Determination of Residual Stress in GTA Multi-pass Welds in Stainless Steel Pipe by Means of Numerical Simulation and Comparison with Experimental Measurement

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Summary

The aim of this study was to analyze the temperature fields and the residual stress state in multi-pass welds made in SUS304 stainless pipe by a gas tungsten arc welding process. With the help of the ABAQUS software, uncoupled thermal-mechanical 2-D and 3-D finite element models were developed. The FE models were used to determine the transient temperature and the residual stress filed during and after welding. Effect of cooling rate on the welding residual stresses was also investigated. Meanwhile, experiments were carried out to verify the simulated results. The simulated results are in very good agreement with the experiment.

Introduction

Welding is a reliable and efficient metal joining process. The welding process is used in almost all industries. The circumferential butt weld is a common type of joint in piping systems in power plant. Owing to the relatively large wall thickness in such piping systems, the butt weld is often constructed of several weld passes. Due to the intense concentration of heat in the heat source of welding, the regions near the weld line undergo sever thermal cycles. The thermal cycles cause non-uniform heating and cooling in the material, thus generating inhomogeneous plastic deformation and residual stresses in the weldment. The presence of residual stresses can be detrimental to the performance of the welded product. Tensile residual stresses are generally detrimental, increasing the susceptibility of fatigue damage, stress corrosion cracking and fracture. When assessing the risk for growth of defects such as surface flaws in piping systems the welding residual stress may give a large contribution to the total stress field than stress caused by design loads [1]. Moreover, in order to prevent inter-granular stress corrosion cracking (IGSCC) in the root area of welds in austenitic steel, it is necessary to satisfy certain requirements concerning process condition, material properties and welding residual stress. Therefore, a good estimation of the welding residual stress field is then needed.

In the present study, 2-D and 3-D FE models for determining the temperature fields and the residual stresses in multi-pass butt welds in piping system were developed. The development of the temperature and stress fields during the entire history in the course of welding was simulated numerically by using a commercially available FE Code (ABAQUS Code) for non-linear analysis. In this study, experiments were carried out to verify the effectiveness of the developed numerical model. The experimental and numerical results show a very good agreement.

Experimental Procedure

The material used in this study was SUS304TP 4Bsch40 pipe with outer diameter of 114.3 mm, thickness of 6 mm, and length of 800 mm. The welded pipe and the shape of

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groove are schematically shown in **Fig. 1**. The filler metal is Y308L.

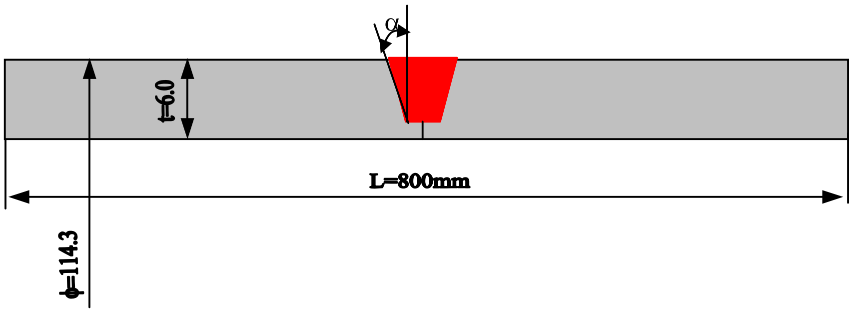

Fig.1 Dimensions of welded pipe and shape of groove.

Welding condition is shown in **Table 1**, and welding position is flat position welding. During welding the torch was fixed and the pipe was rotated. The pipe was welded by two pass welding method as shown in **Fig. 2.** The inter-pass temperature is slightly higher than room temperature (25 ^{o}C).

Table 1. Welding Condition

Pass	Current (A)	Voltage (V)	Speed (mm/min)	Heat input (kJ/mm)
1	140	9.5	80	1.0
2	160	9.5	80	1.1

In the experiment, the thermal cycles at several locations on inside and outer surfaces are measured using the thermal couples as shown in Fig. 2. After completion of welding, the strain gages with 1 mm length were used to measure the welding residual stress.

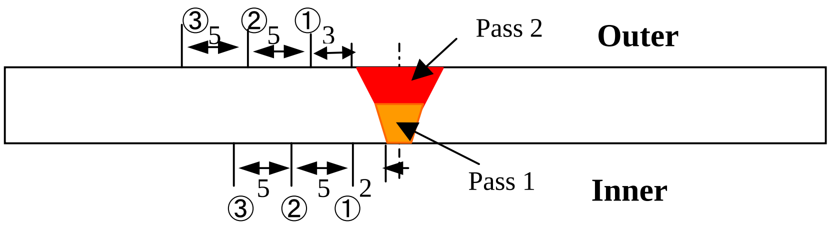

Fig. 2 Weld pass and locations of temperature measurements.

FE Modeling

The temperature fields and the evolution of the residual stresses are investigated by means of finite element method. In order to accurately capture the temperature fields and the residual stresses in the welded pipe, a three-dimensional finite element model was developed.

The thermo-mechanical behavior of the weldment was simulated using uncoupled formulation. In this study, a 3-D pipe model was developed to simulate the temperature fields and welding residual stresses at first. Secondly, based on the results of the 3-D model, a 2-D axisymmetric model was also created to calculate the temperature fields and the residual stress fields. Thirdly, the simulated results of the 2-D model and the 3-D model were compared with the experimental results.

Because of the symmetry, one half of the model was selected as the analysis model. The 3-D FE model is shown in **Fig. 3** with 9600 brick elements and 12300 nodes. It has a fine grid in the welding zone. In this study, the heat from the moving welding arc was applied as a volumetric heat source with a double ellipsoidal distribution proposed by Goldak et al [2]. The arc efficiency η, is assumed to be 70 % for the TIG welding process. The 2-D axisymmetric model is shown in **Fig. 4**.

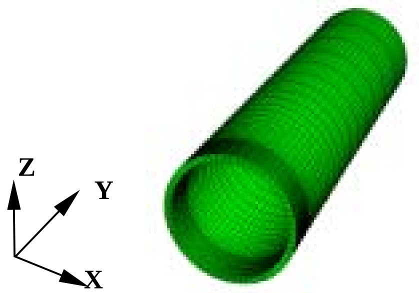

Fig. 3 3-D simulated model.

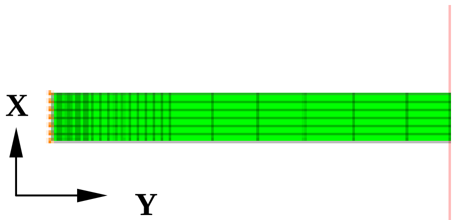

Fig. 4 2-D simulated model.

Simulated Cases of 3-D Model

In order to clarify the influence of cooling rate on the welding residual stresses, three cases with different conductivity and heat transfer coefficient were simulated. In case A, a relatively large heat transfer coefficient and a relatively large conductivity are used. In case B, the conductivity of the base metal and weld metal was assumed to be half of the case A within the range between 25 ^{o}C and 1000 ^{o}C, and a relatively small heat transfer coefficient was used. In the case C, the conductivity at room temperature was used within the range between 25 ^{o}C and 1000 ^{o}C, and the heat transfer coefficient was the same as that of the case B.

Simulated Results of Thermal Analysis

Figure 5 shows the thermal cycles of the case A and the case B at the three locations of the inside surface (θ=180^{o}) defined in Fig. 2. The experimental results are also plotted in the same figure. It is clear that the peak temperature of each location especially in those locations away from weld zone is not significantly affected by the conductivity and heat transfer coefficient. It can be also seen that the peak temperatures predicted by FEM are almost the same as those of experiment. However, the cooling rate is influenced by the conductivity and heat transfer coefficient. From this figure, we can also see that the cooling rate of experiment is between the case A and the case B. **Figure 6** shows the thermal cycles at three locations where θ is 180^o in the case C and the experimental results. From this figure, it can be observed that the experimental results and numerical ones show a very good agreement.

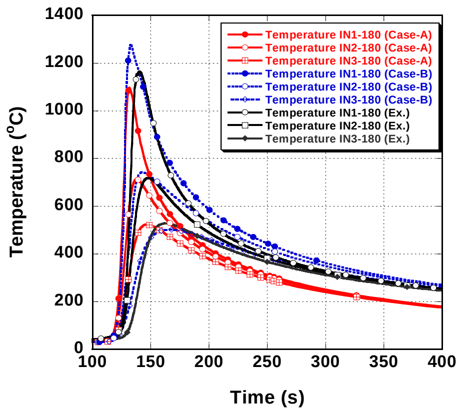

Fig. 5 Thermal cycles of cases A and B.

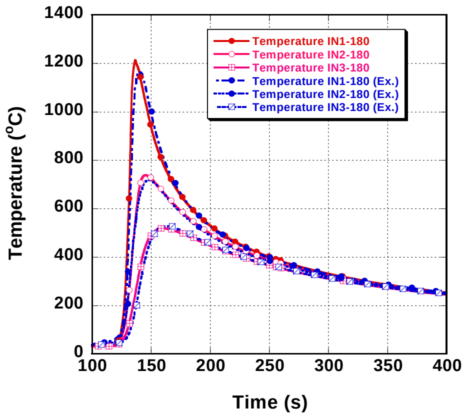

Fig. 6 Thermal cycles of the cases C.

Influence of Cooling Rate on Residual Stress

The axial stress on the outside surface was selected to discuss the influence of cooling rate on welding residual stress. **Figure 7** shows the axial stress distributions on the outside surface of the case A and the case B. It can be observed that even though the cooling rate is very different in the two cases, the final welding residual stresses in axial direction are much similar. This tells us that the welding residual stress is not sensitive to cooling rate when the solid phase transformation does not happen during the welding.

Characteristic of Welding Residual Stress Distribution

As an example, the hoop stress on inner surface of the case C was selected to study the characteristic of distribution of welding residual stress. **Figure 8** shows the hoop stresses at different locations with different angle θ. In Fig. 8, when θ is 0 degree the hoop stress distribution in weld zone and its vicinity is slightly different from that of other three angles (θ=90, 180 and 270 degree) because of the end effect. When θ is 90 degree the hoop stress at Y=30 mm is smaller than that of the other three locations (θ=0, 180 and 270 degree). However, in general, the hoop stress is not significantly sensitive to the angle θ.

According to the above results, even though the residual stress at the starting position of welding and its vicinity is different from the other locations, in general the residual stress distribution has a homogeneous characteristic with respect to the circumferential direction. Thus, it is meaningful to compare the simulation results of the 3-D model with the results simulated by the 2-D axisymmetric model.

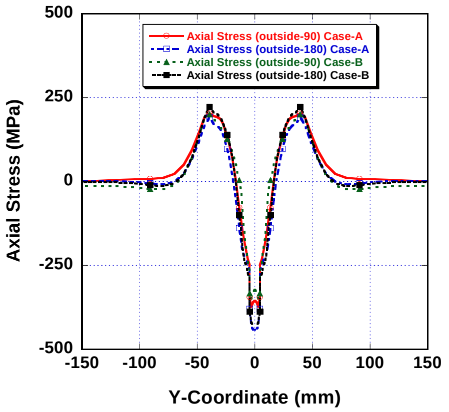

Fig. 7 Axial stress of case A and case B.

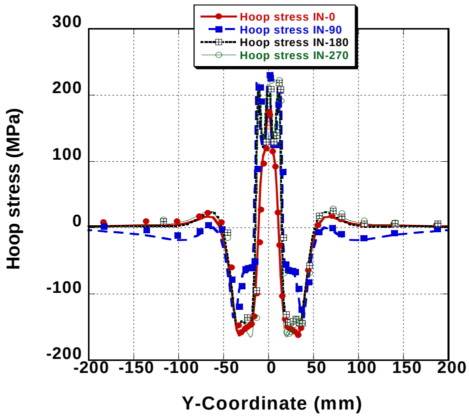

Fig. 8 Axial stress of case C.

Comparison with 2-D Model as well as Experiments

The residual stresses of the case C at the locations where θ is 180 degree along the axial direction were selected to compare with the results of the 2-D model and the experiment. **Figures 9** and **10** show the axial stress and hoop stress on the inside surface along the axial direction, respectively. The solid circles represent the results of the experiment measured by strain gauge, and the solid curves the results of the 3-D model, and the broken curves the results of the 2-D model. From the two figures, small differences are observed in the weld zone among the experiment, the 3-D model and the 2-D model. This is because the reinforcement was not accurately considered in the FE models. Except this zone, both the axial stress and hoop stress are in very good agreement with one another among the experiment, results of the 3-D model and the results of the 2-D model.

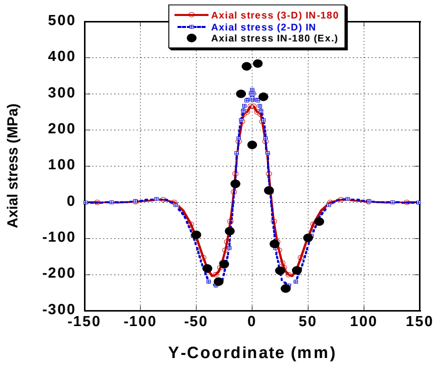

Fig. 9 Axial stress at inside surface.

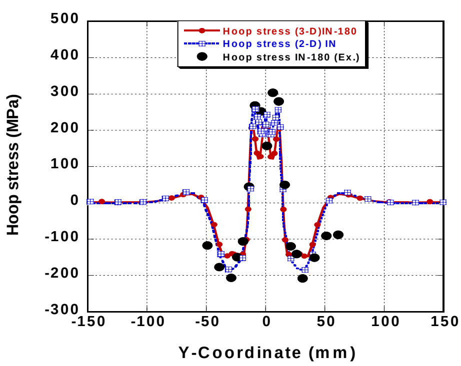

Fig. 10 Hoop stress at inside surface.

Figures 11 and **12** show the axial stress and the hoop stress on the outside surface along the axial direction, respectively. It can be observed that the axial stresses of both the 3-D model and the 2-D model are in good agreement with the experiment. For the hoop stress on outside surface, the stress distribution predicted by the 3-D model is similar to that simulated by the 2-D model. At the weld zone and its vicinity, the hoop stress distribution measured by experiment is also similar to the simulation results. Within the range where the distance is larger than 40 mm from the weld centerline, the hoop stress measured by experiment is larger than the simulation results. This difference is caused by the initial residual stress introduced by the manufacture process before welding.

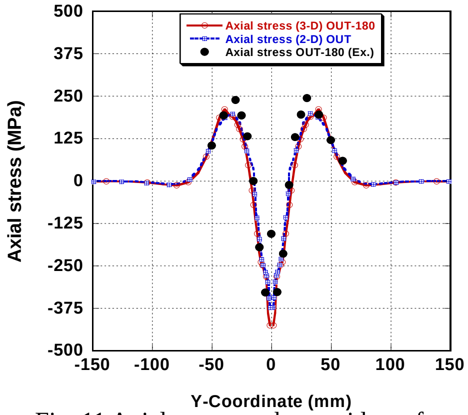

Fig. 11 Axial stress on the outside surface.

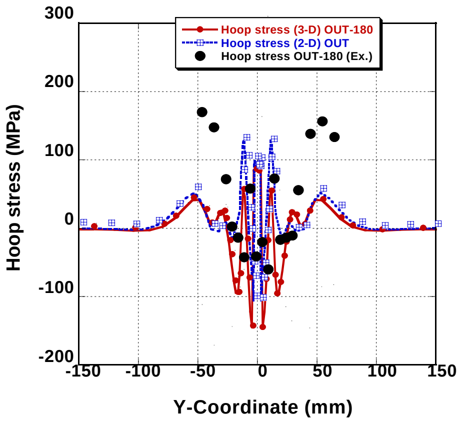

Fig. 12 Hoop stress on the outside surface.

According to the comparison and discussion, we can conclude that the 2-D axisymmetric model can be effectively used to simulate the welding residual stress for stainless steel (SUS304) pipe.

Conclusions

1) The welding residual stress in SUS304 pipe is not affected by the cooling rate. Because no solid phase transformation happens during cooling in stainless steel, the finial inherent strain (plastic strain) is determined by spatial temperature distribution during welding and the restraint condition. Therefore, the final residual stress does not depend on the cooling rate.

2) Both the 2-D axisymmetric FE model and the 3-D FE model predicted satisfactory results of welding residual stress. The simulation results are in much good agreement with the experiments. Using the 2-D model, a large amount of computational time can be saved without sacrificing the accuracy.

References

1. B. Brickstad and B.L.Josefson, A parametric study of residual stresses in multi-pass butt-welded stainless steel pipes, *International Journal of Pressure Vessels and Piping*, 75(1998) pp.11-25.
2. Goldak. J, Aditya Chakravarti and Malcolm Bibby, A new finite element model for welding heat sources, *Metallurgical Transactions B*, Vol. 15, June 1984, pp.299-305.