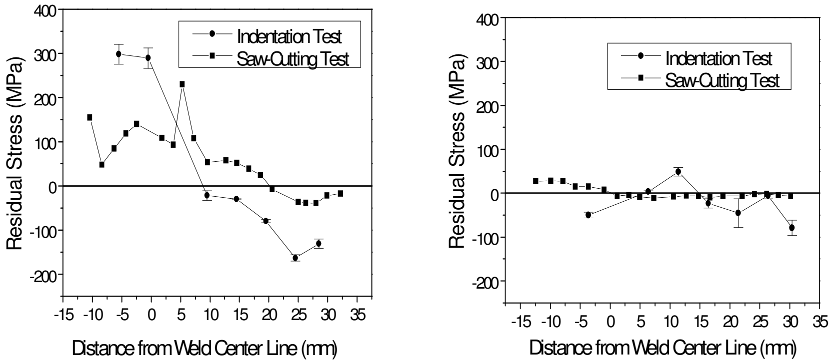
Natural-gas transmission pipe was made by welding API X65 steel pipeline of diameter and thickness 30 in and 17.5mm, respectively. Seam-welded pipes were welded together circumferentially. The chemical compositions of the API X65 base metal are 0.08C-0.019P-1.45Mn-0.003S-0.31Si (wt%). The girth weld joint was made by gas tungsten arc welding (GTAW) and shielded metal arc welding (SMAW) with V-groove configuration. A335 P12 steel was obtained from a girth-weld joint of cold reheater pipeline from a fossil-fuel power plant. It was machined into X-groove configuration and welded by first by GTAW and then by SMAW. Welding was carried out under the same conditions as those used during the construction of the plant facilities. The chemical composition of A335 P12 base metal is 0.08C-0.01P-0.45Mn-0.01S-0.31Si-1.15Cr-0. In addition, no significant defects were found in the completed weldments by X-ray examination. Post-weld heat treatment (PWHT) was conducted on some of the A335 P12 samples for residual stress relaxation, and. test results for these specimens were compared with those from the as-welded specimens.

The indentation testing machine was the Advanced Indentation System 3000^{TM} made by Frontics, Inc. In order to evaluate the reference residual stress in the weldment, two kinds of destructive tests, saw-cutting and hole-drilling, were performed to validate the advanced indentation method. To measure the distribution of the longitudinal residual stress with the saw-cutting and hole-drilling techniques, strain gauges were attached along the distance from weld centerline to measure the relaxed residual stress during cutting or drilling. Signals from strain gauges were obtained from a multichannel amplifier. The relaxed strain values were easily converted to residual stress by multiplying by the elastic modulus. The indentation tests were performed before and after cutting. Indentation arrays using Vickers indenter were made on the polished surface near the cutting line at 5-mm intervals. Maximum load and loading-unloading speed were 50kgf and 0.5mm/min, respectively.

Experimental result and discussions

Fig. 3 summarizes the results of saw-cutting tests and the indentation technique and shows the distribution of longitudinal residual stresses of the PWHT and as-welded specimens. The saw-cutting tests show that the maximum residual stress existing near the weld centerline in the as-welded specimen (before PWHT) is up to 250MPa, which is above the minimum required yield strength (220MPa) of the A335 P12 base metal of the pipe. The high residual stress disappeared in PWHT specimen, as expected, confirming that post-weld heat treatment is very effective in relaxing residual stresses.

The variation in residual stress measured by indentation tests is also shown in Fig. 3. The variation tendencies of residual stresses are similar to those in saw-cutting tests. The high residual stresses observed in as-welded specimen were clearly relaxed.

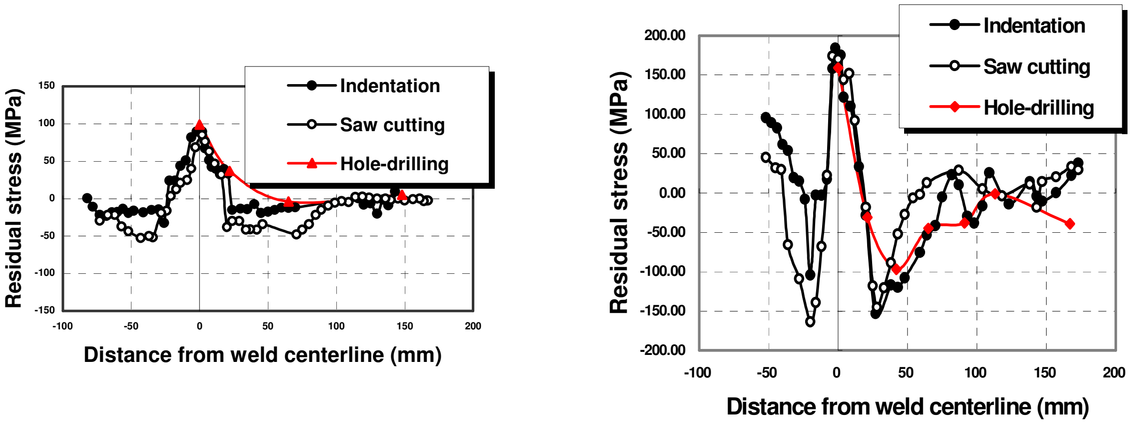


(a) (b)

Fig. 3 Comparison of residual stresses measured by indentation technique with those obtained from saw-cutting tests: (a) as-welded specimen (before PWHT) and (b) PWHT specimen.

There was a small difference between residual stresses measured by the indentation test and those measured by the saw-cutting test that arises from the different kinds of residual stresses measured in each test. The stress measured by the indentation technique was obtained based on the assumption of equi-biaxial stress of both longitudinal and transverse stress, while the residual stresses obtained from the saw-cutting tests are purely longitudinal stress.

The welding residual stresses were obtained in the welded API X65 and SS400 pipelines using indentation, saw-cutting and hole-drilling methods. Here, the stress-free states were predicted from the flow stress ratio (which is independent of residual stress) of the weld metal or HAZ to base metal remote from weld-affected zone. In addition, the stress directionality factor k was pre-determined and non-equi-biaxial stress states could be considered. More detail on these procedures will be given in a later study. The results are shown in Fig. 4. The indentation results agree well with both kinds of reference test results. In particular, the most important tensile residual stresses in weld metal were almost identical in all tests. The above results show that the advanced indentation technique can be applied to nondestructive evaluation of residual welding stresses in industrial facility piping.



(a) (b)

Fig. 4 Direct comparison of residual stresses measured by indentation technique with those obtained from saw-cutting and hole drilling tests; (a) SS400 and (b) API X65

Summary

Welding residual stresses were evaluated by the instrumented indentation technique based on the invariance of contact hardness regardless of residual stress, despite the shift in the indentation loading curve with residual stress. The modeling of contact morphology and stress decomposition under a rigid indenter can explain the quantitative relation of residual stress and indentation load. To verify the indentation technique, welding residual stresses in A335 P12, API X65 and SS400 welded pipeline were evaluated and compared with reference saw-cutting and hole-drilling tests. Good agreement was found between the instrumented indentation and reference tests.

Acknowledgments

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