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Residual stress determination in a dissimilar weld overlay pipe by neutron diffraction

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ABSTRACT

Residual stresses were determined through the thickness of a dissimilar weld overlay pipe using neutron diffraction. The specimen has a complex joining structure consisting of a ferritic steel (SA508), austenitic steel (F316L), Ni-based consumable (Alloy 182), and overlay of Ni-base superalloy (Alloy 52M). It simulates pressurized nozzle components, which have been a critical issue under the severe crack condition of nuclear power reactors. Two neutron diffractometers with different spatial resolutions have been utilized on the identical specimen for comparison. The macroscopic 'stress-free' lattice spacing (d_o) was also obtained from both using a 2-mm width comb-like coupon. The results show significant changes in residual stresses from tension (300–400 MPa) to compression (−600 MPa) through the thickness of the dissimilar weld overlay pipe specimen.

1. Introduction

Many of the penetration nozzle components and piping systems in the nuclear power plants include dissimilar metal welds [1,2]. The dissimilar metal joining structure, for example, typically connects the ferritic carbon steel (SA508) and austenitic stainless steel (316L) in the pressurized water reactors (PWR) [3–5]. The two dissimilar metals have been usually joined by using a Ni-based alloy welding consumable (Alloy 82 or 182). Recently, serious cracking has been reported in several dissimilar metal joining structures mainly due to primary water stress corrosion cracking (PWSCC) [6,7]. The transition zone of the dissimilar metal weld is known to have a high susceptibility to PWSCC and it often becomes a preferred crack growth path in the nuclear reactor piping systems [4]. Thus, there are significant concerns with regard to the safety and integrity of the dissimilar welding components for the various penetration nozzles and pressurized pipes in nuclear power plant applications.

It has been suggested that residual stresses in welds have a significant contribution to the PWSCC and fatigue crack growth rate combined with the applied loading and degrades material properties under extreme operating conditions [8–11]. In particular, tensile residual stress is known to be critical to increase the potential risk of initiating PWSCC. Moreover, the residual stress profile through the thickness of the pipe can influence the stress intensity factor, which is directly related to the crack growth rate in the perspective of the fatigue and fracture engineering [10]. Thus, safety in design and structural integrity assessment requires an accurate determination of the residual stresses in the welding components under the corrosive, pressurized operating environments.

A number of studies have been extensively performed to understand the correlation between PWSCC and residual stresses in the dissimilar welds of the penetration nozzles. Examples include microstructure and mechanical property studies on the PWSCC [10–12], computational simulations [13–17], and destructive/non-destructive measurements [18–20] of the residual stresses in the dissimilar welds. Deng et al. reported that the axial component of the residual stress reaches about 120 and 200 MPa based on the finite element modeling and strain gauge measurements, respectively, at the inner wall of a dissimilar welded pipe between the low alloy steel and stainless steel 316L with Alloy 82 consumables [17]. Recently, overlay processing has been highlighted as an optimistic method to moderate the stress distribution in the dissimilar weld and the probability of the PWSCC [21–24]. Song et al. simulated the residual stress distribution through the thickness of the overlaid pressurized nozzle in the reactor system and presented that the compressive hoop stress decreases to about −400 MPa in the inner pipe wall as the number of the layers increase [24]. At this

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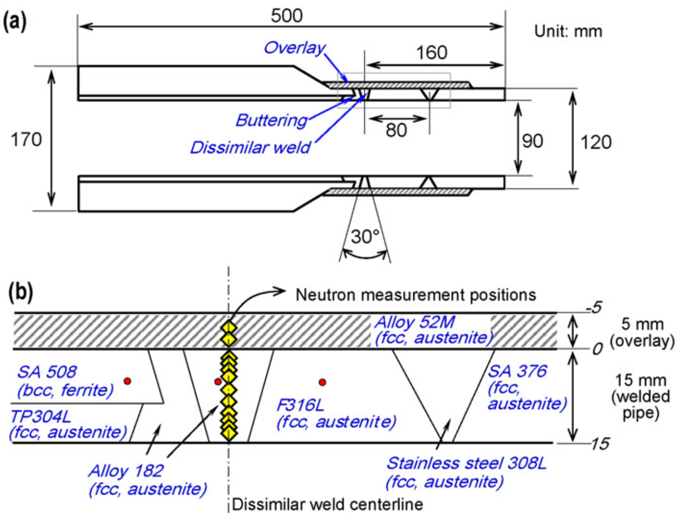

Fig. 1. (a) Schematic of the dissimilar weld overlay pipe specimen, (b) measurement locations of the specimen in the neutron-diffraction experiments.

moment, it is important to measure the distribution of the residual stresses through the thickness of the dissimilar weld overlay pipe, which has been studied to prevent the high potential for severe circumferential cracks in nuclear power reactors.

In this paper, we determined the through-thickness distribution of the residual stresses in the dissimilar welded pipe and compared to its overlay structure using neutron diffraction. Specifically, the residual stresses were measured along the weld centerline (Alloy 182) from the outer surface toward the inner wall of the pipe specimen, which connects the ferritic steel (SA 508) and austenitic steel (F316L). Finally, the integrity of the inner pipe wall was investigated in the dissimilar weld overlay pipe component.

2. Experimental details

Two kinds of specimens were prepared to examine the distribution of residual stresses through the thickness of the pipes. One is the dissimilar welded pipe and the other one is an overlay pipe, which is reinforced on the outer surface of the dissimilar welded pipe. The schematic of the pipe specimen is shown in Fig. 1(a). It simulates the nozzle joining component of the nuclear power plants. The total length of the pipe was 500 mm, and the diameters of the inner and outer pipe were about 90 and 120 mm, respectively. Fig. 1(b) shows the schematic of the specimen in detail. The dissimilar joint consists of the bcc ferritic steel (SA508 Gr.3C.1) and fcc austenitic steel (F316L) combined with the Ni-based welding consumable (Alloy 182). Another dissimilar welded pipe specimen was prepared with the same dimension and welding parameters, and it was overlaid with a 5-mm thick layer of the Ni-base superalloy (Alloy 52M) onto the outer surface of the 15-mm thick dissimilar welded pipe. Note that the edge of the SA 508 nozzle was buttered by Alloy 182, Fig. 1(b). The size of the groove bottom of the dissimilar weld and the buttering was about 5.3 mm and 6.5 mm, respectively.

The nominal chemical compositions of each metal part in the specimen are summarized in Table 1. A number of passes of the gas tungsten arc welding (GTAW) and the shield metal arc welding (SMAW) were performed to join the dissimilar metal parts. The welding parameters were in the range of 120–130 A, 10–12 V, 9–10 cm/min (GTAW) and 120–140 A, 21–26 V, 13–16 cm/min (SMAW). Three layers of about 18 passes in each layer created the overlay, which covers a wide region of the dissimilar welded pipe as shown in Fig. 1(a).

Microstructure was investigated at the cross-section of the weld specimen using an optical microscope, Fig. 2. The samples were cold-mounted, ground, polished, and etched by using 3% natal solution for SA 508, electrolytic etching for Alloy 182, and Kalling's reagent for F316L. At the mid-thickness of the pipe (marked locations in Fig. 1b), microstructure of the SA508 shows typical tempered bainite, Fig. 2(a), the Alloy 182 shows a fully austenite structure, Fig. 2(b), and the F316L exhibits equiaxed austenitic grains with delta ferrite, Fig. 2(c) [12]. Note that the average grain size of the Alloy 182 was about 200 μm by the linear intercept method.

3. Neutron diffraction

3.1. Measurement details

Neutron diffraction has become a well-established method to determine the residual stresses in a wide range of engineering structure components [25,26]. It has benefits such as the deep-penetration, three-dimensional mapping, and volume-averaged bulk measurement capabilities. These characteristics make neutron diffraction to be a powerful tool for the measurements of residual stresses at depth in welds [27]. Relatively small beam gauge volume ($\sim$1 mm^3) may not represent an enough volume averaged value in a large grained specimen and also require long count times due to the limited flux, while large gauge volume ($\sim$100 mm^3) can neglect a steep gradient of stress fields within the gauge volume. Thus, we applied two different spatial resolutions for the current study; Mode (1) high spatial resolution (1 mm of beam size) and Mode (2) relatively low spatial resolution (3 or 4 mm of beam size). Under the same measurement time, mode 1 inherently causes larger errors than mode 2, but mode 1 can obtain more numbers of data close to the material surface than mode 2 [25]. Furthermore, two neutron diffractometers have been utilized for duplicate measurements due to critical importance of validation. The Residual Stress Instrument (RSI) at High-flux Advanced Neutron Application Reactor of Korea Atomic Energy Research Institute was applied for the mode 1, Fig. 3(a) [28]. The Neutron Residual Stress Mapping Facility (NRSF2) at the High Flux Isotope Reactor of Oak Ridge National Laboratory was used for the mode 2, Fig. 3(b) [29].

In the neutron diffraction measurements of residual stresses, it is necessary to measure the interplanar spacings (d) with their scattering vectors parallel to the three orthogonal orientations of the pipe specimen, i.e., axial, hoop, and radial directions, as shown in Fig. 3(a). The specific locations for the residual stress measurements are −3, −1 (overlay part), 1, 2, 3, 4, 6, 8, 10, 12, 13, and 14 mm (dissimilar weld part) marked in Fig. 1(b). Note that the outer surface of the dissimilar welded pipe was named as 0 mm. For the RSI experiments (mode 1), the incident neutrons have a wavelength (λ) of 1.46 Å, and the diffraction angle (2θ) was 84.6° for the (3 1 1) reflection from the fcc austenitic Alloy 182. The scattering volume was 1 mm × 1 mm × 20 mm for the axial and radial components and 1 mm × 1 mm × 8 mm for the hoop component, which were defined by a pair of incident and detector slits. Both components retained 1-mm spatial resolution along the thickness direction (radial direction), Fig. 1(b). The ±3° oscillations of the diffraction vector (Q) can provide the sufficient intensities for the peak fitting and lessen the issues of the grain size and texture in welds [25]. It should be noted that "a window" was cut in the side wall of the pipe specimens in order to decrease the total beam path length for the set up of the hoop component. The size of the window was about 30 mm in height along the axial direction and 70 mm in width along the hoop direction. It was taken at about 140 degree rotated location from the measurement location along the axis of the axial direction.

For the NRSF2 experiments (mode 2), the applied scattering volumes were 3 mm × 3 mm × 3 mm in the dissimilar welded pipe