In-situ Residual Stress Analysis during Thermal Cycle of a Dissimilar Weld Joint Using Neutron Diffraction and IEFEM*

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Residual stress is one of important issues for optimizing the manufacturing process and ensuring the structural integrity of welded components. Many results on the issue have been reported, however, the residual stress relaxation mechanism of dissimilar weld joint by the thermal cycle is not yet enough clarified. In this study, the residual stress evolution process of a dissimilar weld joint during thermal cycle was investigated using in-situ neutron diffraction technique and the Idealized Explicit Finite Element Method (IEFEM). The base materials of the dissimilar weld specimen were a SUS316L stainless steel and a NCF600 nickel alloy. The obtained results clearly show that the residual stress especially in the NCF600 side decreased in the first thermal cycle due to yielding of the NCF600. This yielding was caused by an estimation that the total stress, which is the sum of the initial welding residual stress and the thermal stress, exceeded the yield strength of NCF600 during the heating process.

Key Words: Dissimilar weld, Residual stress, Thermal stress, Thermal cycle, In-situ neutron diffraction, Nondestructive stress measurement, IEFEM, Mechanical relaxation

1. Introduction

Dissimilar metal weld joints are widely used in industrial applications especially in power plant structures. A complex stress state can be generated in the dissimilar weld joint during operation due to the superposition of welding residual stresses, the stresses caused by external forces and temperature changes, and sometimes peening residual stresses for preventing stress corrosion cracking. Stress states strongly affect on the initiation and propagation of stress corrosion cracking and fatigue cracking, therefore, assessments of structural integrity should take into account the stress state during operation. There are many reports about the residual stress of dissimilar weld joints [1-3]; however, the residual stress relaxation mechanism at relatively low temperatures, for example, 593 K, which corresponds to the operating temperature of pressurized water reactors, has not yet enough clarified.

Residual stresses are in an equilibrium state that balances the compressive residual stresses with tensile residual stresses in a component. Therefore, in-depth profiles of residual stress should be examined to clarify the residual stress evolution process. The in-depth profiles of stress/strain in bulk materials can be measured nondestructively by the neutron diffraction method because of the large penetration depth of neutrons. A residual stress map in a whole section of a steel plate with 50 mm thickness can be obtained nondestructively using neutron diffraction [4].

In this study, the residual stress behavior under thermal cycle of a dissimilar weld joint was investigated using the neutron

diffraction method and the Idealized Explicit Finite Element Method (IEFEM) [5]. The residual stress relaxation process in the thermal cycle is discussed based on the experimental and analytical results.

2. Experimental procedure

2.1 Specimens

Materials of base plates were a stainless steel JIS SUS316L and a nickel base alloy JIS NCF600, and weld metal was a nickel base alloy Alloy82. The base plates were heat-treated after machining at 1173 K for 3.6 ks to relieve machine induced residual stresses [6]. A dissimilar welded plate with the size of $100 \times 100 \times 10$ mm³ were prepared by a multi-pass Tungsten Inert Gas welding (TIG) process. Nine passes were applied with the welding condition shown in Table 1. After the welding, the excess weld metal and the bottom part with the thickness of 2 mm were removed by machining and then the ultrasonic shot peening was applied on the specimen surface to simulate actual components. Table 2 shows the material properties of each material at 593 K corresponding to the maximum temperature in the thermal cycle in this study [7].

2.2 Residual stress measurements by neutron diffraction

Neutron diffraction experiments were performed to determine residual stresses inside specimens nondestructively according to the ISO standard [8]. The neutron diffraction technique is based on the Bragg's law shown in Eq. (1).

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Table 1 Welding conditions.

Pass	Current (A)	Voltage (V)	Welding speed (mm/s)	Wire feeding speed (g/s)
1	100	10	1.5	0
2	100	10	1.5	0.06
3	120	10	1.5	0.09
4	150	10	1.5	0.14
5	150	10	1.5	0.14
6	150	10	1.5	0.14
7	150	10	1.5	0.14
8	170	10	1.5	0.14
9	170	10	1.5	0.14

Table 2 Material properties at 593 K [7].

Material	Coefficient of linear expansion ($\times 10^{-6} \text{ K}^{-1}$)	0.2% yield stress (MPa)
NCF600	13.7	350
Alloy82	14.7	426
SUS316L	17.1	168

Fig. 1 Experiment layout for the in-situ neutron stress measurement at TAKUMI in J-PARC.

Fig. 2 Section surface of the specimen. In-situ stress measurements were conducted at the depth of 4.2 mm from the top surface.

$$\lambda = 2d^{hkl} \sin \theta^{hkl} \quad (1)$$

where λ is the wavelength, d^{hkl} is the lattice spacing of hkl diffraction plane, θ^{hkl} is the Bragg scattering angle. From eq. (1), the lattice spacing d^{hkl} can be determined by measuring the θ^{hkl} in the angle dispersive (AD) method, or by measuring the λ in the time-of-flight (TOF) method. And then, an elastic lattice strain, ε , is calculated by following equation:

$$\varepsilon = \frac{d^{hkl} - d_0^{hkl}}{d_0^{hkl}} \quad (2)$$

where d_0^{hkl} is the stress-free lattice spacing. Residual stress components are calculated by substituting the measured strains into stress-strain relationships in the elastic mechanics.

Residual stress 2D maps in the cross section of the specimen before and after the thermal cycle (593 K, 120 min.) were measured at room temperature using the neutron strain scanner KOWARI with the AD method in OPAL reactor of the Australian Nuclear Science and Technology Organisation. Residual stress mappings before and after the thermal cycle were performed on the same specimen. Diffraction measurements were made on the 311 diffraction of Ni or γ -Fe phase with a monochromatic neutron beam ($\lambda = 0.1523 \text{ nm}$) at a 2θ angle of about 90° . The gage volumes were $1 \times 1 \times 1 \text{ mm}^3$ for the x -direction and $1 \times 1 \times 27 \text{ mm}^3$ for the y -direction. Totally 250 points were scanned in the area of $\pm 20 \text{ mm}$ from the weld center of the whole thickness of the specimen.

In-situ residual stress measurements inside the sample during the thermal cycle (291 K $\rightarrow$ 373 K $\rightarrow$ 473 K $\rightarrow$ 593 K $\rightarrow$ 423 K $\rightarrow$ 296 K) were performed using the neutron engineering diffractometer TAKUMI with the TOF method in the Materials and Life Science Experimental Facility of Japan Proton Accelerator Research Complex (J-PARC). The specimen mounted on the heating chamber was set on the sample stage of TAKUMI oriented 45 degree to the incident beam as shown in Fig. 1. In-situ stress measurements were conducted at the depth of 4.2 mm from the top surface with the gage volume of $2 \times 2 \times 2 \text{ mm}^3$ as shown in Fig. 2. The average lattice constant in a measured direction was determined by a Rietveld refinement software, Z-Rietveld [9], and was used subsequently for the determination of the residual stress.

2.3 FEM analysis

Figure 3 shows the 3D FE analysis model of the welded plate. Residual stress behaviors during the multi-pass welding process and the thermal cycle were analyzed by the IEFEM method as a three-dimensional multi-pass moving heat source problem. The analysis model is meshed with hexahedral elements and the number of nodes and elements are 139,791 and 116,300, respectively. The minimum mesh size was 0.4 mm. The temperature dependent material properties assumed in this analysis are shown in Figs. 4 (a)-(c) [7]. The isotropic hardening is employed as a work hardening rule. The computer employed in this analysis has an Intel Core i7 3.2 GHz processor CPU, 64GB of memory and NVIDIA GeForce GTX 980 GPU.

3. Result and discussion

3.1 Experimental results

Fig. 3 3D analysis model of the multi-pass welded joint.

Figure 5 (a) and (b) show the residual stress distributions before and after the thermal cycle, respectively. Tensile residual stresses are observed near the weld metal in Fig. 5 (a), and are relatively high at around 4.2 mm in depth from the top surface. The tensile residual stresses decrease by the thermal cycle especially in the NCF600 side as shown in Fig. 5 (b). To clarify the reason for reduction of the tensile residual stress, the in-situ residual stress measurements were performed at the depth of 4.2 mm.

The residual stress distributions at RT, 593 K, and RT after 593 K are shown in Fig. 6. In the nickel side which contains the NCF600 base plate and the weld metal Alloy82, the tensile residual stress increases at 593 K and then decreases in the cooling process. On the other hand, the residual stress behavior in the SUS316L side shows completely opposite trend, i.e. the residual stress decreases with increasing temperature and increases in the cooling process. This behavior can be explained by the difference in linear expansion coefficients of materials. The linear expansion coefficient of the nickel alloy materials (NCF600 and Alloy82) is smaller than that of SUS316L as shown in Table 1. Consequently, the nickel side was stretched by the SUS316L side in the heating process, and oppositely the SUS316L side was compressed by the nickel side. The residual stress after 593K is about 50 MPa lower in comparison with the initial value in the nickel side, while the relaxation of residual stress is about 20 MPa or less in the SUS316L side.

Figures 7 (a) and (b) show the residual stress behaviors during the first and second thermal cycles at the NCF600 side ($y = -4$ mm) and the SUS316L side ($y = 7$ mm), respectively. In the heating process, the tensile residual stress increases in the NCF600 side, while decreases in the SUS316L side. Black symbols in the Figs.

(a) NCF600

(b) SUS316L

(c) Alloy82

Fig. 4 Temperature dependent material properties used in the FE analysis [7].

7 (a) and (b) indicate the yield strengths of NCF600 and SUS316L [7], respectively. The tensile residual stress in the NCF600 side (Fig. 7 (a)) increases with increasing temperature, while the yield strength decrease. The tensile residual stress exceeds the yield strength when the temperature is around 370 K in the first heating process. This condition may cause the NCF600 to yield and plastically deform, and generate the redistribution of residual stress due to the stress relaxation. On the other hand, the residual stress in the SUS316L side is already higher than the

Fig. 5 Residual stress distributions measured before (a) and after (b) thermal cycle. The direction of residual stress is in x-direction. Dotted lines in the figure mean the interface between weld metal and base plate.

yield strength at room temperature (Fig. 7 (b)). The residual stress, however, decreases with increasing temperature being in parallel tendency of decreasing yield strength. This condition may affect no residual stress relaxation.

3.2 IEFEM results

Figure 8 shows the IEFEM results about the residual stress distribution variations during the thermal cycle. The initial residual stresses near the weld bead are about 550 MPa for the NCF600 and 450 MPa for the SUS316L. These values almost coincide with the experimental values, which are about 400 and 370 MPa, respectively. The residual stresses at 593 K in the NCF600 are higher than that of the initial residual stress except for the point of $y = -4.5$, while that in the SUS316L side are lower than the initial residual stress. The analyzed residual stress behaviors during the thermal cycle at $y = -5$ mm (NCF600 side) and 7 mm (SUS316L side) are shown in Fig. 9. The residual stress in the NCF600 increases with increasing temperature. On the other hand, the residual stress decreases in the SUS316L side. These tendencies in Figs. 8 and 9 coincide with the experimental results shown in Figs. 6 and 7 respectively. From the experimental and analytical results, we could say that the IEFEM

Fig. 6 Residual stress distributions at 4.2 mm depth during the first thermal cycle.

Fig. 7 Stress changes in the 1st and 2nd thermal cycles.

well simulates the welding residual stress and its behavior in the thermal cycle.

As explained in Figs 6 and 7, it was suggested the yielding occurred in the first heating process at the NCF600 side. Figure 10 shows the IEFEM results of the plastic strain evolution during the thermal cycle. The plastic strains in the NCF600 and the weld metal change in the first heating process.

Fig. 8 Analyzed residual stresses distributions at 4.2 mm depth.

Fig. 9 Analyzed stress changes in the first thermal cycle.

Fig. 10 Analyzed distributions of plastic strain in welding direction ϵ_{xx}^p . Note dotted red line areas in the figure.

From the above, it is obvious that the yielding is one of the reasons for the residual stress relaxation in the first heating process. In other words, the mechanical relaxation would occur because the total stress, which is the sum of the initial welding residual stress and the thermal stress, exceeded the yield strength of NCF600 at a certain temperature during the first heating process.

4. Conclusion

In-situ residual stress measurements inside the sample during thermal cycles were successfully performed using the neutron diffraction technique at J-PARC, and the experimental evidence for clarifying the residual stress relaxation process in the thermal cycle of the dissimilar weld joint were obtained. The experimental results coincided quantitatively with the analytical results obtained by the IEFEM method. In conclusion, it was found that the residual stress relaxation during the first thermal cycle was caused mainly by the yielding of the NCF600 side. The yielding would occur because the total stress, which is the sum of the initial welding residual stress and the thermal stress caused by the difference in linear expansion coefficients, exceeded the yield strength of NCF600.

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