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Residual Stress Evaluation for Weldment of Structural Components Using Instrumented Indentation Technique

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We suggest a new instrumented indentation technique for estimating residual stress in weldments. This technique is based on the key concepts that the deviatoric stress part of the residual stress changes the indentation load-depth curve, and that through analysis of the difference between the residual stress-induced indentation curve and residual stress-free curve, the quantitative residual stress of the target region can be evaluated. To verify the applicability of the suggested technique, indentation tests and conventional tests were performed on natural gas pipeline weldments. The estimated residual stress values obtained using the indentation technique showed good agreement with those from conventional tests.

INTRODUCTION

Residual stresses caused by inhomogeneous thermal and mechanical loads during welding affect subsequent fracture and fatigue behaviour, stress-corrosion cracking and the like (Lu et al., 1996; Ruud et al., 1985). Thus the quantitative measurement of welding residual stress is important for the safe use and economical maintenance of industrial structures and facilities. Over the last few decades, a number of nondestructive methods has been developed, such as X-ray diffraction, the ultrasonic method, Barkhausen noise and neutron diffraction; these are based on the relationship between the physical or crystallographic parameters and the residual stress (Lu et al., 1996). Since the stress-sensitive parameters are, however, highly sensitive to metallurgical factors as well, applying these techniques to welded joints with rapid microstructural gradients is very difficult.

Thus an indentation technique, causing nearly nondestructive contact and being insensitive to environmental interferences, has been suggested for application in this research field (Sines and Carlson, 1952). However, the initial challenge was somewhat unsuccessful and pointless, because the alteration in hardness caused by the residual stress was less than 10% of its unstressed value. Recently, an instrumented indentation technique (IIT) that measures continuous deformation behaviour beneath an indenter as a curve of indentation load versus indenter penetration depth has been highlighted as an alternative to conventional mechanical tests (Doerner and Nix, 1986; Oliver and Pharr, 1992; Lee and Kwon, 1999; Ahn and Kwon, 2001; ISO—International Organization for Standardization—14577; KS—Korean Standards—B 0950). This technique has many advantages, such as good data reproducibility, feasibility for in-field applications, simplicity of testing procedure, and nondestructiveness. It has been used to evaluate various mechanical properties such as hardness, elastic modulus (Doerner and Nix, 1986; Oliver and Pharr, 1992), yield strength, tensile strength, work-hardening index (Ahn and Kwon, 2001) and fracture toughness (Lee and Kwon, 1999); analysis procedures for plastic stress-strain response and hardness are currently being standardized (ISO 1457; KS B 0950).

The stress sensitivity of the instrumented indentation curve and the application potential of this technique have been recognized by several researchers (LaFontaine et al., 1991; Zagrebelny and Carter, 1997).

However, most indentation studies for measuring stress have been tentative and somewhat empirical. Tsui et al. (1996) studied the influence of in-plane stress on indentation plasticity by investigating both the shape of the indentation curve and the remnant contact impressions. They reported that hardness was invariant regardless of the applied stress, and this was supported by subsequent finite element analysis (Bolshakov et al., 1996). Suresh and Giannakopoulos (1998) developed a theoretical model deriving a stress value from the ratio in the contact area of stressed and unstressed materials by separating out a plastic-deformation-related differential stress. However, hydrostatic stress still remained part of the differential contact stress, and the necessity of contact area observation for each indentation lessens the convenience of instrumented indentation. Thus, Lee and Kwon (2003) developed another instrumented indentation model that quantified the residual stress by analyzing the effect of surface stress on contact pressure in terms of shear plasticity. However, current theoretical models are difficult to apply to a general biaxial stress state because of their fundamental assumption of a simple equibiaxial stress state.

This study adapts Lee and Kwon's stress model to a general biaxial stress state and uses this model to characterize a friction stir-welded API X80 steel by suggesting proper assumptions for the stress directionality and reference stress-free information. The residual stresses estimated are compared with those from an energy-dispersive X-ray diffraction technique. In addition, the

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KEY WORDS: Instrumented indentation, residual stress, friction stir welding, API X80 steel, stress directionality, energy dispersive X-ray diffraction.