Journal of
Mechanical
Science and
Technology

Journal of Mechanical Science and Technology 21 (2007) 426~435

Effects of Initial Condition of Steel Plate on Welding Deformation and Residual Stress due to Welding

PARK. J. U[a], LEE H. W.[b,*]

[a]Department of Civil Engineering, Chosun University, 375 Seosek-Dong, Dong-gu, Gwangju, Korea
[b]Department of Materials Science and Engineering, Dong-A University, 840, Hadan-dong, Saha-gu, Busan

(Manuscript Received May 29, 2006; Revised October 11, 2006; Accepted October 16, 2006)

Abstract

The effects of initial deflection and initial residual stress in steel plate on the out-of-plane deformation and residual stress due to welding are investigated from analysis results of thermal elastic-plastic FEM modeling with large deflection theory. Initial residual stress due to plate forming has very little effects on welding deformation and welding residual stress. For initial deflection, with concave profile (Type I), welding induced deformation has the same type as initial deflection and its magnitudes are small. When initial deflection is in the direction parallel to weld line (Type II), welding induced deformation has minor variations. When initial deflection is bended in the direction normal to weld line (Type III), welding deformation was largely generated along the width direction of the steel plate. On the other hand, the variation in type of initial deflection does not affect the residual stress and plastic strain.

Keywords: Welding deformation, Residual stress, Initial condition, Non-conformable strain, FEM analysis

1. Introduction

When steel structures are manufactured, a rapid thermal cycle of heating and cooling is generated around welded joints by the heat source, and an uneven distribution of temperature is set up due to the temperature field variation based on the heat source movement (Watanabe, 1965). The thermal expansion and shrinkage around welded joints due to this uneven distribution of temperature are constrained by the low temperature region far from the welded joints. Consequently, welding deformation and residual stress are produced and their magnitudes vary with the welding conditions and the degree of thermal and mechanical constraints. Welding deformation (Tsai, 1999; Michaleris, 1997; Lee, 2002; Deo, 2003; Yim, 2005) and residual stress(Ueda, 1971; Murakawa, 1996; Park, 1999; Han, 2002; Kang, 2006) have adverse effects on the accuracy of assemblage, external appearance and strengths characteristics, etc. Especially, welding deformations produced during assembly lead to variations in dimensions of structures during the manufacture of large steel structures such as ships that require much time and expenses for repair and consequently become the chief causes for decreasing the productivity. To prevent these problems, a margin for welding shrinkage is allowed in the design stage, based on the experience and measured data. However, the existing methods for deter-mining this margin do not take into account variations in welding methods, welding materials, and structural shapes, etc. Therefore, predictions of the welding deformation and residual stress before welding are required to develop a system to control or to prevent them. As the skilled workers are also decreasing in number, the above concept is one of the most important problems to be solved in the construction of welded steel structures.

*Corresponding author. Tel.: +82 51 200 7752; Fax.: +82 51 200 7759
E-mail address: hwlee@dau.ac.kr

This present work investigates the effects of initial condition (such as deflection and residual stress occurring during the manufacture of steel plate) on the out-of-plane deformation and residual stress due to welding. For the purpose, initial condition of steel plate is obtained via three dimensional inherent stress analyses after scattering the whole plate randomly with non-conformable strains. Under the initial condition, butt-welding for the steel plate is simulated via thermal elastic-plastic analysis program with large deflection theory. From the analysis results, the effects of initial condition on welding deformation and residual stress are investigated.

2. Verification of thermal elastic-plastic analysis program with large deflection theory

To verify the validity of the thermal elastic-plastic analysis program developed for this work, both experimental and analysis results are compared and investigated. To obtain more accurate results, specimens with initial deflection and without residual stress were used.

2.1 Experimental method

Mild steel specimens with dimensions 500 mm in length (L), 500 mm in width (B) and 6 mm in thickness (h) with maximum initial deflection of 25 mm were used. Fig. 1 shows groove type and the initial deflection created by mechanical bending process. Two rectangular plates with the initial deflection are tack-welded at four specific parts along the weld line.

With the specimens clamped using support-pins, welding in a flat posture was done by auto-MAG (Metal Active Gas) welding with parameters V=23 V, I=133 A, and v=2 mm/s. Ar+20%CO_2 as shielding gas, YM-12 of 1.2 mm in the diameter as filler wire and ceramic as backing material were used. Temperature distribution is measured in real time by putting thermocouples on the surface of the specimens in the direction normal to weld line. The initial deflection and the out-of-plate deformation, of the specimen clamped at four support pins after marking measuring points on the surface, are obtained from the values averaged by measuring each of them three times with dial-gauge. Fig. 2 shows the measured initial deflections as symbols.

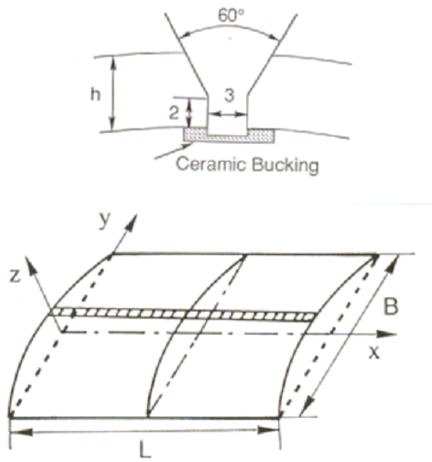
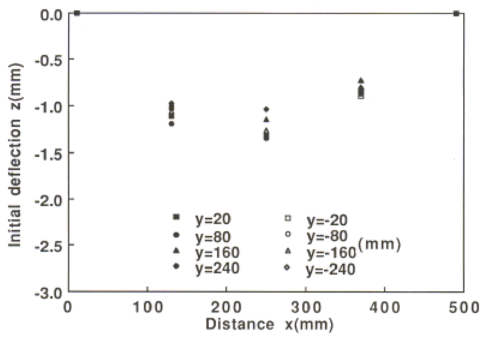
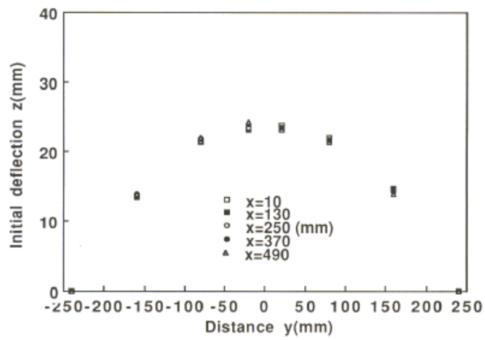


Fig. 1. Type of initial deflection and groove.



(a) Parallel to weld line



(b) Normal to weld line

Fig. 2. Initial deflection.

To reduce the complication, the measured results of initial deflection and out-of-plane deformation are rearranged on the basis of the measuring point within 10(mm) from the edge of the plate. The residual stress value is taken as the values obtained via stress relaxation method the strain gauges attached on the top and rear surface of the specimen in the direction

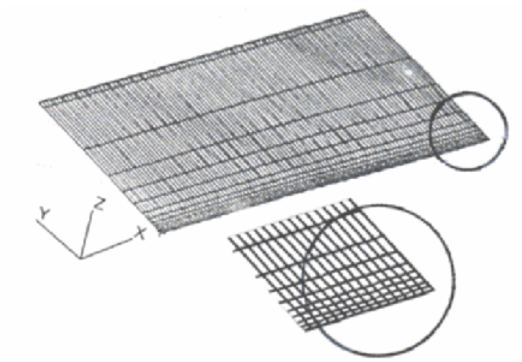


Fig. 3. Mesh division for simulation.

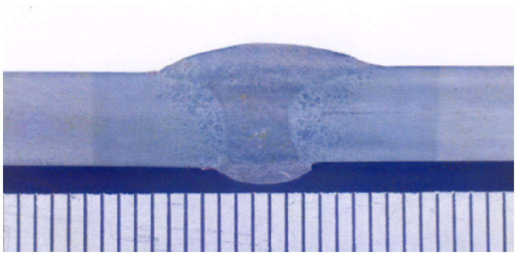


Fig. 4. Macrograph of the deposited metal.

normal to weld line from the center of the specimen.

2.2 Analysis method

In fact, welding stress and deformation are highly complicated problems under thermal mechanical phenomena requiring metallurgic process such as melting and solidification. Three-dimensional thermal-elastic-plastic FEM using four nodes quadrilateral iso-parametric shell element is employed for the present study. The finite element simulation considers both the thermal and the mechanical process in the form of thermal expansion and the dependence of mechanical properties on temperature.

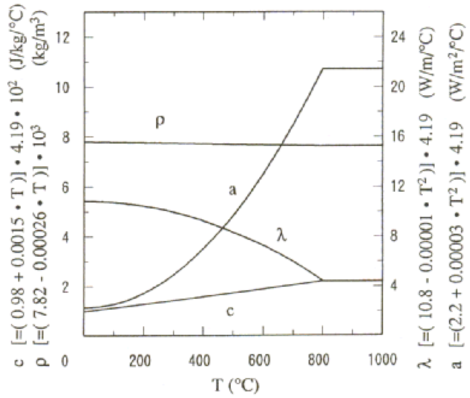
Since the butt joining of the plates is geometrically symmetrical with respect to weld line, half model is considered as shown in Fig. 3

The welding arc power (Q=1,223(J/mm)) is obtained by applying the welding experimental parameters in Eq. (1).

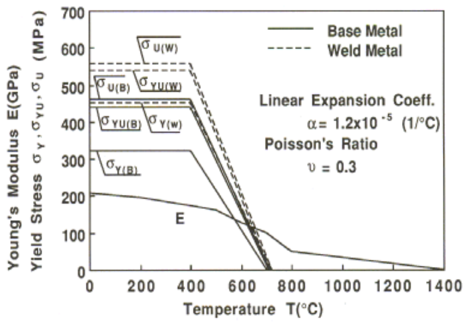
$$Q = \frac{\eta \cdot V \cdot I}{v} \text{(Joule/mm)} \tag{1}$$

where, η: arc efficiency, V: welding voltage (V), I: welding current (A),

v: welding speed (mm/sec)



(a) Physical constants



(b) Mechanical properties

Fig. 5. Thermal properties.

The heating input(q) per the unit time and volume for each deposited metal is obtained from Eq. (2). Also, the effect of the thermal source movement in welding is obtained by varying heating input (q) in each weld element in order of the time (t) taken to weld it (Shim, 1993).

$$q = \frac{Q \cdot l}{4.19 \cdot A \cdot l \cdot t} (\text{cal/mm}^3 \cdot \text{s}) \tag{2}$$

where, *l*: welding length(mm), t: welding time (=*l*/v)

Groove type is taken as I-groove type as obtained from Macro section view of the welded joints as shown in Fig. 4. Quasi-steady static thermal conduction analysis considers the temperature dependent physical constant of a material as in Fig. 5 (a), and large deflection theory based thermal elastic-plastic analysis considers the temperature dependent mechanical properties of a material as in Fig. 5 (b).

The initial deflection used in analysis is a straight

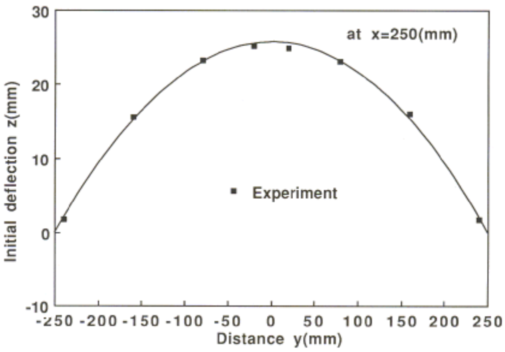


Fig. 6. Approximation of initial deflection for analysis.

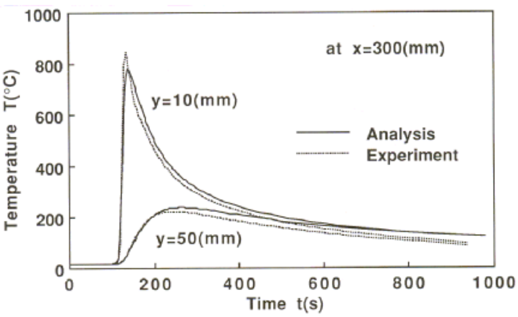


Fig. 7. Temperature history.

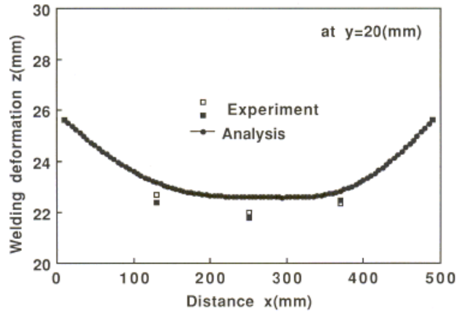
line in the direction parallel to weld line (Because the errors of the initial deflections between both edges and the center are within 1 mm, it is regarded as a straight line). The initial deflection normal to weld line, as shown in Fig. 6, is obtained by fitting the experimental result to solid lines.

2.3 Comparison between experimental and analysis result

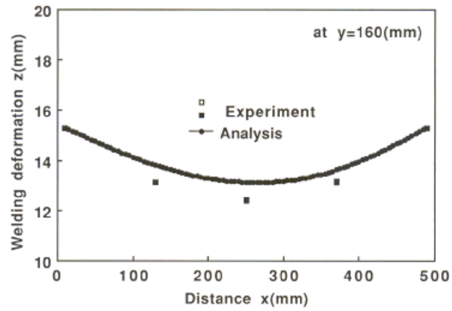
2.3.1 Experimental result

Figure 7 shows the measured result of temperature history as solid lines. The measuring points are 10 and 50mm away from weld line. Judging from the experimental result, when the thermal source of welding gets closer to the measuring point, the temperature around the measuring point suddenly rises and, as time goes by, is cooled because of thermal transmission on the surface and thermal conduction in the inner part of the steel plate.

Figure 8 shows the measured result of out-of-plane deformation in the direction parallel to weld line as symbols. Fig. 9 shows the out-of-plane deforma-tion normal to weld line. Judging from the results, out-

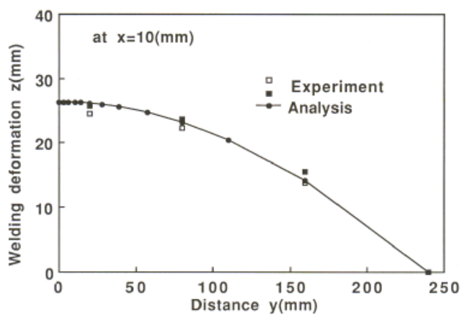


(a) At y=20 mm.

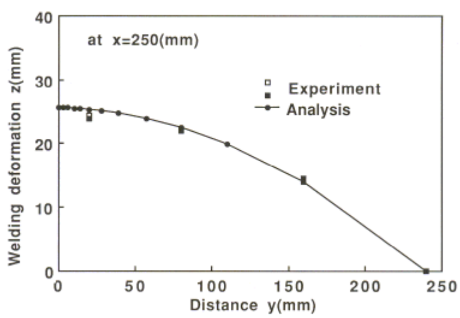


(b) At y=160 mm.

Fig. 8. Out-of-plane deformation in parallel to weld line.



(a) At x=10 mm



(b) At x=250 mm

Fig. 9. Out-of-plane deformation in normal to weld line.

of-plate deformation in the direction parallel to weld line is bended more downward than initial deflection. Its magnitude tends to decrease gradually as the distance from the weld line increases.

Figure 10 shows residual stress in the direction parallel to weld line as symbols. Judging from the results, residual stress occurs in the form of the extension stress in the neighborhood of weld line, decreases gradually as getting farther away from the weld line, and emerges to compressive stress about y= 45 mm.

2.3.2 Analysis result

Figure 7 shows the temperatures as dotted lines. The temperatures are part of the temperature history obtained via quasi-steady static thermal conduction analysis considering the efficiency for the movement of a thermal source. The experimental result agrees with the analysis result.

Figure 8 shows a part of the out-of-plane deformation in the direction parallel to weld line, which was obtained via the thermal elastic-plastic large deformation analysis. Fig. 9 shows the out-of-plane deformation normal to weld line. The experimental result and the analysis result agree with each other.

Figure 10 shows a part of residual stress in the direc-tion parallel to weld line as solid line. The experi-mental result and the analysis result generally agree with each other, although there is difference in the results by 50 MPa around the weld line.

As mentioned above, we verified the validity of the results analyzed via thermal elastic-plastic large deformation analysis program devised for this work.

3. Effects of initial stress

In butt-welding of plates with initial deflection as shown in Fig. 11, thermal elastic-plastic FEM analysis is done both with the initial stress as in Fig. 12 and without it. Then, the effects of initial stress on out-of-plane deformation and residual stress due to welding are investigated.

3.1 Analysis Model and temperature distribution

Figure 13 shows the model for analysis. The mild steel plates of 600 (mm) in length (L), 600 (mm) in width (B), and 6 (mm) in thickness (h) were used. Initial deflection and residual stress (hereinafter called as initial stress) generated during the manufacture of

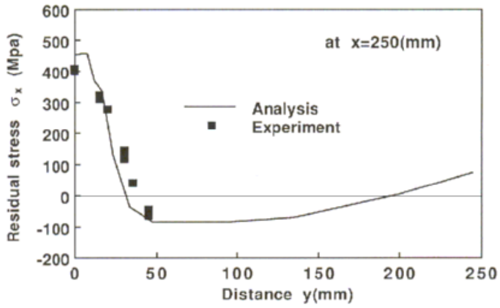


Fig. 10. Residual stress.

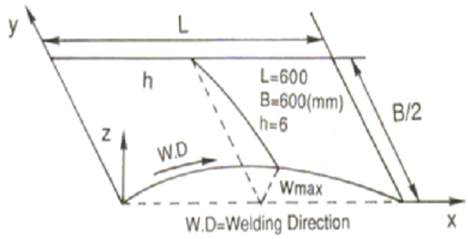
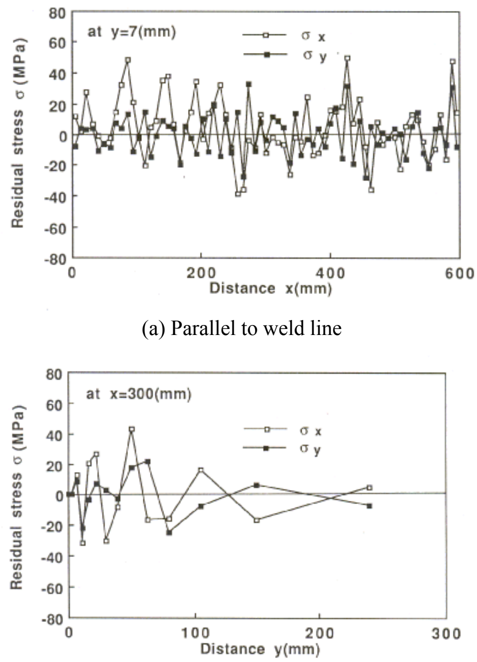


Fig. 11. Out-of-plane deflection due to plate forming.



(a) Parallel to weld line

(b) Normal to weld line

Fig. 12. Residual stress produced due to plate forming.

steel plates are obtained via three-dimensional inherent stress analysis after scattering inherent strain (non-conformable strain) over the entire plate by rand-

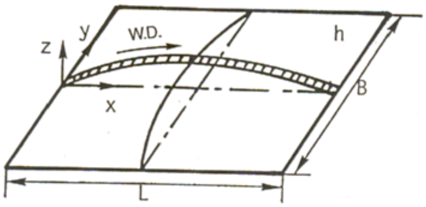


Fig. 13. Model for analysis.

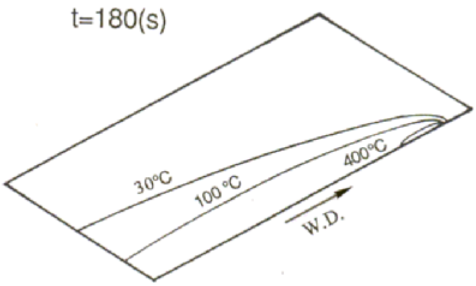
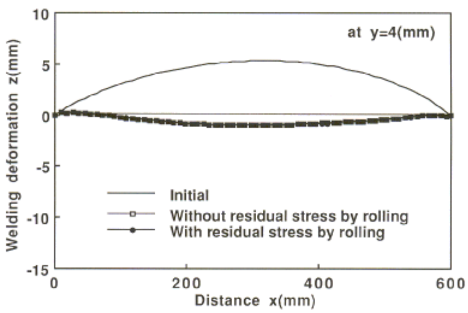
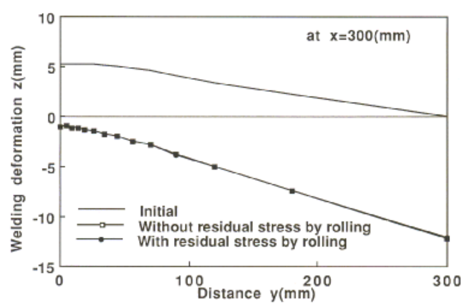


Fig. 14. Temperature distribution.



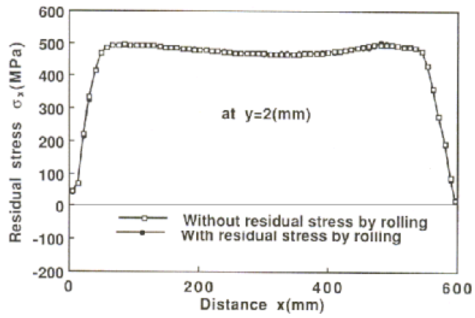
(a) Parallel to weld line



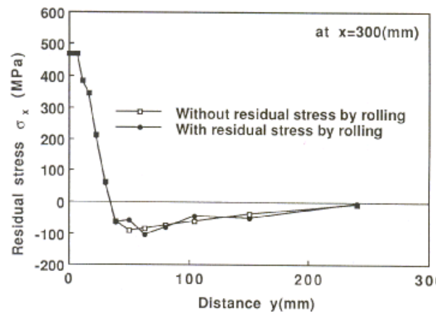
(b) Normal to weld line

Fig. 15. Displacement in z-direction produced by welding.

domizing. Fig. 11 and Fig. 12 show the initial deflection and the initial stress respectively. The magnitudes of non-conformable strain are limited so that the maximum initial deflection might become 5 mm (Hano, 1990) and maximum initial stress 50 MPa



(a) Parallel to weld line



(b) Normal to weld line

Fig. 16. Residual stress produced by welding.

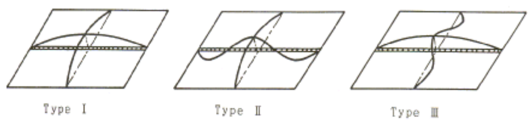


Fig. 17. Configurations of initial deflection.

(Horikawa, 1987). Naturally, initial stress in the initial state of steel plate balanced by it self.

Welding is done in the x-direction along the center of analysis model with I-groove as in Fig. 11, with arc power (Q) 1140 J/mm and welding speed (v) 3 mm/s.

Figure 14 shows a part of temperature distributions obtained via quasi-steady state heat conduction analysis at welding time(t) 180s. In thermal elastic-plastic stress analysis, this temperature history is used for all cases provided in this research.

3.2 Effects on out-of-plane deformation

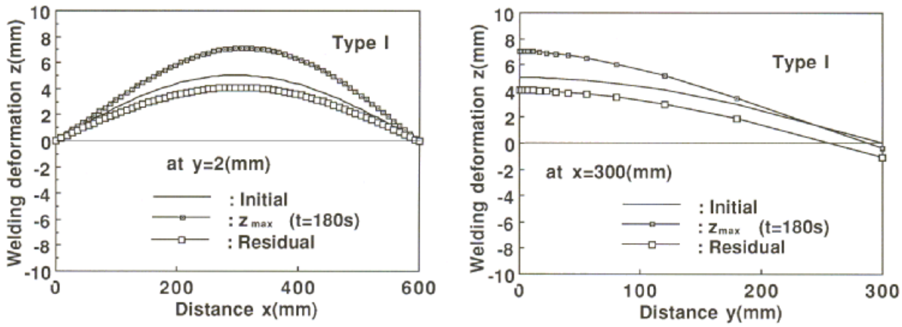
Figure 15 shows the result of thermal elastic-plastic stress analysis. Whether initial stress exists or not, the out-of-plane displacements due to welding coincide with each other which confirms that the initial stress does not have effects on the out-of-plane deformation.

3.3 Effects on residual stress

In butt welding, as transverse shrinkage in the direction normal to weld line occurs almost uniformly, the stress component σ_y is much smaller than σ_x in the direction parallel to weld line. Therefore, this work observes only the σ_x.

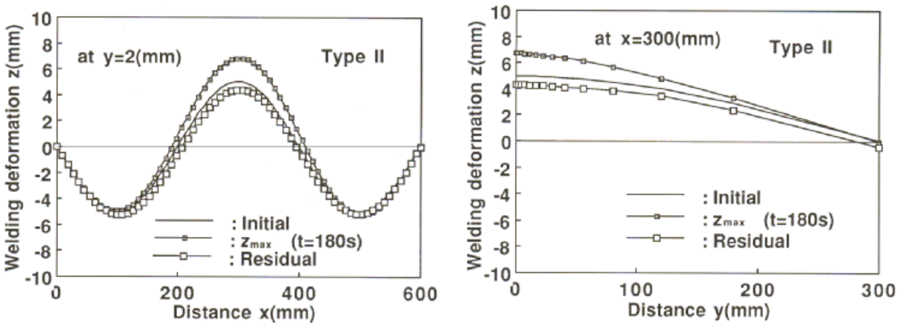
Figure 16 shows the stress component σ_x. As the metal around welded joints is heated up to a high temperature and melted, the pre-initial stress is released. Then, again stress newly occurs in the process of cooling and remains as residual stress at room temperature. Thus the initial stress does not have effects on the neighborhood of the welded joints. On the other hand, although residual stress in the part far from weld joints is influenced by initial stress, its absolute value is small enough to be ignored.

As mentioned above, initial residual stress occurring during the manufacture of steel plate doesn't have effects on the out-of-plane deformation and



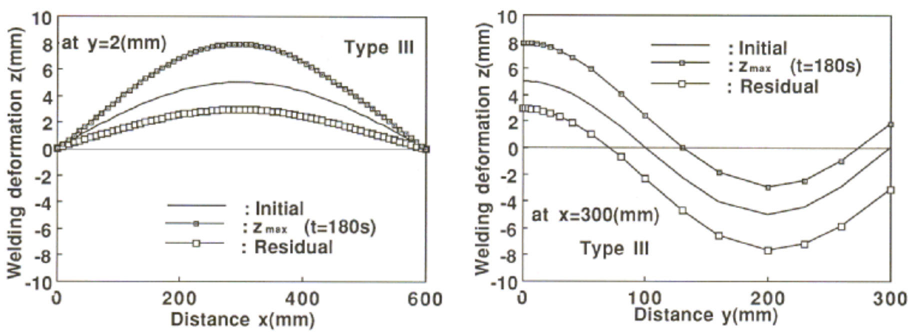
(a-1) Parallel to weld line. (a-2) Normal to weld line.

(a) Type I



(b-1) Parallel to weld line. (b-2) Normal to weld line.

(b) Type II



(c-1) Parallel to weld line. (c-2) Normal to weld line.

(c)Type III

Fig. 18 Out-of-plane deformation produced by welding.

residual stress due to welding.

4. Effects of initial deflection

This section disregards initial stress for the reason mentioned above and only concentrates on effects of initial deflection on the out-of–plane deformation, residual stress and plastic strain due to welding by varying the type of initial deflection.

4.1 Effects on out-of-plane deformation

Figure 17 shows three types of initial deflection. The maximum initial deflection is ±5 mm.

Figure 18 shows transient and residual stress of the out-of-plane deformation on the weld line (y=0 mm) and in the middle part of plate (x=300 mm), obtained by thermal elastic-plastic FEM analysis by varying the type of the initial deflection (Type I, Type II, Type III).

Judging from the result, regardless of the types of the initial deflection, the out-of-plane deformation occurs extending initial deflection until t=180 s, reaches the maximum and from that limit start reducing the initial deflection. The magnitudes of the out-of-plane deformation are in the order Type I < Type II = Type III. That is, the variation in the type of initial deflection has very little effects on general tendency of the out-of-plane deformation, but makes the magnitudes of the out-of-plane deformation different.

Out-of-plane displacement (the difference between maximum residual deformation and initial deflection) in the direction parallel to weld line shows the same tendency regardless of the type of the initial deflection but in magnitudes, appears different, as in the order Type II< Type I <Type III.

When initial deflection is in the direction parallel to weld line (Type II), the out-of-plane displacement is smaller because the thermal source of welding offsets welding deformations each other moving up and down the neutral axis. When it is bended in the direction normal to weld line (Type III), the out-of-plane displacement is larger because bending moment, which is generated by the distance between the neutral axes and expansion or shrinkage due to welding, is larger than Type I and Type II.

On the other hand, the out-of-plane displacement in the direction normal to weld line shows different tendency according to the type of the initial deflection. In Type III, when the initial deflection is bended in the direction normal to weld line, the out-of-plane displacement occurs larger maintaining the type of the initial deflection. It is the reason that stiffness of steel plate itself is larger than Type I and Type II.

As we have seen, the type of the initial deflection has large effects on the out-of-plane deformation. In Type I, the out-of-plane deformation remains the same type of initial deflection but its absolute value is smaller than the initial deflection. In Type II, out-of-plane displacement is small but the out-of-plane deformation maintains large because initial deflection remains in itself. In Type III, the out-of-plane deformation becomes small near the weld line and large in the inner part of the plate. Consequently, whole residual out-of-plane deformation remains large, as the bending moment generated due to welding deformation is large.

4.2 Effects on residual stress and plastic strain

Residual stress and plastic strain due to welding are mostly generated by difference between thermal expansion and shrinkage. Especially, the expansion and shrinkage in the direction parallel to weld line are more important factors. Therefore, this section investigates residual stress and plastic strain in the direction parallel to weld line.

Figure 19 shows the stress component σ_x in the direction parallel to weld line. The distribution of residual stress is influenced by the type of the initial deflection, but its magnitudes is small enough to be ignored.

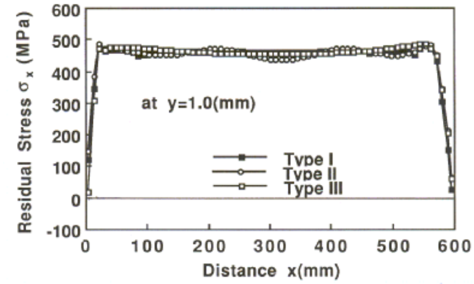
Figure 20 shows the plastic strain component ε^p_x in the direction parallel to the weld line. ε^p_x is generated only near the welded joints but its magnitudes is rarely influenced by the type of initial deflection.

As we have seen, the variation in type of initial deflection has very little effects on residual stress and plastic strain due to welding.

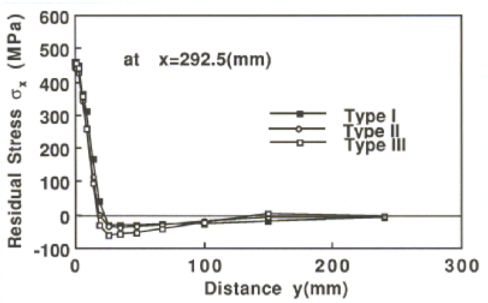
5. Conclusion

The effects of initial stress present in steel plate during forming, on out-of-plane deformation and residual stress due to welding were investigated.

(1) It can be said that initial stress does not have effects on the out-of-plane deformation and residual stress due to welding. Although residual stress in the part far from weld joints is influenced by initial stress,

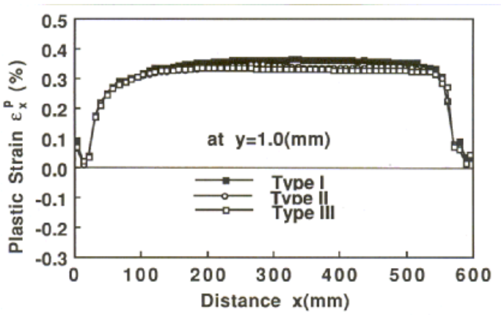


(a) Parallel to weld line

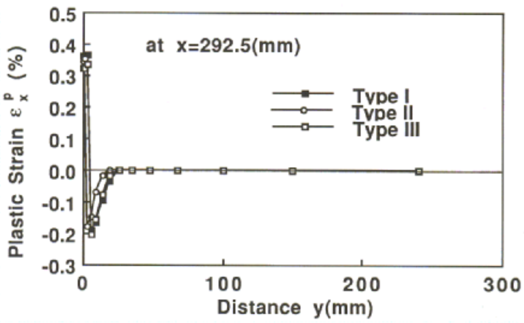


(b) Normal to weld line

Fig. 19. Residual stress according to initial type.



(a) Parallel to weld line



(b) Normal to weld line

Fig. 20. Plastic strain according to initial type.

because its absolute value is small enough to be ignored.

Secondly, the effects of the type of initial deflection on the out-of-plane deformation, residual stress, and plastic strain due to welding were investigated.

(2) If the temperature history was same, the general tendency of the out-of-plane deformation was same regardless of the types of the initial deflection. That is, the out-of-plane deformation occurred extending initial deflection until t=180 s, reaches maximum at t= 180s and then, occurred reducing the initial deflection.

(3) The variation in the type of initial deflection had large effects on out-of-plane deformation.

In Type I, which has the same type of initial deflection in the direction both parallel to and normal to weld line, the out-of-plane deformation remained the same type of initial deflection but its absolute value was smaller than the initial deflection.

In Type II, which has initial deflection bended in the direction parallel to weld line, out-of-plane displacement due to welding was small but the out-of-plane deformation maintained large because initial deflection remained in itself.

In Type III, which has initial deflection bended in the direction normal to weld line, the out-of-plane deformation became small near the weld line and large in the inner part of the plate. Consequently, whole residual out-of-plane deformation remained large, as the bending moment generated due to welding deformation was large, the out-of plane displacement occurred largely.

(4) The distributions of residual stress and plastic strain were influenced by the type of the initial deflection, but its magnitude was small enough to be ignored.

Nomenclature

- I : Welding current(A)
- l : Welding length(mm)
- Q : Welding arc power (J/mm)
- Q : Welding heating input per the unit time and volume (cal/mm^3-s)
- V : Welding voltage(V)
- V : Welding speed(mm/sec)
- t : Welding time(=l/v)
- ε^p_x : Plastic strain component in the direction parallel to weld line
- η : Welding efficiency
- σ_x : Stress component in the direction parallel to

weld line

σ_y : Stress component in the direction normal to weld line

Acknowlegement

This study was supported by research funds from Chosun University, 2006.

Reference

Watanabe, M., Satoh, K., 1965 "Welding Mechanics and Its Application," *Asakura-shuppan*, pp. 29~42.

Tsai, C. L., Park, S. C., Cheng, W. T., 1999 "Welding Distortion of a Thin Plate Panel Structure," *Welding Journal*, vol. 78, No. 5 pp. 156s-165s.

Michaleris, P., DeBiccari, A., 1997 "Prediction of Welding Distortion," *Welding Journal*, Vol. 76, No. 4, pp. 172s~181s.

Deo, Mv, Michaleris, P., 2003 "Mitigation of Welding Induced Buckling Distortion Using Transient Thermal Tensioning," *Science and technology of Welding and Joining*, Vol. 8, No. 1, pp. 49~54.

Deo, Mv., Michaleris, P., Sun, J., 2003 "Prediction of Buckling Distortion of Welded Structures," *Science and Technology of Welding and Joining*, Vol. 8, No. 1, pp. 55~61.

Mano, H., Masaoka, H., Ito, T., 1990 "Statistical Characteristics on the Compressive Ultimate Strength of Deck Panels," *Journal of the Kansai Society of Naval Architects*, Vol. 21, pp. 145~156.

Horikawa, K., Isimoto, K., 1987 "TMCP Steel Applied to a Bridge," *Report of JWRI*, pp. 9~18.

Ueda, Y., Yamakawa, T., 1971 "Analysis of Thermal Elastic-Plastic Stress and Strain During Welding by Finite Element Method," *Trans. of the Japan Welding Society*, Vol. 2, pp. 90~98.

Murakawa, H., Luo, Y., Ueda, Y., 1996 "Prediction of Welding Deformation and Residual Stress by Elastic FEM Based on Inherent Strain (First Report) Mechanism of Inherent Strain Production," *Journal of the Society of Naval Architects of Japan*, Vol. 180, pp. 739~751.

Yim, H. J., Lee, D. Y., Lee, J. Y., Kwon, K. E., Shin, J. G., 2005 "Development of an Efficient Method to Consider Weld Distortion in Tolerance Analysis," *Trans. Of the KSME(A)*, Vol. 29, No. 10, pp. 1377~1383.

Shim, Y. L., Lee, S. G., 1993 "Modeling of Welding Heat Input for Residual Stress Analysis," *Journal of the Korean Welding Society*, Vol. 11, No. 3, pp. 110~123.

Lee, G. H., Kim, J. T., Na, S. J., 2002 "A Study on Measurement of Micro Weld Deformation by Using PS-ESPI," *Trans. Of the KSME(A)*, Vol. 26, No. 12, pp. 2535~2540.

Han, S. H., Lee, T. K., Shin, B. C., 2002 "A Quantitative Estimation of Welding Residual Stress Relaxation for Fatigue Strength Analysis," *Trans. Of the KSME(A)*, Vol. 26, No. 10, pp. 2018~2025.

Kang, W. J., Kim, G. H., 2006 "Residual Stress of the Lower Control Arm Subjected to Cyclic Loading," *Trans. Of the KSME(A)*, Vol. 30, No. 5, pp. 602~608.

Satoh, K., 1988 "Handbook of Welding Structures," *Kuroki-shuppan*, pp. 157~169.

Park, J. U., 1999 "Effects of Omotoa; Defects on Welding Deformation and Residual Stress," *Jornal of KWS*, Vol. 17, No. 4, pp. 287~295.