Numerical Investigation on Residual Stresses of the Safe-End/Nozzle Dissimilar Metal Welded Joint in CAP1400 Nuclear Power Plants

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Received: 8 April 2018 / Revised: 30 July 2018 / Published online: 3 September 2018
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Abstract

The residual stress evolution in a safe-end/nozzle dissimilar metal welded joint of CAP1400 nuclear power plants was investigated in the manufacturing process by finite element simulation. A finite element model, including cladding, buttering, post-weld heat treatment (PWHT) and dissimilar metal multi-pass welding, is developed based on SYSWELD software to investigate the evolution of residual stress in the aforementioned manufacturing process. The results reveal a large tensile axial residual stress, which exists at the weld zone on the inner surface, leads to a high sensitivity to stress corrosion cracking (SCC). PWHT process before dissimilar metal multi-pass welding process has a great influence on the magnitude and distribution of final axial residual stress. The risk of SCC on the inner surface of the pipe will increase if PWHT process is not taken into account. Therefore, such crucial thermal manufacturing process such as cladding, buttering and post-weld heat treatment, besides the multi-pass welding process, should be considered in the numerical model in order to accurately predict the distribution and the magnitude of the residual stress.

Keywords CAP1400 nuclear power plants · Nozzle · Safe-end · Dissimilar metal welding · Residual stress

1 Introduction

CAP1400 is an advanced pressurized water reactor (PWR) nuclear power technology with independent intellectual property rights developed in China. Dissimilar metal weld joints are widely used in CAP1400 nuclear power plants. For example, the typical dissimilar metal joint consists of a low alloy steel pressure vessel nozzle welded to an austenitic stainless steel safe-end. As an important part of a loop pressure boundary, the joint is subjected to high temperature, high pressure and complex alternating stress in the operation of nuclear power plant equipment. Extensive research and experience in nuclear power plants indicate that the dissimilar metal welds of safe-end and nozzle are a

weak component of the system, which is prone to stress corrosion cracking (SCC), and the service life is much shorter than the design life [1–3]. Residual stress is one of the important factors that leads to the SCC problem [4–7]. Therefore, it is important to study the evolution law of residual stress during the manufacturing process for the control of the parameters during manufacturing process and the assessment of the life of the nozzle/safe-end joint.

The manufacturing process for nozzle/safe-end joint comprises several thermal procedures including cladding, buttering, post-weld heat treatment (PWHT) and dissimilar metal multi-pass welding. Because of the complex structure and manufacturing process for nuclear power plants, it is difficult to measure the residual stress by experiment and analyze the evolution law of residual stress during the manufacturing process. Recently, a number of numerical simulations based on thermo-elastic-plastic finite element analysis have been performed to evaluate residual stress in dissimilar metal weld joints. Song et al. [8–10] presented the finite element simulation results of residual stresses in dissimilar metal welds of a Korean PWR pressurizer safety/relief nozzle. One of important findings from their work is that the tensile residual stresses exist both at the inner surface and at the outer surface of dissimilar metal

Available online at <http://link.springer.com/journal/40195>

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welds after dissimilar metal welding. Moreover, the authors analyze the influences of similar metal welding, hydrotest and overlay welding on the residual stress. Dehaghi et al. [11] investigated the distribution and magnitude of the residual stresses created by thermal processes of the main feed water nozzle in a 100-MW AP1000 power plant reactor. Taking larger size of actual safe-end/nozzle welding joints into consideration, most researchers use a mock-up to investigate residual stress distributions [12–19]. In order to assess the susceptibility of components to PWSCC (primary water stress corrosion cracking), Smith et al. [5, 12] performed a detailed finite element simulation covering the full manufacturing history of pressurizer safety/relief valve (SRV) nozzle dissimilar metal weld mock-ups, without and with the full structural weld overlay. The simulated results of residual stress are verified by using the deep hole drilling (DHD) and incremental deep hole drilling (iDHD) techniques. The simulated results show that the omission of the buttering, post-weld heat treatment and weld preparation machining stages has little effect on predicted stresses in the dissimilar metal weld, and hence, it does not need to be modeled.

The welding residual stress depends on the geometry and material of the nuclear plant structure, like the radius-to-thickness ratio [8, 9, 20]. The safe-end/nozzle structure in CAP1400 nuclear power plants has a larger radius-to-thickness ratio than that of a Korea PWR nuclear plant [8]. The radius and the thickness are 319 mm and 74.5 mm, respectively, and the radius-to-thickness ratio is approximately 4.3. Therefore, it is necessary to carry out the distribution of the residual stress of safe-end/nozzle in CAP1400 and lay the foundation for the evaluation of the sensitivity of SCC. Unlike Smith et al. [5, 12], Deng et al. [16] and Katsuyama et al. [21] believe that the cladding, buttering and post-weld heat treatment have an effect on the distribution and magnitude of the final residual stress. The model established in this work takes into account the above processes in order to analyze the evolution of the residual stress during the whole manufacturing process.

In this work, a heat source fitting (HSF) tool in SYS-WELD software was used to fit the heat source model of cladding, buttering and groove welding in the field process. A bead-on-plate tungsten inert gas (TIG) experiment was performed to obtain the temperature field and the cross-section morphology of the weld. The welding heat source model was checked by comparison of the thermal cycle, the cross-section morphology of the weld and the residual stress between experiment and simulation. The residual stress on the plate surface was tested by X-ray diffraction (XRD) method. The reliability of simulation results for cladding process was verified by the experimental and simulated residual stress. Furthermore, a whole procedure finite element (FE) model including cladding, buttering,

post-weld heat treatment and dissimilar metal multi-pass welding processes for safe-end/nozzle in CAP1400 nuclear power plants was developed to analyze the evolution of residual stress during the manufacturing process and investigate the distribution and magnitude of the final residual stress.

2 Experimental Procedure

The heat source model for the actual welding process needs to be established before analyzing the evolution of residual stress in CAP1400 nozzle/safe-end welded joint. The TIG arc welding method was used to conduct cladding, buttering and dissimilar metal multi-pass welding. The corresponding process parameters are shown in Table 1. It can be seen that the same process parameters were used during cladding, buttering and multi-pass welding. A bead-on-plate TIG welding experiment was carried out with TA1600 welding robot. The base metal and the welding wire were SA508 steel and ER308L, respectively. The dimensions of base metal specimen are 130 mm (length) $\times$ 80 mm (width) $\times$ 7 mm (thickness). The parameters of welding process were welding current 150 A, voltage 11 V and welding speed 3 mm/s. Before TIG welding, three K-type thermocouples with a wire diameter of 0.45 mm were spot-welded on the top surface of the specimen and used to record temperature history at various distances from the weld centerline during TIG welding. The residual stress profiles on the plate surface were measured by XRD method after TIG welding. XRD method is widely used in the residual stress testing [13, 22, 23]. The locations of the residual stress measurement and three thermocouples are shown in Fig. 1. TC1, TC2 and TC3 present the spot-welded positions of K-type thermocouples. TS1, TS2, TS3 and TS4 are the positions of the residual stress measurements.

3 Finite Element Modeling

3.1 Model Description

Figure 2 depicts a nozzle/safe-end in CAP1400 nuclear power plants. Relevant materials and dimensions are also included in the figure. First the cladding zone was deposited on the inside surface with stainless steel wire by automatic TIG arc welding. The cladding zone consisted of two layers with a total thickness of ~ 6 mm. The deposited material was ER308L. Near the buttering zone, the deposited material was changed to Inconel 52M wire. The thickness of cladding zone is about 9 mm with three layers. After cladding, the buttering zone was deposited on the low

Fig. 2 Dimension and finite element model for CAP1400 nozzle/safe-end welded joint

$$q_{\text{rad}} = -\sigma_{\text{SB}}\epsilon_0 \left[(T_s + 273.15)^4 - (T_\infty + 273.15)^4 \right], \quad (3)$$

where σ_{SB} is Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ J K}^{-4} \text{ m}^{-2} \text{ s}^{-1}$) and ϵ_0 is the emissivity (0.8).

According to the relevant research results, a double ellipsoidal heat source proposed by Goldak et al. [24] as shown in Fig. 3 was employed in this work because it had been found to be the most appropriate model for simulating the TIG welding process. The heat density, represented by q_f or q_r within the front and the rear semi-ellipsoids at an arbitrary (x, y, z) , was described as follows:

$$q_f(x, y, z, t) = \frac{6\sqrt{3}f_f\eta UI}{a_f b c \pi \sqrt{\pi}} \exp \left(-3 \left(\frac{x - vt}{a_f} \right)^2 - 3 \left(\frac{y}{b} \right)^2 - 3 \left(\frac{z}{c} \right)^2 \right), \quad (4)$$

$$q_r(x, y, z, t) = \frac{6\sqrt{3}f_r\eta UI}{a_r b c \pi \sqrt{\pi}} \exp \left(-3 \left(\frac{x - vt}{a_r} \right)^2 - 3 \left(\frac{y}{b} \right)^2 - 3 \left(\frac{z}{c} \right)^2 \right), \quad (5)$$

where a_f , a_r , b and c are the ellipsoidal heat source parameters as shown in Fig. 3. q_f and q_r represent the length of the front and the rear semi-ellipsoid, respectively. η is the heat efficiency. U and I are the arc voltage and welding current. v means the welding speed, and t stands for the welding time. f_f and f_r are the energy coefficients corresponding to the front (f) and the rear (r) of ellipsoid heat source and $f_f + f_r = 2$. The power density distribution inside the front quadrant is higher than that in the rear quadrant. Therefore, the factor f_f is larger than f_r .

3.3 Mechanical Analysis

After the thermal analysis was produced, the mechanical analyses were conducted to calculate the residual stress distribution using the temperature histories computed by the thermal analysis as the input thermal load. The same finite element model used in the thermal analysis was employed. The thermo-elastic-plastic material model, based on the von Mises yield criterion and the isotropic strain hardening rules, was used to compute the stress.

Generally, during the welding process, besides the elastic, plastic and thermal strains, the strains due to solid-state phase transformation and plasticity strain rate (TRIP)

Fig. 3 Schematic of double ellipsoid heat source model

also made some contributions to the total strain. Because the period with high temperature during the entire thermal cycle was very short (only a few seconds), a TRIP behavior was neglected in the present study. The total strain rate $\dot{\epsilon}$ generated during welding process can be expressed as the sum of the individual strain increments as follows:

$$\dot{\epsilon} = \dot{\epsilon}_e + \dot{\epsilon}_p + \dot{\epsilon}_{tp} + \dot{\epsilon}_{ph}, \quad (6)$$

where $\dot{\epsilon}_e$, $\dot{\epsilon}_p$, $\dot{\epsilon}_{tp}$ and $\dot{\epsilon}_{ph}$ are the elastic strain rate, plastic strain rate, thermal strain rate and phase transformation strain rate, respectively.

The elastic strain rate was modeled by using the isotropic Hook's law with temperature-dependent Young's modulus and Poisson's ratio. The thermal strain rate was computed by using the temperature-dependent coefficient of thermal expansion. For the plastic strain rate, a rate-independent plastic model was employed with the following features: the von Mises yield surface, temperature-dependent mechanical properties and linear kinematic hardening model. The dependency of yield strength upon temperature and phase fraction was taken into account.

Regarding mechanical boundary conditions, the roller boundary and clamped conditions were applied to the ends of the nozzle and safe-end, respectively. That is, the axial displacement of the nozzle end is restrained, and the end of the safe-end is fixed.

3.4 Material Properties

The materials of nozzle and safe-end are SA508Gr.3 ferritic low alloy steel and 316LN austenitic stainless steel, respectively. The deposited materials for cladding, buttering and dissimilar metal multi-pass welding are ER308L and Inconel 52M, respectively. The temperature-dependent thermal physical and mechanical properties of the above materials are shown in Fig. 4. E is Young's modulus, ν is Poisson's ratio, λ is thermal conductivity, c is specific heat, α is thermal expansion coefficient, and σ_y is yield strength. The performance properties of SA508 Gr.3 steel are measured. The performance properties of other materials are taken from Ref. [25].

There are various models for the investigation of heat treatment process. Model of stress relief due to plasticity is a well-known model in which reduction in yield strength at high temperatures is considered as the main cause of stress relief. It has been revealed that the creep model has the most effects on stress relief compared with other models. Therefore, Norton's steady-state creep model was used for evaluation of creep behavior and stress relief during creep process by heat treatment. It can be formulated by Eq. (7):

$$\dot{\epsilon} = A\sigma^n, \quad (7)$$

where the stress σ is in MPa, the exponent n is dimensionless while the coefficient A has the same unit as creep strain rate (s^{-1}). The creep properties of similar materials are used to replace the creep properties of the above materials. The values of A and n in Eq. (7) are from Ref. [7] as shown in Table 2.

4 Results and Discussion

4.1 Heat Source Model Fitting

The HSF tool is available within SYSWELD code, which enables the users to calibrate the parameters of heat source model in an iterative manner. Firstly, the HSF tool was used to get the parameters of double ellipsoid heat source model as shown in Eqs. (4) and (5) based on the transverse cross-section shape and the size of weld bead measured in experiment roughly under the same welding process parameters. On the basis of the parameters defined by the HSF tool, a transient thermal analysis of TIG welding process was carried out to record the temperature histories of some specific points. And then, the thermal cycles of the points obtained by the experiment and the calculation were compared. The parameters describing the heat source were adjusted iteratively until the morphology of molten pool, and the welding thermal cycle curve agreed well with those of the test base plate. As a result, an accurate heat source model could be determined.

The temperature of fusion zone was set at or above the liquidus temperature of 1450 °C. Figure 5 shows the comparisons of the predicted and the measured transverse cross-section morphology and sizes. It can be seen that the results of calculated weld geometry and size show a good agreement with those of the experiment.

Figure 6 compares the temperature histories at thermocouple locations between the experimental and the computed results for TC1, TC2 and TC3 points. Some differences could be found in the peak temperature values and the heating and cooling curves. The difference of peak temperature values may be attributed to minute inaccuracies involved in thermocouple locations, relatively coarser mesh away from the fusion zone, and the simplifications assumed during numerical simulation. The difference of the heating and cooling curves may be assigned to the constant values of the heat transfer coefficients used for simulation, which in most of the welding simulations are defined as functions of temperature. Nevertheless, the overall simulated thermal cycles are good enough to perform the mechanical analysis further.

Through the comparisons of the weld bead profiles and temperature histories of measuring points between

Fig. 4 Thermodynamic properties for nuclear materials: **a** ER308L, **b** 316L steel, **c** Inconel 52 M, **d** SA508III steel

Table 2 Values of A and n from Ref. [7]

Material used in this work	Material used in Ref [7]	A	n
SA508 Gr.3	SA533B-1	2.82×10^{-17}	5.24
ER308L	Type 309L SS	1.49×10^{-28}	9.88
Inconel 52M	Alloy 82	1.68×10^{-22}	6.11

Fig. 5 Comparisons of the experimental and the calculated results of weld cross-section morphology and size

Fig. 6 Comparisons of welding thermal cycle curves between experiment and simulation for TC1, TC2 and TC3 points

Table 3 Fitting parameters for double ellipsoid heat source model

Q_f (W/mm ³)	Q_r (W/mm ³)	a_f (mm)	a_r (mm)	b (mm)	c (mm)	Q (W)
25	30	3	4	3	1.5	1100

experiment and calculation, the parameters of heat source model could be obtained as shown in Table 3.

4.2 Model Reliability Verification

It is difficult to obtain the distribution and magnitude of manufacturing residual stress by site test due to the complexity and larger size of nozzle and safe-end in CAP1400 nuclear power plants. In this work, the reliability of the simulation results is partly verified by comparing the residual stresses generated during the cladding process between simulation and experiment.

The longitudinal and transverse residual stresses on the plate surface were tested by XRD method. The testing positions are shown in Fig. 1. Three-dimensional FE model for a bead-on-plate welding process was established to calculate the temperature field and the residual stress distribution of the weldments. As shown in Fig. 7, the dimension of the model is 130 mm × 80 mm × 7 mm, which is similar to the dimension of TIG welding experimental plate. The FE model was meshed using 73,280 elements, and the total number of nodes in model is 82,593. The smallest element size is 0.5 mm × 0.5 mm × 0.8 mm in the center of model. SYSWELD software was used to simulate the bead-on-plate welding procedure. During the mechanical analysis, the boundary conditions should be used to prevent the rigid body motion. The position of constrains for the plate is shown in Fig. 7. The longitudinal and transverse residual stresses along L1 as shown in Fig. 7 are obtained by FE simulation. Through comparing the experimental and simulated residual stresses, the reliability of simulation results for cladding process is validated.

Figure 8 shows the contours of longitudinal and transverse residual stress distribution on the plate surface by FE simulation, respectively. It is clear that there is a higher

longitudinal (about 600 MPa) and transverse (about 500 MPa) residual tensile stress near the weld. Figure 9 compares the longitudinal and transverse residual stresses on the plate surface predicted by FE model and those measured by XRD method. It can be seen that the simulation results match the measurements well. Away from the weld bead, the longitudinal residual stress changes from tensile to compressive gradually. However, there is a large stress gradient in the transverse residual stress. In the range of 2 mm from the edge of the weld bead, the tensile stress changes rapidly into compressive stress. It is difficult to measure the residual stress in the range of 2 mm from the edge of the weld bead because of the influence of weld seam height.

4.3 Evolution and Distribution of Residual Stress

Figure 10 illustrates the different paths on the safe-end/nozzle welded joint. Figure 11 shows the distributions of axial and hoop residual stresses on the inner surface (Path 4) during the manufacturing processes including cladding and buttering, PWHT and dissimilar metal multi-pass welding. It can be seen that the distributions of axial and hoop residual stresses change sharply within the range between 0 and 100 mm. Wider distribution and higher value of tensile axial and hoop residual stresses are formed after cladding and buttering processes. Within the range over 100 mm, the distribution of the axial and hoop residual stresses has no significant variation and the value of the tensile stresses is about 100 MPa. The buttering process does not significantly affect the axial and hoop residual stresses in this range because the distance from the buttering zone is large enough. Therefore, the axial and hoop residual stresses are mainly determined by the cladding process at this range. After PWHT process, the values of axial and hoop tensile residual stresses are decreased due to the creep stress relaxation of the materials as shown in the same figure. It can also be seen that the gradients of axial and hoop residual stresses decreased dramatically in the buttering zone. Away from the buttering zone, the residual stress on the inner surface is almost eliminated. After dissimilar metal multi-pass welding (DMW), the distributions of axial and hoop residual stresses on the inner surface are changed obviously. Near the weld zone, the axial residual stress has large gradient compared with hoop residual stress. The peak value of axial tensile residual stress is about 650 MPa. The axial and hoop compressive residual stresses are formed near the buttering

Fig. 7 Finite element model for a bead-on-plate welding

Fig. 8 Contours of residual stress distribution: **a** longitudinal, **b** transverse (unit: MPa)

Fig. 9 Comparison of simulation results and measurements of residual stress profiles on the plate surface: **a** longitudinal, **b** transverse

Fig. 10 Schematic diagram for different paths

zone in the nozzle due to welding shrinkage. The axial and hoop residual stress distribution at the range over 100 mm does not change after multi-pass welding.

Figure 12 shows the through-thickness variations of axial and hoop residual stress after dissimilar metal multi-pass welding along Path 1 and Path 2. It can be seen that there are similar distributions for axial residual stresses along Path 1 and Path 2. The axial residual stress is tensile stress near the inner surface and the outer surface and compressive stress at the middle of Path 1 and Path 2.

Compared with axial residual stress along Path 1 near the inner surface and the outer surface, the value of axial residual stress along Path 2 is larger. This is due to the fact that the distance of Path 2 and the last welding pass is shorter than that of Path 1 and the last welding pass. Meanwhile, the hoop tensile stress along Path 2 is in a wider range as shown in Fig. 12b. The value of hoop residual stress on the outer surface is larger than that on the inner surface. The peak value of hoop tensile residual stress is less than 200 MPa and about 500 MPa on the inner surface and the outer surface, respectively.

Figure 13 shows the distributions of axial and hoop residual stresses on the outer surface (Path 3) after dissimilar metal multi-pass welding. It is clear that the axial and hoop residual stresses are in tensile state at both safe-end side and nozzle side. The peak value of the hoop residual stress appears in the dissimilar metal multi-pass welding zone and the Ni-based alloy buttering zone. The peak value of the axial residual stress appears in the Ni-based alloy buttering layer and HAZ of base metal.

PWHT is commonly used to eliminate weld-induced residual stress and improve HAZ toughness. During the manufacturing process in safe-end/nozzle dissimilar metal welded joint of CAP1400 nuclear power plants, PWHT is conducted as an intermediate process. To clarify how

Fig. 11 Axial **a**, hoop **b** residual stress distributions on the inner surface during the manufacturing processes

Fig. 12 Through-thickness variations of axial and hoop residual stresses after dissimilar metal multi-pass welding **a** along Path 1 and **b** along Path 2

Fig. 13 Variations of axial and hoop residual stresses after dissimilar metal multi-pass welding on the outer surface

PWHT process affects the final residual stresses, another simulated case was performed in this work. Compared with the simulation process mentioned above (Case A), PWHT process before dissimilar metal multi-pass welding was not taken into account in Case B. Figures 14 and 15 show the

Fig. 14 Axial residual stress contours of Case A, Case B

contours of the axial and hoop residual stress distribution of the multi-pass welding zone and a part of the nozzle and the safe-end in Case A and Case B, respectively. It can be seen that PWHT has a great influence on the magnitude and distribution of axial residual stress, but less on the hoop

Fig. 15 Hoop residual stress contours of Case A, Case B

residual stress. In Case B, the region of axial tensile stress on the inner surface expands, but the region of axial tensile stress on the outer surface remains unchanged. Meanwhile, the magnitude of axial compressive stress in the middle of the pipe is greatly reduced and the distribution range does not show a significant change.

The simulation results indicate that larger tensile axial residual stress exists near weld zone after dissimilar metal multi-pass welding. Therefore, during the operation of CAP1400 nuclear power plants, the stress corrosion cracking (SCC) is easy to produce on the inner surface under the effect of environment and corrosive medium, which has an impact on the safe operation of nuclear power plants. Moreover, the figures in Fig. 11 clearly indicate that larger tensile axial and hoop stresses remained at the buttering zone before welding, and the dissimilar metal multi-pass welding process changed the prior-existing stress status. Compared with other processes, dissimilar metal multi-pass welding plays a key role in the final residual stress. However, other key manufacturing processes such as cladding, buttering and PWHT in CAP1400 nozzle/safe-end joining should also be considered in the numerical model in order to accurately evaluate residual stress distribution. In particular, PWHT process before dissimilar metal multi-pass welding process has a great influence on the magnitude and the distribution of final axial residual stress.

5 Conclusions

In this work, a finite element model of safe-end/nozzle in CAP1400 nuclear power plants including cladding, buttering, post-weld heat treatment and dissimilar metal multi-pass welding was developed to calculate the evolution of residual stress during the manufacturing process and analyze the distribution of final residual stress. The following conclusions can be drawn.

1. A large tensile axial residual stress, which exists at the weld zone on the inner surface, leads to a high sensitivity to SCC.
2. Besides dissimilar metal multi-pass welding, cladding, buttering and post-weld heat treatment processes also have significant influences on the final residual stress distribution.
3. The post-weld heat treatment process before dissimilar metal multi-pass welding process has a great influence on the magnitude and distribution of final axial residual stress. The risk of SCC on the inner surface of the pipe will increase if PWHT process is not taken into account.

Acknowledgements This work was supported by the Open-ended Fund of the CAS Key Laboratory of Nuclear Materials and Safety Assessment (Grant No. 2015NMSAKF02).

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