Three Dimensional Numerical Simulation of Various Thermo-mechanical Processes by FEM (Report IV) †

— Deformation Analysis of Pipe-Plate Joint with Holes by Multi-pass Welding —

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Abstract

Residual deformations and stresses of a pipe-plate joint with holes after multi-pass welding are analyzed. The numerical simulations are performed using the thermal-elastic-plastic Finite Element Method and three dimensional solid elements are used. The shrinkages of the joint and deformations of holes for bolts which locate around the pipe are analyzed using different geometrical models and welding conditions. The change of the shape and the location of the holes after the circular fillet welding between the pipe and the plate are analyzed. Half-circle joint model and full-circle joint model, instantaneous heat source and moving heat source, single-pass and multi-pass weldings are considered for comparison. The computed results provide a great deal of informations which are very useful for predicting the effects of various welding conditions on residual deformations and also useful for controlling the geometrical accuracy of the pipe-plate joint. The transient and the residual stresses due to the multi-pass welding are also analyzed.

KEY WORDS: (Multi-pass Welding) (Pipe-Plate Joint) (Residual Deformation) (Residual Stress) (Finite Element Method) (Moving Heat Source)

1. Introduction

The pipe-plate joints are widely used in the industries such as in various types of pressure vessels and piping systems. In this paper, a pipe-plate weld joint with eight holes is analyzed. The pipe is welded with the plate by multi-pass fillet welding. The holes are distributed symmetrically on the plate around the pipe. The welding process, which is an irreversible thermo-mechanical process, causes distortion of the shape of the holes and the change in their locations together with the overall shrinkage of the joint. These may influence the following assembly processes if the welding distortions exceed the allowable tolerance. Therefore, it is necessary to predict the welding distortions of such welded joints. Three dimensional numerical simulations using the Finite Element Method are employed for this purpose.

In order to solve 3-D thermal-elastic-plastic problems which is close to the practical situation by FEM, modeling of the problem is very important from computing accuracy and efficiency point of view. To examine the effect of modeling, a half-circle pipe-plate model and a full-circle model, moving heat source and instantaneous heat source, multi-pass welding and single-pass welding are considered.

In general, the magnitude and the characteristic of the welding deformations depend on the selected model and the welding conditions. The influence of these factors are examined through numerical simulation.

2. Multi-pass Welding of Pipe-Plate Joint with Holes

2.1 Pipe-plate joint with holes

A pipe ($\phi 76\times 8$) is assumed to be inserted and joined with a plate of thickness of 16 mm by multi-pass welding. There are eight through holes ($\phi 26$) located symmetrically around the pipe. The height of the fillet welds connecting the pipe and the plate is 8 mm. The electrodes with diameter of 3.2 mm are used and the

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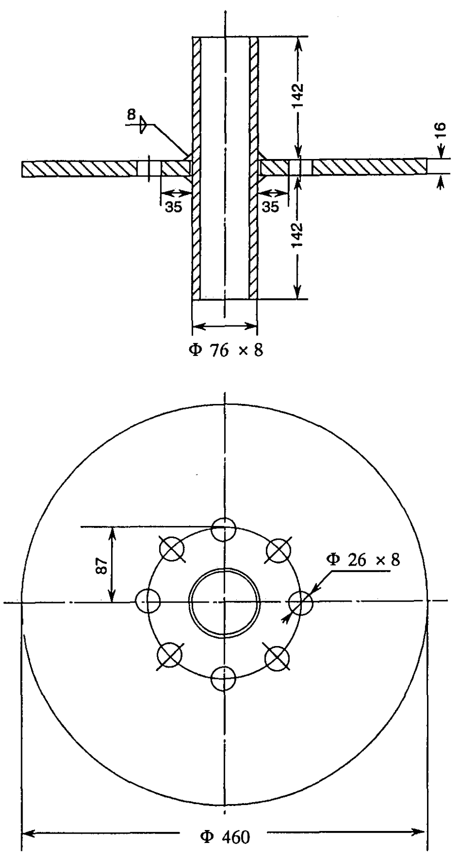


Fig.1 Pipe-plate joint with through holes.

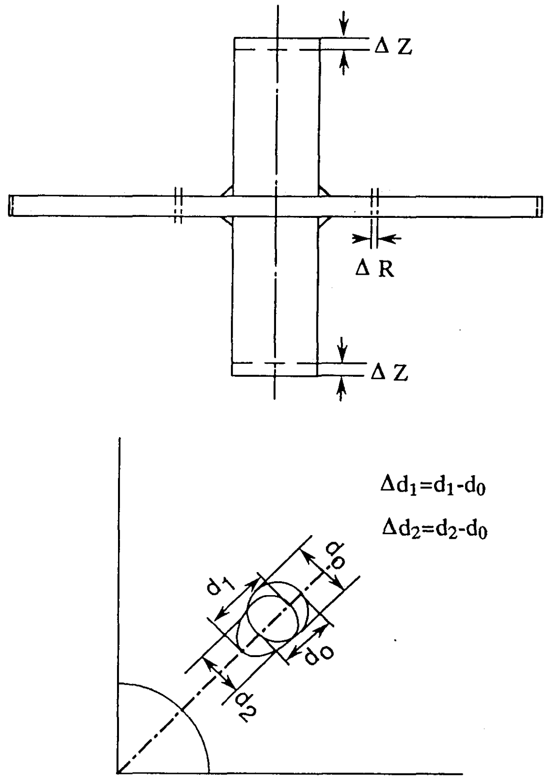


Fig.2 Welding deformation of pipe-plate joint.

welding current is about 100-120 A for three-pass welding. **Figure 1** shows the diagram of a pipe-plate joint with holes.

2.2 Welding deformations of a pipe-plate joint

After welding, the pipe-plate joint is deformed as shown in **Fig.2**. ΔZ is the shrinkage of the pipe in the axial direction. ΔR is the changes of the location of the hole center in the radial direction. Δd_1 and Δd_2 are the changes of diameters of the holes in radial and circumferential directions, respectively.

3. Models for Analysis

3.1 Mesh division

Mesh divisions of the two models are shown in **Figs.3-(a)** and **(b)**. Model-1 is a half-model for predicting the welding deformations under the different welding conditions. Model-2 is a full-model for showing the characteristics of welding deformation of holes by full-circular moving heat source.

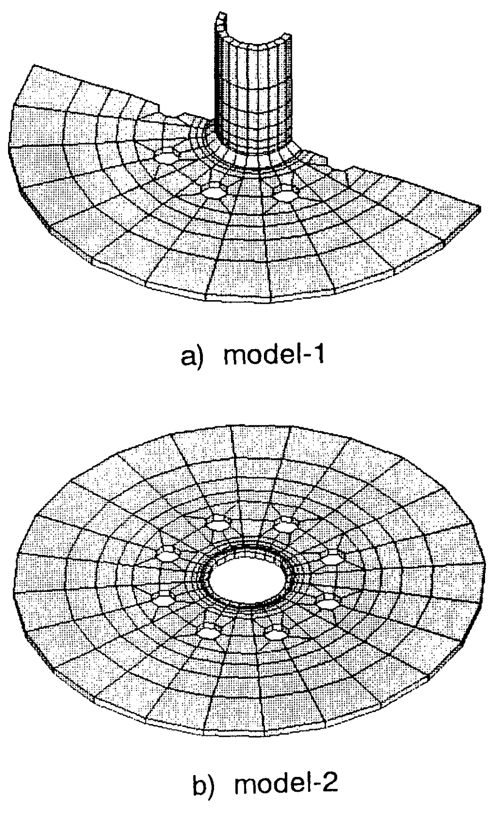


Fig.3 Mesh division.

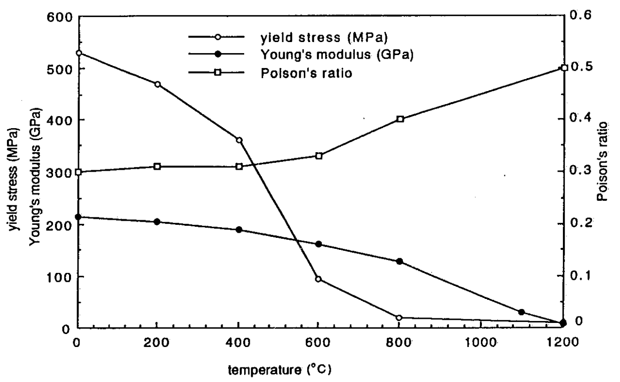


Fig.4 Temperature dependency of yield stress, Young's modulus and Poison's ratio.

3.2 Multi-pass welding

The real fillet welds are laid by three-pass welding. During the welding of each pass, the elements for the newly welded pass are assumed to exist from the beginning. Only, very small values of Young's modulus and yield stress are assumed for those elements until they are filled with the weld metal and cooled down to the temperature at which the material shows appreciable stiffness and strength. The single-pass welding is also considered for comparison. In this case, the heat input is assumed to be three times greater than that for each pass in the multi-pass welding, so that the the total amount of the heat input is kept the same.

3.3 Moving heat source and instantaneous heat source

In the case of moving heat source, the heat source is assumed to move along the circumferential seam connecting the pipe and the plate at the speed of 2.5 mm/sec. In the case of instantaneous heat source, the heat input is assumed to be applied along the welding line instantaneously. The heat input rate is assumed to be 21.6 J/(mm^3·sec).

3.4 Material properties

The properties of material and their temperature dependency used in the simulation are shown in **Fig.4**. The thermal and the physical properties of the material are assumed as follows:

heat conductivity

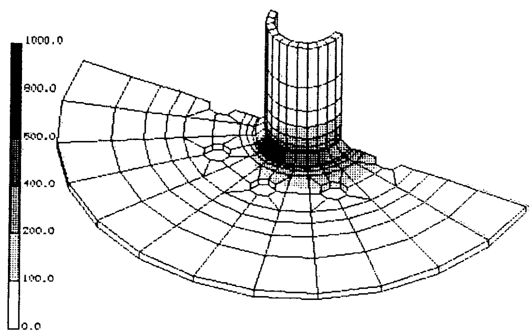
$\lambda = (54.43 - 4.2 \times 10^{-5} T^2) \times 10^{-3}$ J/(mm·s·°C) (1)

thermal capacity

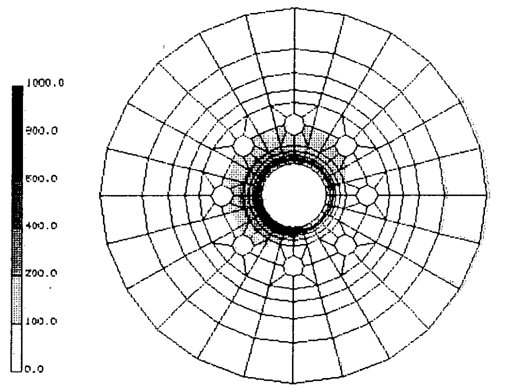
$c = 0.41 + 6.3 \times 10^{-4} T$ J/(g ·°C) (2)

density

$\rho = (7.82 - 2.625 \times 10^{-3} T) \times 10^{-3}$ g/mm^3 (3)



a) model-1



b) model-2

Fig.5 Temperature fields by moving heat source.

heat transfer coefficient

$\beta = 33.5 \times 10^{-6}$ J/(mm^2·s·°C) (4)

thermal expansion coefficient

$\alpha = 1.3 \times 10^{-5}$ °C^{-1} (5)

4. Simulation Results and Discussions

4.1 3-D heat conduction analysis by FEM

Three-dimensional heat conduction analysis by FEM is used in all the simulations. **Figures 5-(a) and (b)** show the temperature fields for model-1 and model-2 under the moving heat source, respectively. It can be seen that the temperature field under the moving heat source is unsymmetric and not uniform along the welding line. This causes the difference in residual deformations after the joint is cooled down. The model-1, in which only a half-model is considered, is equivalent to the case in which two arcs are moving in the opposite directions along the weld line. In this case, the temperature near the starting and the finishing ends becomes higher than that of the full-model due to the two heat sources existing close to each other. This will influence the generation of welding deformations.

Table 1 Computed results of welding deformations for model-1.

No	Condition of computations	ΔZ	Deformations of holes			
			hole No.	ΔR	Δd_1	Δd_2
1	Instantaneous heat source with single pass welding	-0.050	1-5	-0.262	0.142	-0.107
2	Instantaneous heat source					
	after 1st pass welding	-0.032	1-5	-0.113	0.061	-0.036
	after 2nd pass welding	-0.034	1-5	-0.145	0.078	-0.048
	after 3rd pass welding	-0.042	1-5	-0.163	0.089	-0.054
3	Moving heat source with single pass welding	-0.260	1	-0.223	0.112	-0.201
			2		0.124	
			3	-0.261	0.138	-0.097
			4		0.148	
			5	-0.260	0.152	-0.011
4	Moving heat source					
	after 1st pass welding	-0.174	1	-0.080	0.047	-0.079
			2		0.046	
			3	-0.105	0.053	-0.021
			4		0.057	
			5	-0.083	0.053	-0.002
	after 2nd pass welding	-0.320	1	-0.066	0.056	-0.139
			2		0.060	
			3	-0.145	0.064	-0.015
			4		0.071	
			5	-0.103	0.062	0.013
	after 3rd pass welding	-0.432	1	-0.059	0.065	-0.176
			2		0.068	
			3	-0.169	0.072	-0.012
			4		0.080	
			5	-0.117	0.067	0.023

Table 2 Computed results of welding deformations for model-2.

No	Condition of computations	Deformations of the holes			
		hole No.	ΔR	Δd_1	Δd_2
1	Moving heat source				
	after 1st pass welding	1	-0.110	0.0518	-0.0631
		2		0.0398	
		3	-0.077	0.0433	-0.0186
		4		0.0481	
		5	-0.089	0.0493	-0.0360
		6		0.0502	
		7	-0.076	0.0501	-0.0478
		8		0.0502	
2	Instantaneous heat source after 1st pass welding	1-8	-0.102	0.0542	0.0308

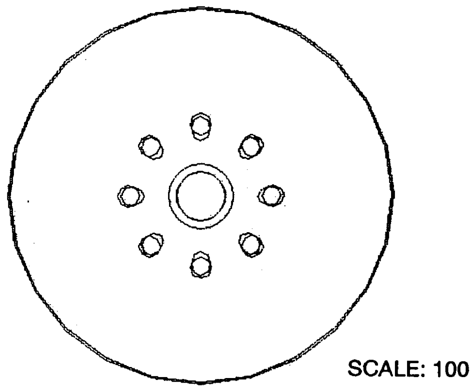
4.2 3-D thermal-elastic-plastic analysis by FEM

For 3-D thermal-elastic-plastic analysis by FEM, the local coordinate system and reduced integration method which have been reported in the previous works[1),2),3)] are also used in this study.

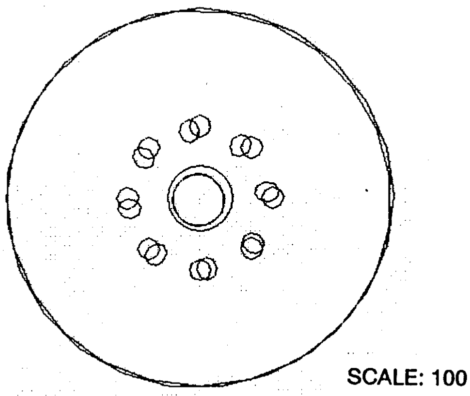
4.3 Computed results of residual deformations

Two models with three different welding conditions as shown in the followings are considered in the simulation:

(1) model-1 with instantaneous heat source by single-pass welding;



(a) by instantaneous heat source



(b) by moving heat source

Fig.6 Residual deformation of model-2.

(2) model-1 with instantaneous heat source by three-pass welding;
(3) model-1 with moving heat source by single-pass welding;
(4) model-1 with moving heat source by three-pass welding;
(5) model-2 with instantaneous heat source by first pass welding;
(6) model-2 with moving heat source by first pass welding.

The computed residual deformations are summarized in **Table 1** and **Table 2**. **Figures 6-(a)** and **(b)** show the residual deformations of model-2 welded by the instantaneous heat source and by moving heat source, respectively.

Based on these results, characteristics of residual deformations of the pipe-plate joint can be described as follows.

(1) The shrinkages are caused in both the pipe and the plate. The axial shrinkage of the pipe, ΔZ , is about 0.4 mm and the radial displacement of the hole center, ΔR, is about 0.06-0.17 mm after three-pass welding by moving heat source.

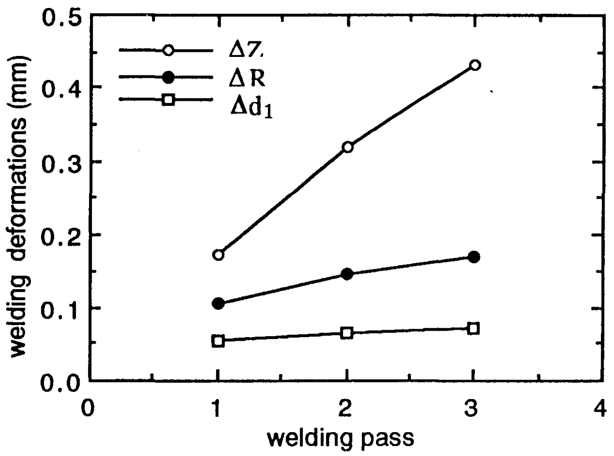


Fig.7 Residual deformations of model-1 due to multi-pass welding.

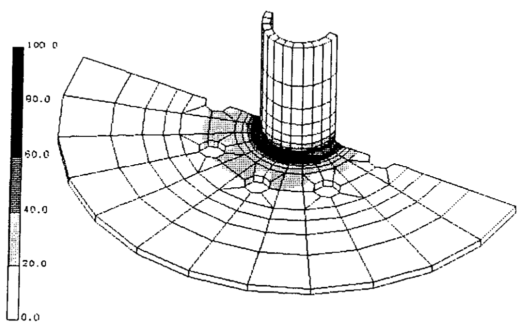


Fig.8 Residual stress of model-1 by moving heat source.

(2) The shape of the deformed hole is like an egg as shown in Fig.2. The diameter in radial direction expands about 0.07-0.08 mm and it reduces in circumferential direction about 0.01-0.17 mm.

(3) If the instantaneous heat source is used instead of the moving heat source, the welding deformations show the symmetry with respect to the center of the pipe. The magnitudes of distortion approximately correspond to the average values of ΔR, Δd_1 and Δd_2 for the case of the moving heat source. However, the computed shrinkage of the pipe, ΔZ, is very small compared to the case of moving heat source. This is due to the fact that the constraint against the axial shrinkage which produces the plastic deformation is small in the case of instantaneous heat source.

(4) The values of welding deformations, ΔR, Δd_1 and Δd_2, for the case by single-pass welding are larger than that by multi-pass welding, because larger heat input is applied in the single-pass welding compared with that of each pass in multi-pass welding. However the shrinkage of the pipe, ΔZ , in the pipe by single-pass welding is smaller than that by multi-pass welding. This may be due to the fact that the shrinkage ΔZ is additive in multi-pass welding and the constraint which produces plastic strain becomes smaller when the heat input is large as in the equivalent single-pass welding. Therefore, it is not recommended to use the equivalent single-pass welding model instead of the multi-pass welding from the accuracy point of view.

(5) **Figure 7** shows the residual deformations of model-1 during multi-pass welding with moving heat source. It can be seen that the first pass of the welds causes the largest deformations as shown by the values of ΔZ , ΔR and Δd_1 in Table 1, where ΔR and Δd_1 are the deformations at hole-3.

(6) The welding deformations computed by the full-model shows the characteristics which is quite different from those predicted by the half-model. Reasonable shape and location of the holes, which are expected to be closer to the real situation, are predicted only by the full-model. Thus, it is recommended to use the full joint model, if the capacity of the computer is large enough.

4.4 Residual stresses

Figure 8 shows the principal stresses of the model-1 welded by three-pass welding with moving heat source. It can be seen that high tensile stresses are caused in the fillet welds and also at the heat affected zone in both the pipe and the plate.

5. Conclusions

(1) The welding deformations and stresses of a pipe-plate joint with holes have been simulated successfully by 3-D thermal-elastic-plastic FEM analysis.

(2) After multi-pass welding by moving heat source, the shrinkages are caused in both pipe and plate. The shape and the location of the holes are unsymmetric when the moving heat source is assumed.

(3) The average values of residual deformations in the plate can be predicted fairly well by the model assuming instantaneous heat source. However, it is not the case for the shrinkage of the pipe.

(4) It is not accurate to use single-pass welding instead of multi-pass welding for predicting the residual deformations in both plate and pipe.

(5) In the case of multi-pass welding, the shrinkage of the pipe, ΔZ, at each welding pass is almost the same. While, ΔR and Δd_1 for the first pass is much bigger than these for the following passes.

(6) To ensure the accuracy of the predicted deformation, it is recommended to use full-model if the capacity of the computer permits.

References

1) Y. Ueda, J. Wang, H. Murakawa and M. G. Yuan, "Three Dimensional Numerical Simulation of Various Thermal-mechanical Processes by FEM (Report I) -- Methods for Improving the Convergence of 3-D Analysis of Welding--", Trans. JWRI, Vol.21, No.2(1992), pp.251-257.
2) Y. Ueda, H. Murakawa, J Wang and M. G. Yuan, "Three Dimensional Numerical Simulation of Various Thermal-mechanical Processes by FEM (Report II) -- Deformation Analysis of Compressors under Assembly by Shrinkage Fit--", Trans. JWRI, Vol.21, No.2(1992), pp.259-264.
3) Y. Ueda, J. Wang, H. Murakawa and M. G. Yuan, "Three Dimensional Numerical Simulation of Various Thermal-mechanical Processes by FEM (Report III) -- Deformation Analysis of Compressors under Assembly by Plug Welding--", Trans. JWRI, Vol.22, No.1 (1993), pp.127-134.