Residual Stress Analysis of Dissimilar Weld Joint between Cast Iron Pipe and Steel Flange

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In the present study, a large-scale finite element analysis of welding thermal elastic-plastic behavior was conducted for the purpose of estimating the residual stress distribution at dissimilar welds between a cast-iron pipe and steel flange. Based on the calculation results, the effect of welding pass and heat input conditions on the distribution of residual stress was investigated. The results showed that tensile residual stress occurred along the interface between a cast-iron pipe and steel flange, regardless of the welding pass and heat input conditions. Note that the calculated tensile residual stress becomes smaller for a large-heat-input and small-pass-number condition, compared to a small-heat-input and large-pass-number condition. This is because transverse residual stress induced by welding is strongly affected by the balance of plate thickness and heat input, which is a cause of the bending moment at welds. Thus, we concluded that the transverse residual stress could be controlled along the interface between a cast-iron pipe and steel flange by optimizing the welding conditions according to the weld joint configuration. Through a welding test and an experiment using deep hole drilling, a relatively small tensile residual stress was obtained for a large-heat-input and small-pass-number condition.

Key Words: Finite Element Analysis, Welding, Residual Stress, Cast-iron Pipe, Steel Flange, Dissimilar Weld Joint, Deep Hole Drilling

1. Introduction

Since cast iron has a high carbon content, thermal cycle-induced microstructural changes can be more complicated than in steel. In particular, welding-induced cracking may occur due to material embrittlement and high residual tensile stress. In general, pre-heat treatment and post-heat treatment are used to prevent weld cracking. However, these methods are not suitable for efficient production. Therefore, a simpler way to ensure weldability is desired, and it would be useful if weld cracking could be prevented by optimizing the welding conditions.

In the present study, we focus on dissimilar weld joints between a cast-iron pipe and steel flange as an example of a welding application in cast-iron structures. In this situation, there is a risk of weld cracking between the pipe and the flange. This crack is particularly affected by the radial tensile stress along the interface. As such, through thermal elastic-plastic analysis, we investigated the effect of welding conditions on reducing the radial residual stress along the interface. Based on the analysis results, we used an appropriate welding procedure to prevent welding-induced cracking. In addition, in order to validate the usefulness of this welding procedure, we conducted a welding test and a measurement experiment by deep hole drilling (DHD).

2. Effect of welding conditions on radial residual stress along the interface

2.1 Thermal elastic-plastic analysis

We conducted a numerical analysis assuming a dissimilar weld between a ductile cast-iron pipe and steel flange. Figure 1 shows an overall view of the numerical model, and Fig. 2 shows cross sections of five types of numerical models. As boundary condition, heat transfer (heat transfer coefficient: $1.0 \times 10^{-5}$ W/mm²K) and heat radiation (thermal emissivity: 0.3) based on the Stefan-Boltzmann law were applied, and constraints on model rotation and movement were given. Table 1 shows five types of welding heat input conditions, and Table 2 shows the total number of elements and the minimum element size for the numerical models. In this analysis, ductile cast iron was assumed for the pipe, and general structural rolled steel SS400 was assumed for the flange. Figures 3 and 4 show the thermo-physical and mechanical properties used. These properties were determined based on commonly-used and measured values of similar materials.

In order to investigate the effect of the welding sequence, we set conditions A and B. Conditions A and B use the same numerical model, but in condition A the fillet side is welded first, whereas in condition B the groove side is welded first.

Next, in order to investigate the effect of welding heat input per unit time $q$ or welding speed $v$, conditions C and D were set so that the same welding heat input per unit length $Q$ could be achieved under different welding speed conditions.

Finally, in order to investigate the effect of the total number of welding passes, we set condition E as the large-pass-number condition and condition F as the small-pass-number condition.

These heat input conditions were determined based on the welding conditions in construction work. Under these conditions,
we performed a thermal elastic-plastic analysis using the iterative substructure method\(^3\) in order to reduce the calculation time.

| Condition | Heat input per unit time, \(\eta IY - q\) (J/s) | Welding speed, \(v\) (mm/s) | Heat input per unit length, \(Q\) (J/mm) |
|-----------|---------------------------------|-----------------|-------------------------------|
| A, B      | 4250                            | 18.0            | 236.1                         |
| C         | 6082                            | 10.0            | 608.2                         |
| D         | 3041                            | 5.0             | 608.2                         |
| E         | 4250                            | 5.3             | 798.9                         |
| F         | 4250                            | 18.0            | 236.1                         |

Fig. 1  Overall view of the numerical model.

Fig. 2  Details of cross sections of numerical models around the welded part.

Table 1  Heat input conditions used in the numerical simulation.

| Condition number | Total number of elements | Minimum element size (mm) |
|------------------|--------------------------|---------------------------|
| A, B             | 86310                    | Axial 0.8, Radial 1.0, Circumferential 4.0 |
| C, D             | 72450                    | Axial 1.0, Radial 1.5, Circumferential 4.0 |
| E                | 74052                    | Axial 1.5, Radial 1.6, Circumferential 4.0 |
| F                | 72358                    | Axial 1.5, Radial 1.6, Circumferential 4.0 |

Fig. 3  Thermo-physical properties used.

Fig. 4  Mechanical properties used.
2.2 Effect of welding sequence

We investigated the effect of the welding sequence on the radial residual stress along the interface between the cast-iron pipe and the steel flange. Figure 5 shows the radial residual stress after each pass under condition A, and Fig. 6 shows the results for condition B. Figure 7 shows the radial residual stress along the interface after welding for conditions A and B.

Figures 5 and 6 show that the residual stress distribution does not change from the 1st pass to the 4th pass for condition A or from the 6th pass to the 9th pass for condition B. Furthermore, as shown in Fig. 7, the radial residual stress distribution at the interface after welding is approximately the same for conditions A and B. This suggests that fillet welding does not significantly affect the radial residual stress at the interface. Based on the results, the effect of the welding sequence is small in terms of whether the groove side or the fillet side is welded first.

2.3 Effect of heat input per unit time and welding speed

We investigated the effect of welding heat input per unit time $q$ and welding speed $v$ on the radial residual stress along the interface. Figure 8 shows the radial residual stress after each pass under conditions C and D.

As shown in Fig. 8, the radial residual stress distribution at the interface is approximately the same for conditions C and D. This suggests that heat input $q$ and welding speed $v$ do not significantly affect the radial residual stress at the interface. Therefore, the radial residual stress along the interface is governed not by the welding heat input per unit time $q$ or the welding speed $v$, but rather by the welding heat input per unit length $Q (= q/v)$.

2.4 Effect of the total number of welding passes

We investigated the effect of the total number of welding passes on the radial residual stress along the interface. Figure 9 shows the radial residual stress after each pass under condition E, and Fig. 10 shows the results for condition F. Figure 11 shows the radial residual stress along the interface for conditions E and F. We set condition F to be 30% of the heat input $Q$ of condition E. By reducing the welding deposition per pass, condition F was set to the large-pass-number condition.
Considering the residual stress around the surface ($d = 1\, \text{mm}$, in Figs. 9 and 10) for each condition, the radial tensile stress increased greatly for the 5th pass in condition E and the 9th, 13th, and 16th passes of condition F. In particular, as shown in Fig. 11, condition F has a larger radial tensile residual stress around the surface ($d = 1\, \text{mm}$, in Fig. 11) compared to condition E.

![Fig. 9](image1.png) Radial residual stress along the interface after each welding pass (condition E).

![Fig. 10](image2.png) Radial residual stress along the interface after each welding pass (condition F).

![Fig. 11](image3.png) Radial residual stress along the interface for conditions E and F.

When the hypotenuse side of the groove is welded, the effect of the stress redistribution by welding is small at the interface, and the tensile stress caused by the shrinkage of the weld is accumulated. This suggests that the small-heat-input welding at the groove side can increase the tensile stress at the interface. This is considered to be the cause of the generation of the large radial tensile residual stress under condition F and suggests that the large-heat-input (large-$Q$) and small-pass-number condition is effective in reducing the radial tensile stress along the interface.

3. Validation by welding test and stress measurement

3.1 Experimental condition

We conducted a welding experiment under the large-heat-input and small-pass-number condition and validated the usefulness of such a welding condition in preventing welding-induced cracking. Tables 3 and 4 show the chemical composition of ductile cast iron and filler metal. Table 5 shows the flange dimensions, and Table 6 shows the cast-iron pipe dimensions. Table 7 shows the welding conditions applied in the experiment. The welding was performed in the sequence shown in Fig. 12(a), and the weld cross section shown in Fig. 12(c) was obtained. The DHD technique was applied to this specimen. (The dimensions of drilled and trepanned holes for the DHD technique are shown in Fig. 12(c).) Average value of elastic constants of the cast-iron and steel was used to calculate residual stress. The measured distribution of the radial residual stress along the interface was compared with the calculated results. Figure 12(b) shows the FE model used in the analysis. The material properties shown in Figs. 3 and 4 were used in the analysis.

| Table 3 | The chemical composition of ductile cast iron. |
|---------|-----------------------------------------------|
| C       | 3.65  | Si   | 1.80  | P     | 0.04  | Cu   | 1.00  | Mn   | 1.60  | S     | 0.01  | Mg   | 0.04  | Fe   | Bal. |

| Table 4 | The chemical composition of filler metal. |
|---------|------------------------------------------|
| C       | 0.01  | Si   | 0.52  | P     | 4.04  | Mn   | 0.001 | S    | 0.002 | Ni    | 56.39 | Fe   | Bal.  | Nb+Ta|
|         | 2.47  |
### Table 5: The flange dimensions.

| Outer diameter (mm) | Inner diameter (mm) | Thickness (mm) |
|---------------------|---------------------|----------------|
| 385.0               | 271.8               | 22.0           |

### Table 6: The cast iron pipe dimensions.

| Outer diameter (mm) | Thickness (mm) | Length (mm) |
|---------------------|----------------|-------------|
| 271.0               | 10.0           | 1000.0      |

### Table 7: Welding conditions applied in the experiment.

| Pass number | Welding current (A) | Arc voltage (V) | Welding speed (mm/s) |
|-------------|---------------------|-----------------|----------------------|
| 1           | 300                 | 30.0            | 5.0                  |
| 2           | 210                 | 24.5            | 15.0                 |
| 3           | 250                 | 23.0            | 10.0                 |
| 4           | 260                 | 27.0            | 13.3                 |
| 5           | 235                 | 24.0            | 10.0                 |

### 3.2 Results and discussion

Figure 13 shows a contour map of the radial residual stress of the cross section at the center of the weld line. Figure 14 shows the radial residual stress distribution along the interface between the measurement result by the DHD technique and the numerical analysis results. Comparatively good agreement is observed between the distributions, and both calculated and measured tensile residual stresses are relatively small. In addition, we conducted a penetrant inspection on this specimen and found that no weld cracking had occurred. It was confirmed that the large-heat-input and small-pass-number condition was one of suitable procedure conditions for preventing welding-induced cracking.

### 4. Conclusions

In the present study, the numerical analysis revealed that the tensile radial residual stress at the interface between a steel flange and a cast-iron pipe was reduced under the large-heat-input and small-pass-number condition. We conducted a welding test based on this consideration, and no weld cracking was observed. A relatively small residual tensile stress at the interface was measured using DHD. Based on these results, the radial residual stress along the interface between a cast-iron pipe and a steel flange could be controlled by optimizing the welding conditions.

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