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EFFECT OF GEOMETRIC AND WELDING CONDITIONS ON THROUGH-THICKNESS RESIDUAL STRESS

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ABSTRACT

Recently, stress corrosion cracking (SCC) of core internals and/or recirculation pipes of austenite stainless steel (SUS316L) has been observed. SCC is considered to occur and progress at near the inner surface of the welding zone in butt-welded pipes, because of the tensile residual stress introduced by welding. In present work, three-dimensional and axisymmetric thermo-elastic-plastic finite element analysis have been carried out, in order to clarify the effect of geometric and welding conditions in circumferential welding zone on the residual stress. In particular, butt-welding joints of SUS316L-pipes have been examined. The residual stress was simulated by three-dimensional and axially symmetric models and the results were compared and discussed in detail.

INTRODUCTION

The stress corrosion cracking (SCC) has occurred in the recirculation pipe of boiling water type reactors made from SUS304 stainless steel in the 1970s. Three main reasons for the occurrence and progress of SCC have been identified as (i) sensitization by temperature history of welding (ii) a corrosive atmosphere and (iii) introduction of residual stress by welding. Many prevention countermeasures have been performed for example deaerating operation and material development. The low carbon stainless steels (SUS316L) were developed in order to decrease the effect of sensitization. However, recently, the SCC of core internals and/or recirculation pipes of SUS316L

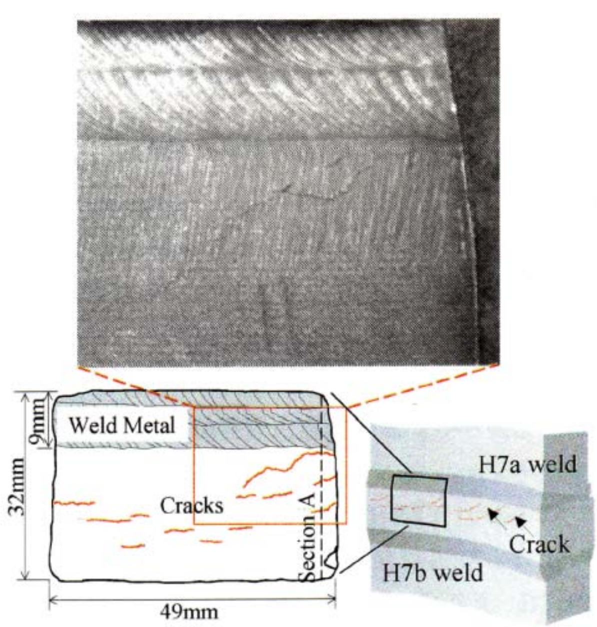


Fig. 1 - Example of stress corrosion crack [1]. Boat sample from Shroud H7a in Kashiwazaki-Kariwa Unit 3 (Material: SUS316L)

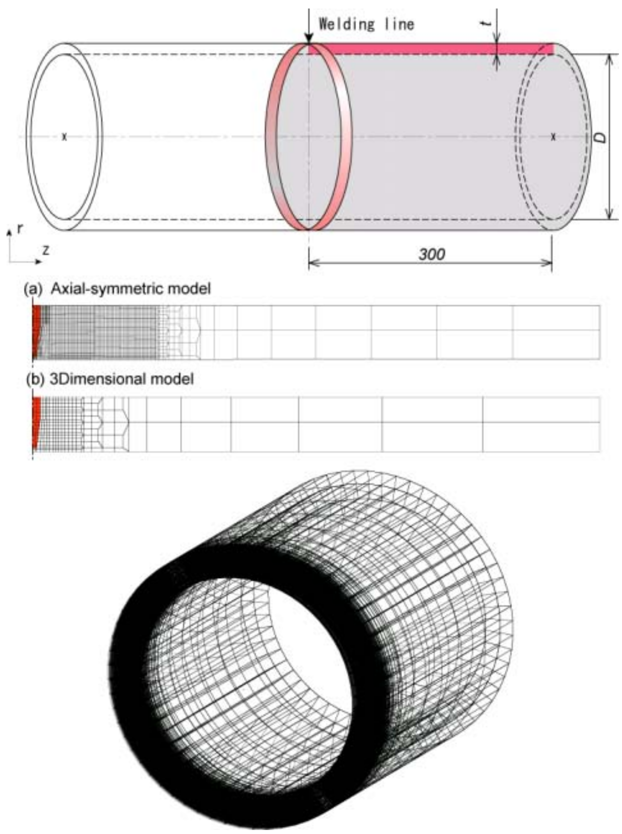


Fig. 2 - Shape of the axial-symmetric- and 3D-analysis models and those cross-section views for circumferential welding.

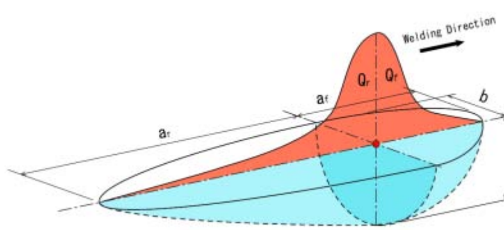


Fig. 3 Goldak model (Q_f and Q_r are heat input parameter, a_f, a_r, b and c are heat shape parameter).

stainless steel has been observed. SCC which occurs without sensitization by welding cannot be explained by existing sknowledge. From this background, the importance of mechanical factors to explain SCC has achieved increasing importance compared to the other two factors of material and environment. Thus detailed evaluation of the residual stress by welding has become an important problem.

Figure 1 shows an example of SCC which occurs along the welding line near the welded zone in a core internal. SCC is considered to occur and progress at near the inner surface of the welding zone in butt-welded pipes, because of the tensile residual stresses introduced by welding. In present work, the finite element method (FEM) of the residual stress were performed in order to clarify the effect of geometric and welding conditions in circumferential welding zone. Target was butt-welding joint of SUS316L-pipes. In particular, butt-welding joints of SUS316L-pipes have been examined. The residual stress was simulated by three-dimensional and axially symmetric models and the results were compared and discussed in detail.

ANALYSIS METHOD

The model for FEM of thermo-elastic-plastic analysis used in the present work is shown in Fig. 2. The simulations are performed with the commercial software SYSWELD. The analysis was carried out in three-dimensional and axisymmetric models as shown in Fig. 2. The geometry analysed is a butt joint in a pipe which is symmetric about the welding line. The material is low-Carbon stainless steel of SUS316L. Circumferential welding was performed in the three-dimensional model whose diameter, plate thickness and length from welding line are 300 mm, 30 mm and 300 mm, respectively (element number = 22980, node number = 21900). Heat source started to move from the position of 0 degree as, and then it moves in the clockwise rotation and its velocity was about 7.85 mm/s. In the axisymmetric model, the heat source go through the model in a direction of plane perpendicularly and its velocity was about 10 mm/s. In case of three-dimensional analysis, the adhesion of the weld metal simultaneously with passage of this heat source is also considered by changing the deactive element into active. Such adhesion of weld metal was also taken into consideration in multi-layer welding in axisymmetric analysis. The shape of the heat source used in this work is so called the Goldak model which can simulate the arc welding by giving Gaussian distribution to heat input factors (Fig. 3) [12].

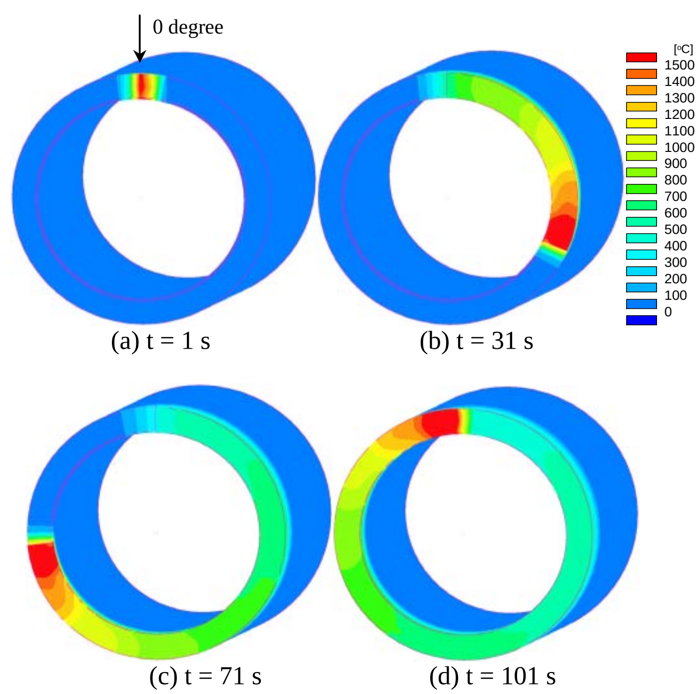


Fig. 4 - Time change of temperature distribution during circumferential butt joint welding of one pass.

RESULTS AND DISCUSSION

Three-Dimensional Analysis

In the three-dimensional model, circumferential welding of one pass was performed. Some examples of temperature distribution by thermal analysis are shown in Fig. 4. The heat source starts to move in the clockwise rotation from position of 0 degree (Fig. 4 (a)). The circumferential welding finishes in 96 seconds, consequently, it cools into room temperature of about 20 degree Celsius by 2500 seconds. The residual stress distributions of circumferential and axial directions are shown in Fig. 5. The residual circumferensial stress in the central cross section of the welding zone becomes tensile in all regions as shown in Fig. 5 (a), although its distribution is complicated near the start/finish end, where is the position of 0 degree, of circumferential welding as shown in this figure. The residual axial stress in the central cross section of the welding zone becomes tensile in the inner surface as shown in Fig. 5 (b). The residual stress gradually decreases with increasing the through-thickness distance from inner surface and it becomes compressive stress near the outer surface. Distribution of axial residual stress near the start/finish end of welding is also complicated comparing with the steady state region of circumferential welding. Both residual circumferential and axial stresses near the start/finish end become larger than that in the steady state region as shown in this figure. The same

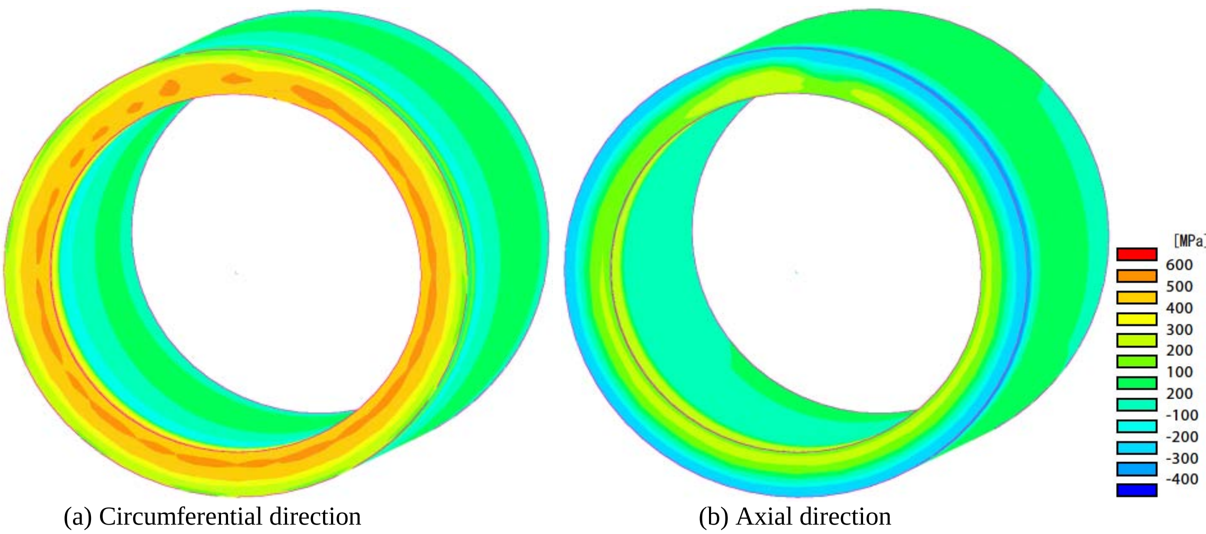


Fig. 5 - Residual stress distributions of circumferential direction (a) and axial direction (b) after circumferential welding for piping butt joint of SUS316L stainless steel (D = 300 mm, t = 30 mm, 1 pass).

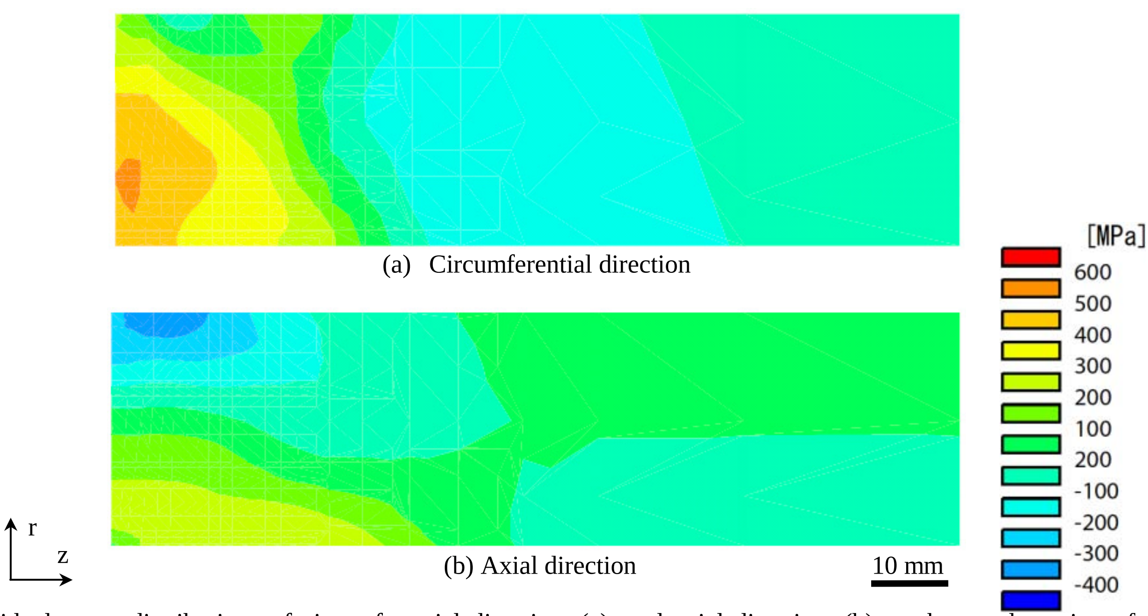


Fig. 6 - Residual stress distributions of circumferential direction, (a), and axial direction, (b), at the steady-region of three-dimensional analysis by circumferential welding for piping butt joint of SUS316L stainless steel (D=300 mm, t=30 mm, 1 pass).

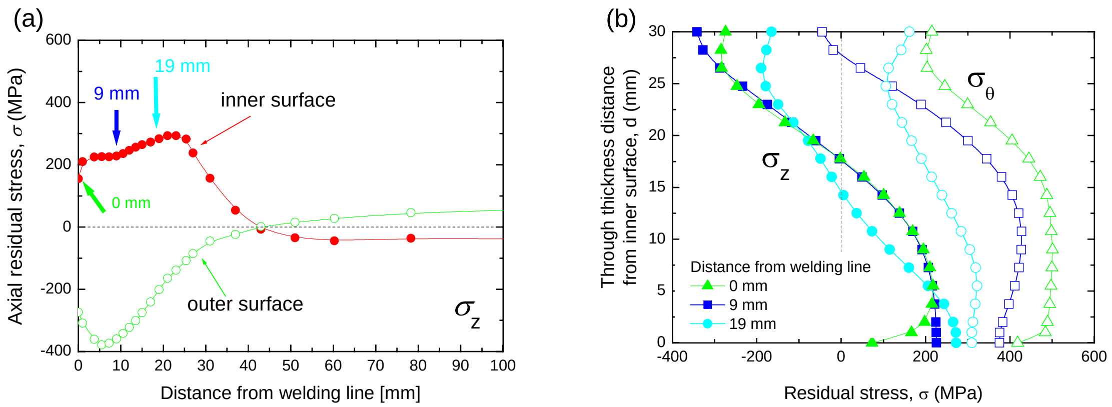


Fig. 7 - Residual stress distributions by circumferential welding for piping butt joint of SUS316L stainless steel. (a) σ_z vs. distance from welding line. (b) σ_θ and σ_z vs. through thickness distance (D = 300 mm, t = 30 mm, 1 pass).

tendencies were observed also in different welding conditions such as diameter, thickness and heat input (number of welding passes were 4 and 8 welding passes). The contour maps of the residual stress distributions of circumferential and axial directions are shown in Fig. 6 (a) and (b), respectively. The tendency of residual stress distribution at the steady region as described above can be seen clearly as shown in this figure i.e. the circumferential residual stress near the welding line becomes tensile and the axial residual stress near the welding line gradually decreases from tensile stress at the inner surface to compressive stress at the outer surface. The residual stress gradually decreases with increasing the through-thickness distance from inner surface and it becomes compressive stress near the outer surface. These tendencies of residual stress in the cross section on inner surface and outer surface, and Fig. 7 (b) shows residual stress distribution in cross section of plate near welding zone at the position of 180° as a representative of the steady region by circumferential butt joint welding. Figure 7 (a) shows that the tensile residual stress occurs in the inner surface near welding line decreases with increasing the distance from welding line after it becomes maximal value at about 20 mm from weld line. This figure also shows that compressive residual stress occurs in the outer surface near welding line also decreases with increasing the distance from welding line. Figure 7 (b) shows that the axial residual stress gradually decreases from tensile stress at inner surface into compressive stress at outer surface. The circumferential residual stress also gradually decreases from tensile stress at inner surface to outer surface, although the positive values are shown in the whole region inside the plate. These behaviors of residual stress in welded zone as shown in Fig. 7 are well known tendencies as written in the previous papers [14, 15]. However, the residual stress distribution near the start/finish end (the position of 0 degree) of circumferential welding is very complicated comparison with the steady region as shown in Fig. 6. Detailed evaluation on the unsteady part of the start/finish end of welding is left for future work.

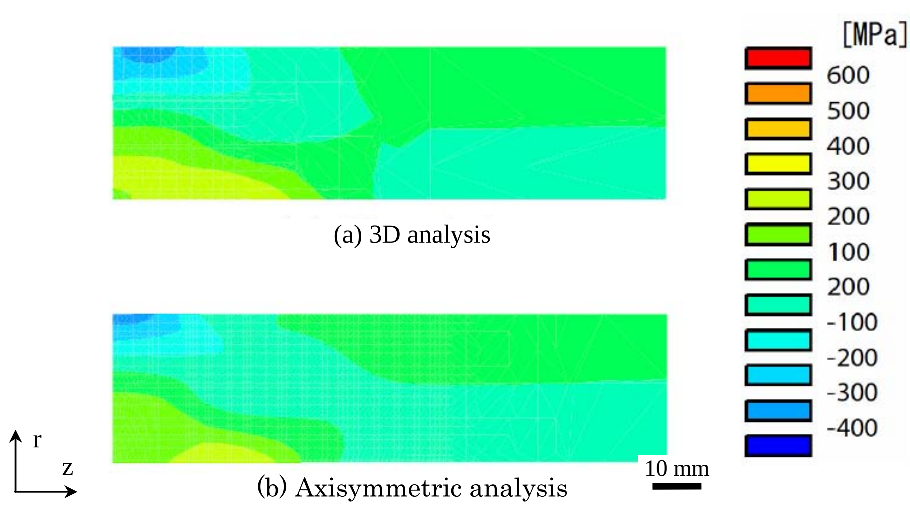


Fig. 8 - Comparison of the axial residual stress between 3D and axisymmetric analysis of idameter (D), thickness (t) and welding number are 381 mm, 10 mm and 1 pass welding, respectively.

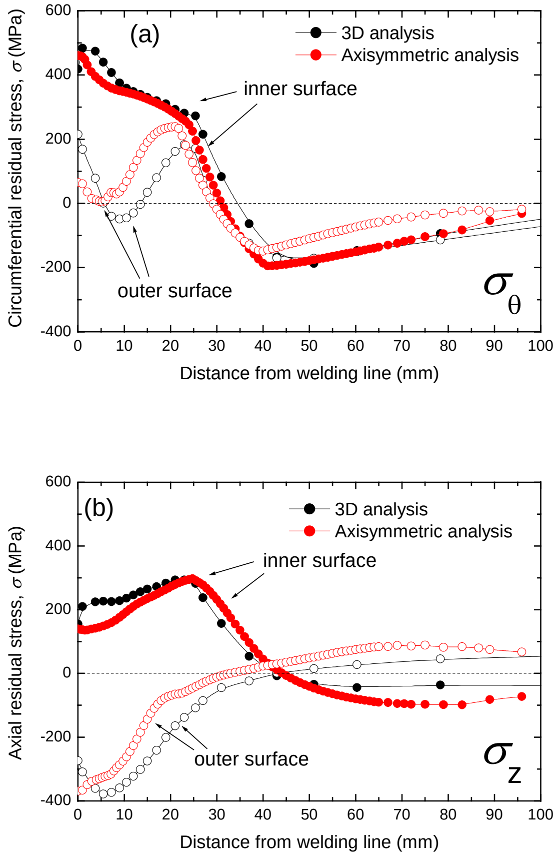


Fig. 9 - Comparison of circumferential residual stress distribution, (a), axial residual stress distribution, (b), as a function of distance from welding line between 3D analysis and axisymmetric analysis.

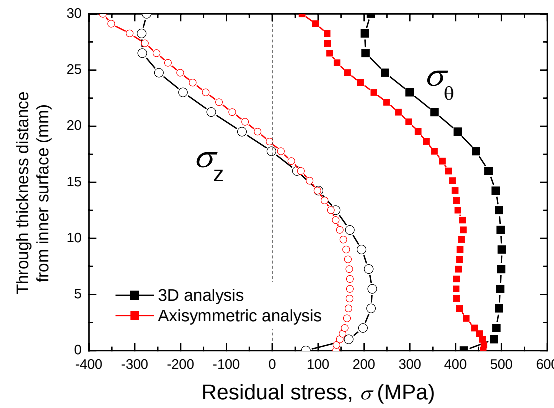


Fig. 10 - Comparison of the axial and circumferential residual stress distributions between three-dimensional and axisymmetric analysis as a function of through thickness distance from inner surface in the cross section of center of welding zone.

Comparison of Residual Stress Distribution by Three-Dimensional Analysis and Axisymmetric Analysis

Figure 8 shows that comparison of axial residual stress near the welding zone between the results of three-dimensional and axisymmetric analysis. Heat source parameters (see Fig. 3) of axisymmetric analysis were decided so that the shape of molten pool and history of temperature change below 1500 degree Celsius agree with those of three-dimensional analysis. The residual stress distribution in the steady region by three-dimensional analysis agrees well with that of axisymmetric analysis as shown in Fig. 8 i.e. the axial residual stress in inner surface and in outer surface near the welding zone are tensile stress and compressive stress, respectively. Figure 9 shows the circumferential and axial residual stress distribution on inner surface and on outer surface by comparing the results of steady region by three-dimensional and axisymmetric analysis. The residual stress distribution of three-dimensional analysis agrees well with that of axisymmetric analysis. The residual stress distributions at the inner surface especially agree each other as indicated by closed circles. The residual stress distribution of both directions on outer surface simulated by axisymmetric analysis could be regarded as a parallel translation along the welding line from the three-dimensional distribution. However, these differences are considered to be very small for the qualitative discussion. Figure 10 shows that the residual stress of axial and circumferential directions in the cross section of center of welding zone. The residual stress distributions of both directions given by three-dimensional analysis agree well with those of axisymmetric analysis. From these facts, the evaluation of the residual stress using by axisymmetric analysis is very effective in the steady region, which occupies most of weld (see Fig. 5). However, it is clear that the three-dimensional analysis is necessary for detailed evaluation of the distribution of residual stress in the unsteady region in start/finish end of circumferential welding.

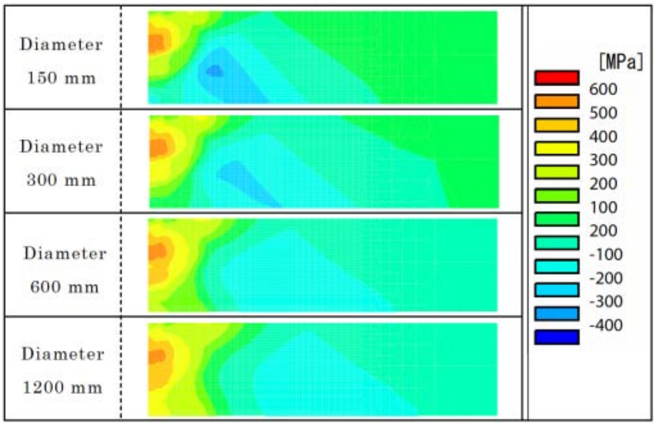
Evaluation of the Residual Stress by Multi-Pass Circumferential welding by Axisymmetric Analysis

In order to clarify the effect of geometric and welding conditions in circumferential welding zone such as diameter, thickness and quantity of heat input on the residual stress by circumferential welding, the axisymmetric analysis was carried out. The condition of the analysis, for example shape of piping but joint and number of welding, are shown in Table 1.

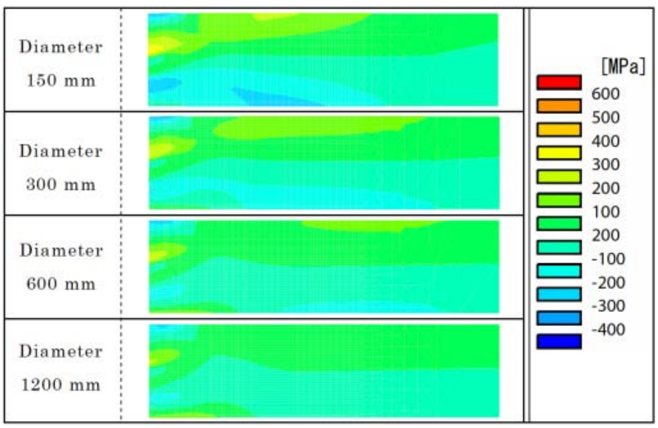
Figure 11 shows the effect of diameter on the residual stress

Table 1 - Condition of circumferential welding

Diameter (mm)	150, 300, 600, 1200
thickness (mm)	7.5, 15, 30, 45
Number of welding pass	1, 4, 8



(a)Circumferential direction



(b) Axial direction

Fig. 11 - Effect of diameter on the circumferential and axial residual stress distribution simulated by axisymmetric analysis (plate thickness = 30 mm, 4 pass).

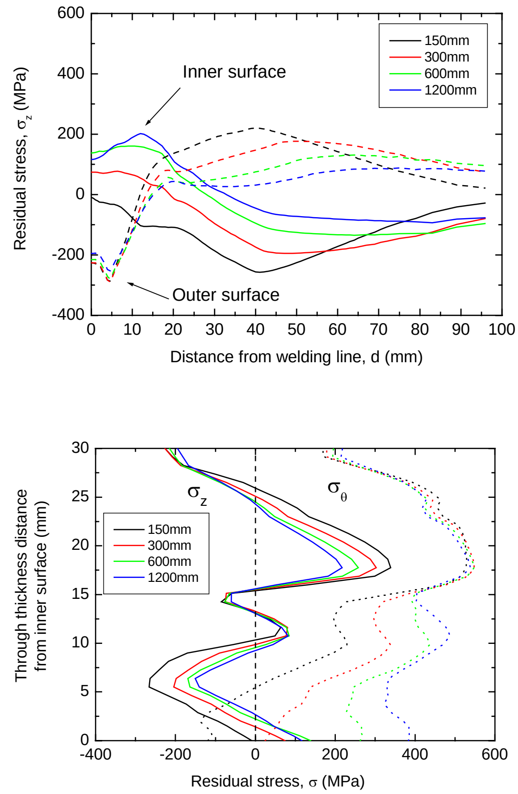
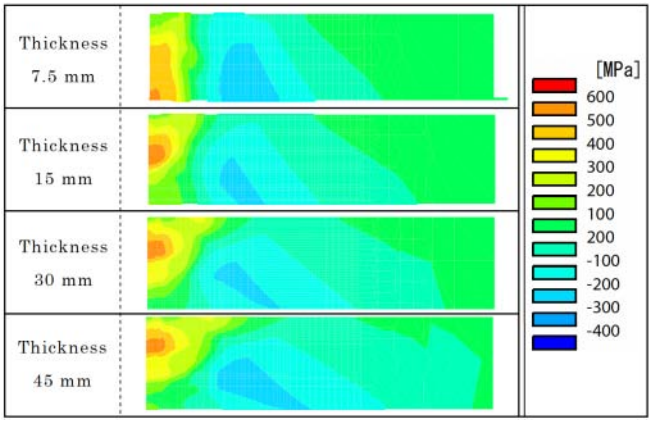


Fig. 12 - Comparison of residual stress distribution between different diameter for same thickness of 30 mm and 4 pass-welding.

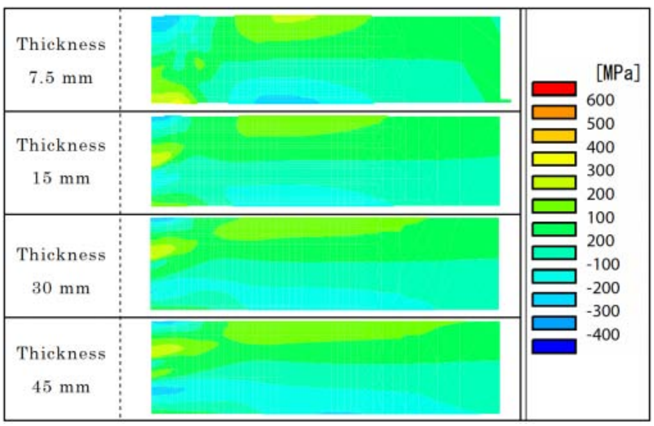
distribution for the same plate thickness of 30 mm and same number of 4 pass-welding. Circumferential residual stress near the welding zone becomes tensile in any cases, although the residual stress on inner surface decreases with increasing diameter as shown in Fig. 12, although that of outer surface is hardly influenced. Axial residual stress near the welding zone on inner and outer surface becomes tensile and compressive stress, respectively as shown in Fig.13, and the compressive residual stress would occur in the middle of plate. The tensile residual axial stress in inner surface near the welding zone decreases with increasing diameter as shown in Fig. 12, although that of outer surface is hardly influenced like the case of circumferential residual stress described above.

Figure 13 shows that the effect of plate thickness on the residual stress distribution for the same diameter of 300 mm and same number of 4 pass-welding. Circumferential residual stress near the welding zone becomes tensile. The maximum tensile stress in the plate occurs near the outer surface since the final welding pass goes though the outer surface in any cases. The tensile stress in inner surface near the welding zone decreases with increasing the thickness of plate, although the residual stress in outer surface does not change so much (Fig. 14). Axial residual stress near the welding zone on inner and outer surface becomes tensile and compressive stress, respectively, and the compressive residual stress would occur in the middle of plate except for the case of plate thickness 7.5 mm. The tensile residual axial stress in inner surface near the welding zone decreases with increasing plate thickness as shown in Fig. 14, although that of outer surface is hardly influenced. The effect of heat input of final welding pass on residual stress distribution near the outer surface is considered to be very important since the residual stress distribution of both directions near the outer surface shows the quite similar distribution as shown in Fig. 14. On the other hand, the residual stress distributions on inner surface and through thickness are influenced by plate thickness since the constraint state from around changes.

The effects of quantity of heat input on the residual stress for different welding number of 1, 4 and 8 pass with diameter of 300 mm and plate thickness of 30 mm are shown in Fig. 15. The circumferential residual stress near the welding zone becomes tensile. The maximal tensile stress in the plate occurs near the outer surface since the heat input of the final welding pass is given near the outer surface in cases of 4 and 8 welding-pass. The tensile stress in inner surface near the welding zone decreases with increasing the number of welding pass, although that in outer surface increases as shown in Fig.16. The axial residual stress near the welding zone on inner and outer surface becomes tensile and compressive stress, respectively. The



(a)Circumferential direction



(b) Axial direction

Fig. 13 - Effect of quantity of heat input on the circumferential and axial residual stress distribution simulated by axisymmetric analysis (Diameter = 300 mm, plate thickness = 30 mm).

compressive residual stress for axial direction would occur in the middle of plate in the case of 4 and 8 welding-passes, although it gradually decreases from inner surface to outer surface in case of 1 welding-pass. These behaviors of residual stress would be quite similar to that of described previous paper[13]. The peak position where the maximal value of tensile stress of circumferential and axial directions becomes closer to the outer surface by increasing number of welding pass since the heat input decreases as shown in Fig. 16. These tendencies of the effect of quantity of heat input on residual stress were quite similar in the case of different diameter of 150 mm, 600 mm and 1200 mm and different thickness of 15 mm and 45 mm.

SUMMARY

The residual stress by circumferential welding for piping butt joint made from SUS316L austenite stainless steel was evaluated by thermo-elastic-plastic analysis of three-dimensional and axisymmetric models in detail. The effect of

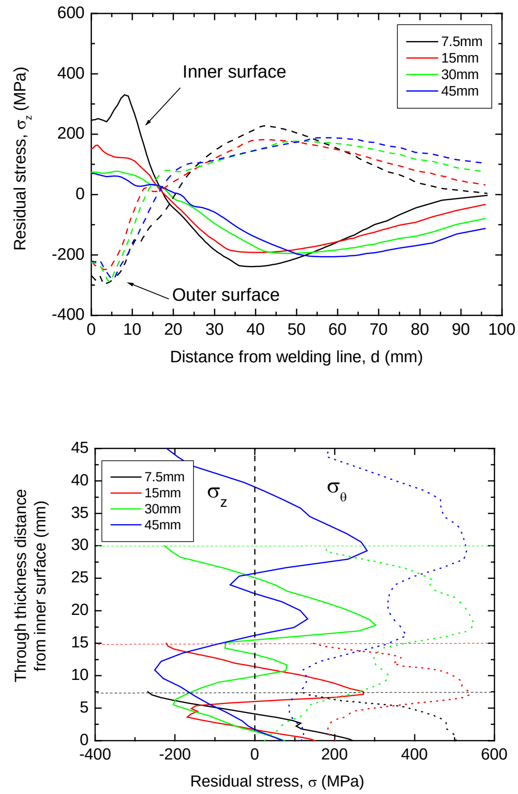


Fig. 14 - Comparison of residual stress distribution between different plate thickness for same diameter of 300 mm and 4 pass-welding.

geometric and welding conditions on the residual stress in the steady region was clarified. It is clear that the three-dimensional analysis is necessary to carry out detailed evaluation of the distribution of residual stress in the unsteady region of start/finish end of circumferential welding

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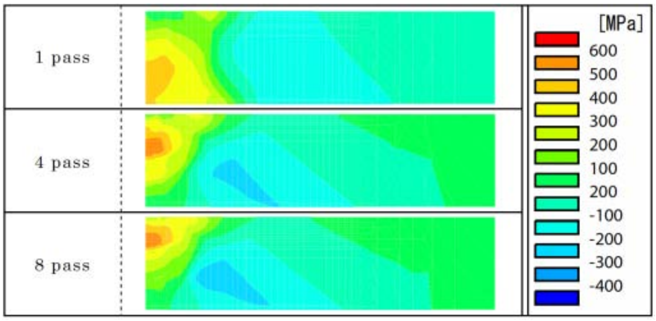
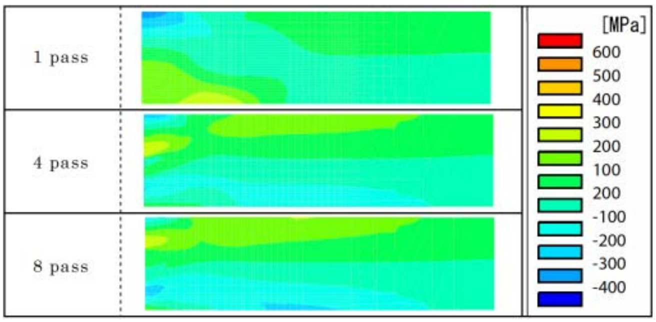


(a)Circumferential direction



(b) Axial direction

Fig. 15 - Effect of diameter on the circumferential and axial residual stress distribution simulated by axisymmetric analysis (plate thickness = 30 mm, 4 pass).

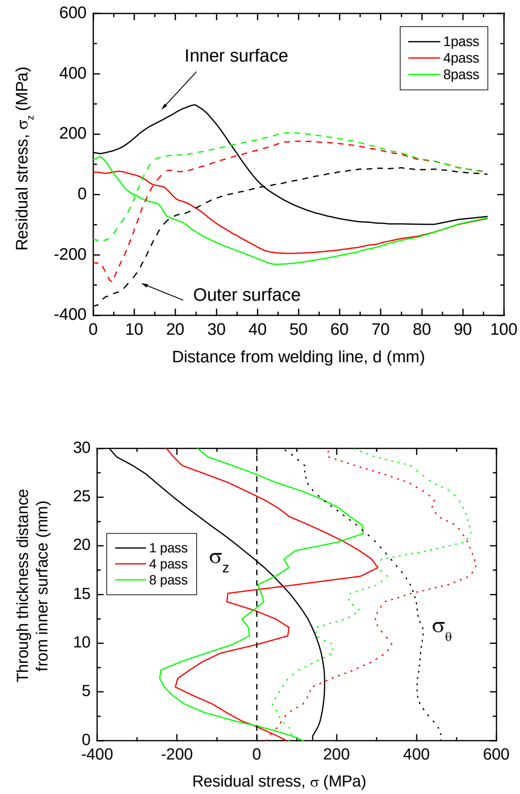


Fig. 16 - Comparison of residual stress distribution between different heat input for same diameter of 300 mm and thickness of 30 mm.

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