Finite element analysis of plastic strain and residual stress in a nozzle dissimilar metal weld under different annealing temperature conditions

Beom-Jin Kim, Jun-Young Jeon*, Chang-Young Oh, Sang-Woo Song
Department of Nuclear Safety Research, Korea Institute of Materials Science, Changwon, Korea, 51508
**Corresponding author: jjy0101@kims.re.kr*

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1. Introduction

Welding is an essential process in the fabrication of pressure vessels and piping systems in nuclear power plants. Dissimilar metal weld (DMW) is applied at the joint between the reactor coolant system nozzle and the safe end. Such welds are susceptible to primary water stress corrosion cracking (PWSCC) [1], and accurate prediction of plastic strain and welding residual stress is therefore required. Finite element analysis (FEA) has been widely used as a primary means for this purpose.

In previous studies [2-3], a simulation procedure for multi-pass welding was established by comparing the major analysis variables with measured deformation and residual stress [2]. It was also shown that the yield strength distribution developed by work hardening during welding must be properly reflected for reliable flaw evaluation, since the stress intensity factor (SIF) equations in ASME BPVC Section XI [4] include the material yield strength in the plastic zone correction [3]. The hardening behavior varies considerably with the annealing condition applied in the simulation, and for Alloy 600 weld metal an annealing temperature setting of 800 ℃ gave the best agreement with the measurements. However, this result was obtained for a single weld metal, and its applicability to DMW has not been confirmed.

In this study, the plastic strain and residual stress predicted under different annealing temperature settings were compared with measurements to derive an annealing setting suitable for the FEA of DMW.

2. SIF calculation in ASME BPVC Sec. XI

The flaw evaluation of welds in operating nuclear power plants requires the calculation of the SIF. ASME BPVC Section XI [4] provides two approaches for this purpose. One uses a polynomial fit of the stress distribution at the flaw plane, and the other is the weight function method. Figure 1 shows the surface and subsurface flaw models defined in the code. For a subsurface flaw, as considered in previous study [3], the polynomial fit approach is given in Eq. (1).

$$K_I = \left(C_0G_0 + C_1G_1 + C_2G_2 + C_3G_3 + C_4G_4\right)\sqrt{\pi a / Q}$$
$$Q = \Phi - q_y; \quad (1)$$
$$q_y = \left[\left(C_0G_0 + C_1G_1 + C_2G_2 + C_3G_3 + C_4G_4\right)/\sigma_{ys}\right]^2 / 6;$$

C_i are the coefficients obtained by fitting the stress distribution over the flaw depth a with a fourth-order polynomial, and G_i are the influence coefficients tabulated in the code. The flaw shape parameter Q is the difference between Φ, a constant related to the flaw aspect ratio, and the plastic zone correction factor q_y, which involves the material yield strength σ_{ys}. The SIF, a linear elastic fracture mechanics parameter, includes a plastic zone correction based on the yield strength.

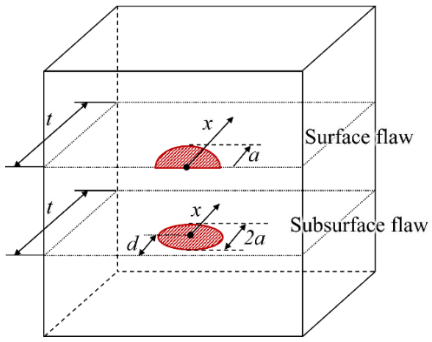

Fig. 1. Flaw model for SIF calculation in ASME BPVC Sec. XI

3. FE model of nozzle DMW

Figure 2 shows the finite element model of the nozzle DMW. Three materials were used: SA508 Gr.3 Cl.1 (nozzle), TP316 (safe-end, pipe and SMW), and Alloy 82/182 (buttering and DMW). Temperature-dependent thermal and mechanical properties of these materials were applied to the analysis. The joint was modeled as a two-dimensional axisymmetric model in ABAQUS [5], using coupled temperature-displacement elements (CAX4T) with 2,261 elements and 2,408 nodes. The DMW was implemented as a multi-pass weld with 23 passes, in which the weld beads were generated by the element birth and death technique.

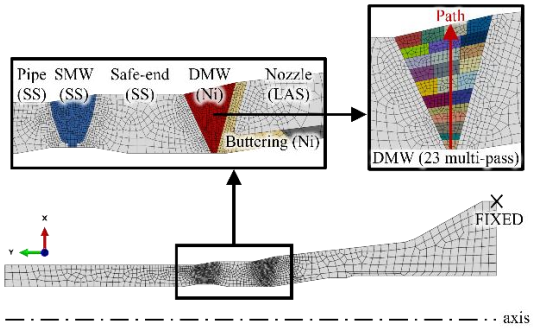

Fig. 2. FE model of nozzle DMW for finite element analysis

A body heat flux model was adopted for the heat input, and natural convection was applied on the outer surfaces. An isotropic hardening model was used for the elastic-plastic analysis. In ABAQUS, the *ANNEAL TEMPERATURE option resets the accumulated plastic strain to zero when the temperature of a material point exceeds the specified value. This option represents the loss of hardening memory by recrystallization during welding, rather than a post-weld heat treatment. Three setting were considered: no annealing, 1,400 ℃, 800 ℃

4. Effect of annealing temperature setting

4.1. Plastic strain

To evaluate the plastic strain in a nozzle DMW after welding, a mock-up specimen was fabricated and the hardness of the weld metal was measured. The measured values were converted into PEEQ using the hardness-plastic strain relation [3]. Figure 3 compares the PEEQ of the mock-up DMW with the FEA results for each annealing condition. The largest PEEQ was predicted without setting, since no relief of plastic strain occurred, and the accumulated PEEQ decreased as the annealing temperature was lowered. The setting of 800 ℃ showed the closest agreement with the measurements, which indicates that the annealing temperature derived for a single weld metal is also applicable to DMW.

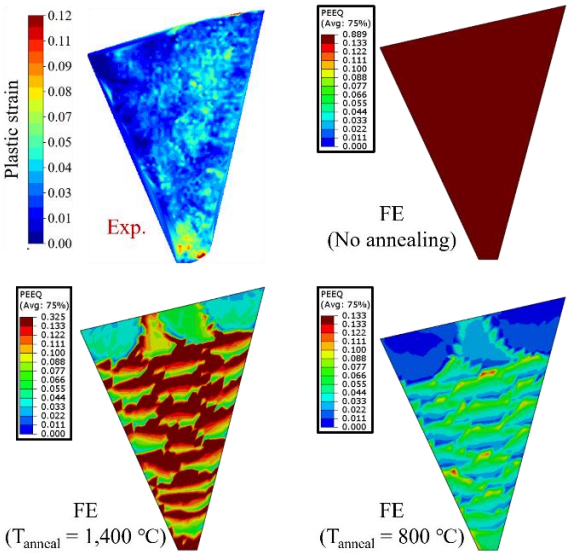

Fig. 3. Comparison of the plastic strain distributions between the measurement and the FEA results under different annealing settings

4.2. Residual stress

Figure 4 shows the residual stress distributions under each annealing temperature setting. The residual stress was extracted along the path at the center of the DMW in the thickness direction, as indicated in Fig. 2. The highest tensile residual stress was predicted without annealing, and the residual stress decreased as the annealing temperature was lowered. This indicates that the annealing setting considerably affects not only the plastic strain but also the predicted residual stress.

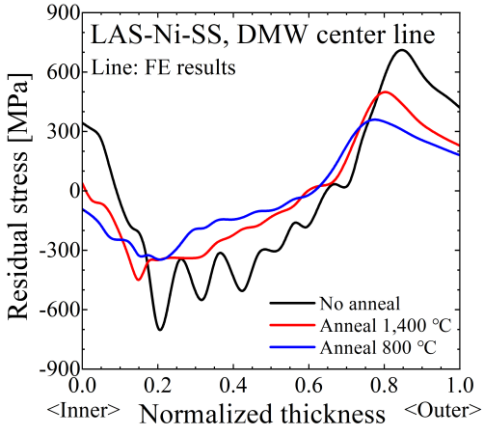

Fig. 4. Residual stress distributions along the DMW center line under different annealing settings

5. Conclusion

In this study, the plastic strain and residual stress under different annealing temperature settings were analyzed for a nozzle DMW, with the aim of calculating the SIF considering material hardening. Compared with the plastic strain converted from the hardness of a mock-up specimen, the setting of 800 ℃ gave the closest agreement, indicating that the annealing temperature derived for a single weld metal is also applicable to a DMW. The residual stress of the mock-up specimen will be measured and compared in a future study, and the SIF will then be calculated using the verified annealing condition.

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