Prediction of welding residual stress profile in dissimilar metal nozzle butt weld of nuclear power plant

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Abstract

This paper provides the through-thickness welding residual stress profile in dissimilar metal nozzle butt welds of pressurized water reactors. There have been incidents recently where cracking has been observed in the dissimilar metal weld. Weld-induced residual stress is main factor for crack growth, and thus, exact estimation of welding residual stress is important. For investigations of welding residual stress profile, the effects of geometric variables, i.e. the thickness and the radius of the nozzle and the length of the safe end, on welding residual stresses, are systematically considered and elastic-plastic thermo-mechanical finite element analyses are conducted. Through-wall welding residual stress profiles for dissimilar metal nozzle butt welds are proposed, which take a modified form of existing welding residual stress profiles developed for austenitic pipe butt weld in R6 code.

Keywords: Welding Residual Stress, Dissimilar Metal Weld, PWSCC

1. Introduction

There have been many studies completed for the welding residual stress in austenitic stainless steel pipe butt weld [Yaghi et al., Brickstad et al., Dong el al., Bouchard et al.]. However, a few problems arise when the welding residual stress profile for the pipe butt weld is employed in the problem of dissimilar metal nozzle butt weld. First,
the nozzle component consists of two welds, dissimilar metal weld connecting the nozzle to the safe end and similar metal weld joining the safe end to the pipe. Recent work reveals that the similar metal weld affects the welding residual stress distribution in the dissimilar metal weld depending on the length of the safe end [Song et al., Rudland et al.]. In addition, the length of the safe end varies with manufacturer. Second, the outer diameter of the nozzle component is tapered. Moreover, the shape of the nozzle component is slightly different from one to another manufactures. Lastly, the nozzle component consists of several materials, i.e. low alloy steel, Ni-based alloy and stainless steel, which means that there is a possible effect of strength mis-match. For these reasons, it appears that all the studies on the residual stress in dissimilar metal nozzle butt weld have been focused on specific nozzle considered in their work.

The present work attempts to provide a generally applicable through-thickness welding residual stress profile in dissimilar metal nozzle butt welds regardless of specific nozzle geometry. Based on examinations of dissimilar metal nozzles used in Korean nuclear power plants, the idealized nozzle shape is proposed to cover various nozzle shapes. Parametric studies on the effects of geometric variables, i.e. the thickness and the radius-to-thickness ratio of the nozzle and the length of the safe end, on welding residual stress are performed. As a result, the through-thickness welding residual stress profile for a dissimilar metal nozzle butt weld is proposed.

2. Characteristics of Dissimilar Metal Nozzle Butt Welds

Fig. 1 shows the various shapes of nozzles used in Korean nuclear power plants. These nozzles include inlet and outlet nozzle to the reactor vessel; spray, safety, relief and surge nozzle on the pressurizer. Although all the nozzles show a similar configuration, the specific shape is different with respect to each manufacturer and nozzle type. To quantify nozzle dimensions, some symbols are employed as denoted in Fig. 2(a). Table 1 summarizes some relevant dimensions of nozzles. As shown in Table 1, the radius-to-thickness ratio \( \frac{r_i}{t_{SE}} \) of these nozzles is less than 5 due to the fact that the primary loop system is relatively thick. And the thickness of the safe end, which is between that of the nozzle and the pipe, is more than 20 mm. Values of \( \frac{w_{SE}}{t_{SE}} \), on the other hand, range from 0.4 to 7.0.

Although a number of materials are involved, common features can be found as follows. The nozzle is made of low alloy steel SA508. Both the buttering and DMWs are made of Ni-based alloys, Alloy 82/182. The pipe and SMWs are made of austenitic stainless steels, F316 or TP304.

Fig. 1. Schematic diagrams of nozzles in pressurized water reactors.
Fig. 2 Schematic diagram of a nozzle component considered in the present work: (a) detailed shape of a surge nozzle in pressurized water reactors and (b) idealized geometry and materials.

Table 1. Dimensions for various nozzles.

<table>
<thead>
<tr>
<th>Plant</th>
<th>component</th>
<th>nozzle</th>
<th>tSE</th>
<th>ri</th>
<th>r_i/tSE</th>
<th>wSE/tSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Reactor</td>
<td>Inlet / Outlet</td>
<td>82.6</td>
<td>346.6</td>
<td>4.2</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>vessel</td>
<td>Safety injection</td>
<td>19.6</td>
<td>43.2</td>
<td>2.2</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Safety / Relief</td>
<td>29.7</td>
<td>65.9</td>
<td>2.2</td>
<td>0.6</td>
</tr>
<tr>
<td>B</td>
<td>Pressurizer</td>
<td>Spray</td>
<td>20.1</td>
<td>47</td>
<td>2.3</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Surge</td>
<td>40.2</td>
<td>142.2</td>
<td>3.5</td>
<td>1.5</td>
</tr>
<tr>
<td>C</td>
<td>Pressurizer</td>
<td>Surge</td>
<td>33.3</td>
<td>124.4</td>
<td>3.7</td>
<td>1.1</td>
</tr>
</tbody>
</table>

3. Finite Element Welding Simulations

3.1. General Aspects

Welding residual stress analysis was conducted using the commercial finite element analysis code, ABAQUS. The un-coupled thermal and stress analysis approach was adopted. Therefore, time dependent temperature histories from the thermal analysis were used as input data for the stress analysis. To simulate the sequential weld deposit, the element add/remove technique in ABAQUS was used. In the thermal analysis, the body flux was used as heat input method. To calculate the body flux, welding efficiency (η), η=0.7, and heat input energy per unit length, E, E=1714 J/mm, are used based on the welding procedure specification. To comply with the maximum inter-pass temperature suggested in the welding procedure specification (normally 170 °C) the cooling time is adjusted appropriately. For cooling conditions, both convection and radiation is considered using the following temperature-dependent heat transfer coefficient.

For mechanical analysis, a non-linear kinematic hardening model is used to consider the Bauchinger effect. The annealing effect is considered by taking the liquidus temperature as the annealing temperature. Although phase transformation during welding occurs at ~750 °C for ferritic steels, it was not considered, as simulation without phase transformation tends to overestimate tensile residual stresses and thus is conservative for the present purpose [Bate et al.].

3.2. Welding Simulations for dissimilar metal nozzle butt weld and pipe butt weld

For the nozzle geometries shown in Figs. 1 and 2a, the real nozzle shapes are idealized by a straight pipe with two welds, one dissimilar and the other similar metal weld (see Fig. 2(b)). The thickness of the idealized nozzle is assumed to be tSE. To see the effect of thickness, tSE, and the radius-to-thickness ratio, r_i/tSE, on residual stresses, three values of tSE, tSE=20, 40, 80 mm, and two values of r_i/tSE, r_i/tSE=1, 5, are considered, respectively. To see the effect of the length of the safe-end on residual stresses, four different values of wSE/tSE are considered, wSE/tSE=0.5, 1.0, 2.0 and 4.0. Note that the effect of the length of the safe-end on residual stresses tends to saturate for wSE/tSE=
4.0. The length of the pipe, $L$, was chosen to be five times the thickness, $L = 5t_{SE}$, which is regarded as sufficiently long to exclude the end effect. And the validity check for the proposed idealized nozzle could be found in Ref. [Song et al.], which shows overall identical results between the actual nozzle and the idealized nozzle.

4. Finite Element Welding Simulations

4.1. FE Results for Through-Thickness Residual Stress in Austenitic Pipe Butt Weld

In this section, the present FE welding residual stresses for austenitic stainless steel pipe butt welds are compared with existing results. Such a comparison could provide confidence in the present FE welding simulations, as the existing residual stress profiles are based on numerous numerical analyses and experimental measurements. Furthermore, as the mechanisms controlling welding residual stresses for butt welds are similar between pipe butt welds and dissimilar metal nozzle butt welds, existing welding residual stress profiles for pipe butt welds could be the basis for constructing residual stress profiles for dissimilar metal nozzle butt welds.

Figure 3 compares FE through-wall residual stress distributions in stainless pipe butt welds with the three existing profiles described above. Results are obtained for $r/t_P = 5$ with $t_P = 20$, 40 and 80 mm. In the figures, the existing profiles are shown in solid lines and the present FE results by symbols. Residual stresses are reported along the center line of the butt weld. The axial residual stress, $\sigma_a$, is normalized with respect to the 1.0% proof strength of the parent material, $\sigma_{1.0p}$, and the hoop residual stress, $\sigma_h$, with respect to the 1.0% proof strength of the weld material, $\sigma_{1.0w}$. For the present work, room temperature properties are used, that is $\sigma_{1.0p} = 328.9$ MPa and $\sigma_{1.0w} = 460.5$ MPa.

Comparing FE results with existing profiles in the codes, R6 level 2 provides overall conservative results due to its intrinsic characteristics of upper bound. The recommended profile of ASME Sec. XI is too simple to represent the gradient of hoop residual stress. On the other hand, the API 579 and R6 level 3 predict significantly lower profiles than that of R6 level 2. This is because API 579 and R6 level 3 is derived from recent measurement data of high quality [Bouchard]. However, R6 level 3 is adopted as an appropriate profile for the pipe butt weld in this paper for two reasons: First, API 579 is overall more conservative than R6 level 3 for both axial and hoop residual stress. In the API 579 code, welding residual stress is normalized with “actual yield strength of material”, which is assumed to be 0.2% proof stress but can’t be assured. Hence, the profile of API 579 in Fig. 3 is expressed with the original form due to its vague definition. Second, R6 level 3 is easy to manipulate because it is composed of physically meaningful terms, i.e. bending, membrane and sine terms.

Fig. 3 Comparison of FE results with existing residual stress profiles for austenitic pipe butt weld with $r/t_R = 5$ and $t_R = 40$ mm. (a) axial and (b) hoop stress.

4.2. FE Results for Through-Thickness Residual Stress in Dissimilar Metal Nozzle Butt Weld

All the residual stresses for the dissimilar metal nozzle butt weld are provided in normalized form. For the normalizing stresses, 1.0% proof stress of parent material, $\sigma_{1.0p}$, and 1.0% proof stress of weld material, $\sigma_{1.0w}$, are
employed as recommended in R6. In this work, \( \sigma_{1.0p} = 328.9 \) MPa of F316L and \( \sigma_{1.0w} = 488.5 \) MPa of Alloy 600 at room temperature are used, respectively.

Before the similar metal weld, the R6 level 3 profile predicts similar tendencies and gives overall good agreements with FE results for the nozzle with \( r_i/t_{SE} = 5 \), though some conservatism or non-conservatism is observed in a partial region. On the other hand, for the nozzle with \( r_i/t_{SE} = 1 \), it gives conservative predictions at the inner surface comparing FE results. After similar metal welding, R6 level 3 becomes more conservative at the inner surface due to the effect of similar metal welding, as shown in Fig. 4 and 5. Two difficulties arise in applying R6 level 3 as a through-wall residual stress profile for dissimilar metal nozzle butt weld: First, the nozzle with \( r_i/t_{SE} = 1 \) (\( r_i/t_{SE} = 1.5 \)) is out of the applicable range of R6 level 3. R6 level 3 was developed to cover the mean radius-to-thickness ratio, \( r_i/t_{SE} \), ranging \( 1.8 \leq r_i/t_{SE} \leq 25 \). However, \( r_i/t_{SE} \) less than 5 is the ratio of interest for the nozzle problem. Second, in the nozzle problem, the bending mechanism induced by the interaction between two welds alters the existing residual stress distribution, thus R6 level 3 becomes conservative even for the nozzle with \( r_i/t_{SE} = 5 \).

To modify the R6 level 3 profile, the following points should be noted. Firstly, the results in Figs 4 and 5 suggest that both axial and hoop residual stress profiles are affected more by \( r_i/t_{SE} \) than by \( t_{SE} \). Residual stresses at the inner surface decrease with decreasing \( r_i/t_{SE} \). The second point is that similar metal welding effectively provides bending stresses on the DMWs, which decrease axial residual stresses at the inner surface. Based on these observations and by conservatively bounding the present FE results, the following profile is proposed for axial residual stresses in dissimilar metal nozzle welds:

\[
\sigma_{axial} = \sigma_{axial}^p \left[ 1 - 2 \frac{x}{t_{SE}} \right] + \sigma_{axial}^h \sin \left[ \frac{\pi}{4} \left( 1 - 8 \frac{x}{t_{SE}} \right) \right] \left( \frac{t_{SE}}{r_i} \right)^{0.5} \left( \frac{\sqrt{2}}{\pi} \sigma_{axial}^h \right) \left( \frac{t_{SE}}{r_i} \right)
\]

(1)

For hoop residual stresses, the following profile is proposed:

\[
\sigma_{hoop} = \sigma_{hoop}^h \left( 0.65 - \delta_u \right) \sin \left[ \frac{3\pi}{2} \left( \frac{7}{6} \frac{x}{r_i} \right) \right] + \left( 0.35 + \delta_u \right)
\]

(2)

The proposed residual stress profile, Eqs (1) and (2), is based on FE results, and thus should be valid for the ranges of geometric variables and parameters used in the FE analysis. Regarding geometry, the present work considers realistic geometric variables based on the nozzles in pressurized water reactors within Korea. The thickness of nozzle, \( t_{SE} \), ranges from 20 to 80 \( mm \), the inner radius to-thickness ratios, \( r_i/t_{SE} \), from 1.0 to 5.0 and the width of the safe-end, \( w_{SE}/t_{SE} \), from 0.5 to 4.0. Finally, the heat input energy, \( E \), was assumed to be \( E = 1714 \) kJ/mm based on welding procedure specifications.
5. Conclusions

This paper presents through-wall welding residual stress profiles in the dissimilar metal nozzle butt weld of a PWR nozzle, via elastic-plastic FE simulations. As the nozzle shows geometric variations on the thickness, the radius-to-thickness ratio and the length of the safe end, an idealized nozzle shape is proposed based on investigations of nozzles used in Korean nuclear power plants for the systematic analyses on geometric parameter.

For comparison purposes, FE analysis for the austenitic pipe butt weld was performed, which entails R6 level 3 profile as a possible through-wall residual stress profile for the dissimilar metal nozzle butt weld due to its accurate prediction and physically reasonable formation. However, comparing FE results for the dissimilar metal nozzle butt weld with the R6 level 3 profile, R6 level 3 is overall more conservative than FE results. This is because the R6 level 3 profile takes no account of the effect of similar metal welding and doesn’t cover small radius-to-thickness ratio, i.e. \( r/t_{SE} = 1 \). For these reasons, the through-wall residual stress profile for the dissimilar metal nozzle butt weld is proposed through modifying the coefficients of existing the R6 level 3 profile. The proposed profile shows much better prediction than R6 level 3 profile for the dissimilar metal nozzle butt weld.

References


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