Through-Thickness Measurements of Residual Stresses in an Overlay Dissimilar Weld Pipe using Neutron Diffraction

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1. Introduction

The distribution of residual stresses in dissimilar material joints has been extensively studied because of the wide applications of the dissimilar welds in many inevitable complex design structures [1-3]. Especially the cracking of dissimilar welding has been a long standing issue of importance in many components of the power generation industries such as nuclear power plant, boiling pressure system, and steam generators [4]. In particular, several failure analysis and direct observations have shown that critical fractures have frequently occurred in one side of the dissimilar welded parts. For example, the heat-affected zone on the ferrite steel side is known to critical in many dissimilar welding pipes when ferrite (low carbon steel) and austenite (stainless) steels are joined [5]. The main cause of the residual stresses can be attributed to the mismatch in the coefficient of thermal expansion between the dissimilar metals (ferrite and austenite). Additional cladding over circumferential welds is known to reinforce the mechanical property due to the beneficial compressive residual stress imposed on the weld and heat-affected zone. However, science-based quantitative measurement of the through thickness residual stress distribution is very limited in literature.

The deep penetration capability of neutrons into most metallic materials makes neutron diffraction a powerful tool to investigate and map the residual stresses of materials throughout the thickness and across the weld [3]. Furthermore, the unique volume-averaged bulk characteristic of materials and mapping capability in three dimensions are suitable for the engineering purpose. Thus, the neutron-diffraction measurement method has been selected as the most useful method for the study of the residual stresses in various dissimilar metal welded structures.

The purpose of this study is to measure the distribution of the residual stresses in a complex dissimilar joining with overlay in the weld pipe. Specifically, we measured the macroscopic residual stresses as a function of distance along the weld centerline in the dissimilar weld pipe with an overlay. The current study is directly related to the life extension of existing nuclear plants around the world where related dissimilar metal welds exist joining the ferritic carbon steel pressure vessel nozzles to the austenitic stainless steel primary water piping.

2. Methods and Results

2.1 Sample preparation

The specimen was prepared to examine the residual stress distribution through the thickness of the dissimilar overlay weld pipe. The pipe specimen is shown in Fig. 1.
The number of passes at the dissimilar metal weld is 19. The heat input of the welding condition was in the range of 8~14 kJ/mm. Figure 2 shows the schematic of the pipe specimen. The edge of the SA508 nozzle became the buttering by Alloy 182. The SA508 nozzle and SA182 safe end were welded by the filler metal. The material of the filler and the buttering was Alloy 182 as marked in Fig. 2. The size of the groove bottom of the dissimilar metal weld and the buttering was 5.34 mm and 6.57 mm, respectively.

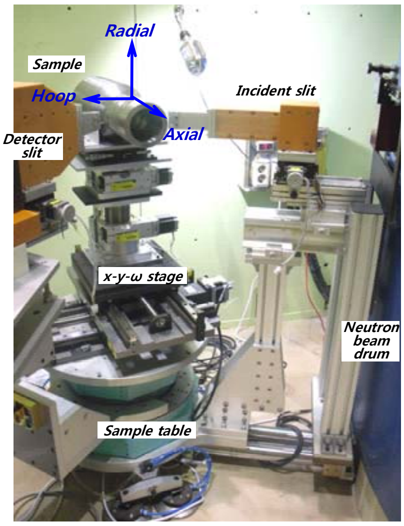

Fig. 1. Experimental set up for neutron diffraction

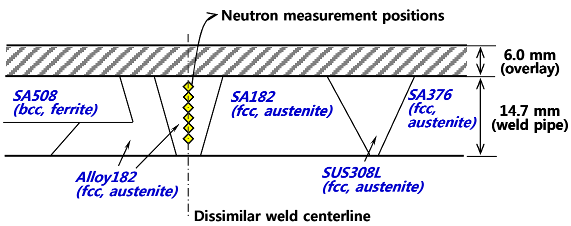

Fig. 2. Schematic of the weld overlay specimen

2.2 Neutron diffraction measurements of residual stresses

Neutron diffraction has been well established for the measurements of residual stresses in a wide range of engineering components [1,3]. The deep penetration capability of neutrons into most metallic materials makes neutron diffraction a powerful tool for measuring residual stresses in welds. The residual stress measurements were performed on the Residual Stress Instrument (RSI) at HANARO (High-flux Advanced Neutron Application ReactOr), KAERI (Korea Atomic Energy Research Institute), Fig. 1.

In this study, the specific locations for the residual stress measurements are 2, 4, 6, 8, 10, and 12 mm from the top surface of the dissimilar metal weld through the thickness of the pipe, Fig. 2. The incident neutron had a wavelength of 2.40 Å. The scattering volume was 2 x 2 x 20 mm^3 (for axial and radial components) and 2 x 2 x 8 mm^3 (for hoop component) that were defined by a pair of incident and detector slits. Neutron diffraction peak of (111) diffracted from the fcc austenite with the diffraction angle of 70° (2θ) was used for the calculation of the lattice strain. Note that the each peak obtained from each measurement position was analyzed using the least squares Gaussian fitting method.

In the neutron diffraction measurements of residual stresses, it is necessary to measure the d-spacings with their scattering vectors parallel to the three principal orientations of the pipe specimen, i.e., axial, hoop, and radial directions, Fig. 1, and determine the elastic lattice strains and stresses based on the Hooke's law. Details were describes in elsewhere [3,6]. In brief, the elastic lattice strain (ε) in a particular direction is calculated in terms of the deviation in the lattice spacing (d) relative to the unstrained (stress-free) lattice spacing (d_o):

$$\varepsilon = (d - d_o)/d_o = -\cot(\theta)\Delta(\theta_o - \theta) \text{ -------- (1)}$$

Generally, Hooke's law is used to convert elastic strain to the principal residual stresses (σ_x, σ_y, σ_z):

$$\sigma_i = \frac{E_{hkl}}{1+\nu_{hkl}}\left[\varepsilon_{ii} + \frac{\nu_{hkl}}{1-2\nu_{hkl}}(\varepsilon_{xx}+\varepsilon_{yy}+\varepsilon_{zz})\right] \text{ ---- (2)}$$

where i = x, y, or z corresponding to the three principal directions, respectively. The quantities of E_{hkl} and ν_{hkl} are the plane-specific analogues of Young's modulus and Poisson's ratio, respectively. The diffraction elastic constants (E_{111}) of 248 GPa and Poissons ratio (ν_{111}) of 0.24 were adopted in literature [3]. The unstrained lattice parameter (d_o) is required for the standard state as a reference. It should be mentioned that the current results were calculated using the "stress-free" do measured at a comb-like specimen, which has been taken from the dissimilar metal weld pipe. The do specimen was cut at the 120° rotated location from the weld centerline, Fig. 2, due to the concern of the stress release of the main pipe specimen.

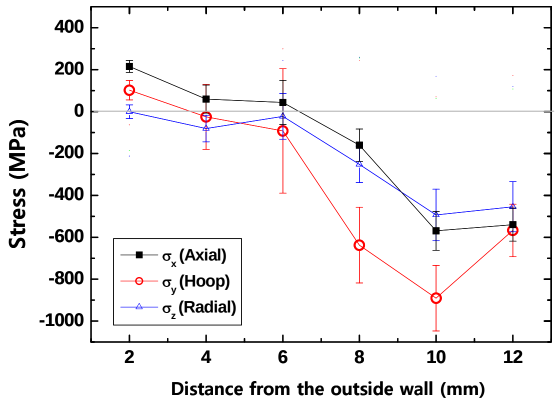

Fig. 3. Residual stress distribution through the thickness of the overlay weld pipe.

2.3 Through-thickness variations of the residual stresses

Figure 5 shows the results of the neutron diffraction measurements. The axial stress (σ_y) is the stress in the axial direction of the pipe and hoop stress (σ_y) is the stress in the circumference direction of the pipe, Fig. 1. The stress values of the experimental measurement (axial and hoop stress) are significantly decreased as increases of the distance from outside wall.

3. Conclusions

In summary, we have measured the residual stresses through the thickness of the dissimilar overlay weld pipe. The result shows that the compressive stress over 600 MPa up to 800 MPa was developed at the 6 to 8 mm distance from the pipe outer surface (11 ~ 13 mm from the overlay surface). It confirms the previous studies and understandings on the stress signs and magnitudes in the overlay dissimilar metal welds based on the several computational calculations and hole drilling method. The results can subsequently be used to test models for the effect of the weld overlay as well as to use that information in understanding possible cracking modes in structures with such welds.

REFERENCES

[1] P. J. Withers and H. K. D. H. Bhadeshia: Mater. Sci. Tech., 2001, 17, 366-375.
[2] K. Masubuchi: 'Analysis of Welded Structures', 1st edn; 1980, New York, Pergamon.
[3] M. T. Hutchings, P. J. Withers, T. M. Holden and T. Lorentzen: 'Introduction to the Characterization of Residual Stress by Neutron Diffraction', 1st edn; 2005, London, Taylor and Francis.
[4] H. P. Seifert, S. Ritter, T. Shoji, Q. J. Peng, Y. Takeda and Z. P. Lu: J. Nuclear Mater., 2008, 378, 197-210.
[5] A. Josep, S. K. Rai, T. Jayakumar and N. Murugan: Inter. J. Press. Vess. Piping, 2005, 82, 700-705.
[6] W. Woo, H. Choo, D.W. Brown, Z. Feng, P.K. Liaw, Mater. Sic. Eng. A 437 (2006) 64.