Title	Features and Production Mechanisms of Residual Stress Generated by Welding and Joining
Author(s)	Kim, You Chul
Citation	Transactions of JWRI. 2003, 32(2), p. 249-258
Version Type	VoR
URL	https://doi.org/10.18910/5211
rights	
Note	

Osaka University Knowledge Archive : OUKA

https://ir.library.osaka-u.ac.jp/

Osaka University

Features and Production Mechanisms of Residual Stress Generated by Welding and Joining †

KIM You-Chul*

Abstract

Thermal distortion and residual stress which are termed welding imperfections are necessarily generated by welding and joining. Residual stress generated by welding and joining was examined here. The production mechanisms of residual stress generated by welding or joining and their features were described. On the other hand, in a series of studies to predict residual stress generated by welding or joining, the results obtained by thermal elastic-plastic analysis based on FEM developed by the author and his colleagues were introduced. Recently, many commercial programs that are easy to use in the fields of welding and joining have been introduced. Candid advice was given for the use of these commercial programs.

KEY WORDS: (Residual stress), (Production mechanism), (Welding), (Joining), (Thermal elastic-plastic analysis), (FEM)

1. Introduction

Distortion and residual stress are necessarily generated in welding and joining. They are generally termed welding imperfections and they influence various strengths of steel structures[1-3]. Among them, it is well known that residual stress not only lowers fatigue strength (related to tensile stress) or buckling strength (related to compressive stress) of steel structures but also participates in the initiation or propagation of brittle fracture (related to tensile stress).

Many studies for the prediction of residual stress[4] have been carried out. After the appearance of computers in the 1940s, a matrix method was developed as the structural analysis method. Then, using a continuum medium, various differential equations were formulated by matrix type. The finite element method (FEM) is the most typical one. Many results were obtained by applying FEM to the fields of welding and joining [3,5].

In this review, the production mechanisms of residual stress generated by welding or joining and their characteristics are described. Moreover, in a series of studies to predict residual stress generated by welding or joining, the results obtained by thermal elastic-plastic analysis based on FEM developed by the author and et al. are introduced.

2. Production Mechanisms of Residual Stress and Its Characteristics

2.1 Welding

When welding is performed in a groove, the deposited metal itself cools down from a melting temperature to room temperature. Contrary to this, the temperature of the base metal rises at first and then cools to room temperature. The part where the structural steel is heated over 700-750℃ is termed the heat affected zone (HAZ). Here, the deposited metal and HAZ are named generically as the welds (weld metal) beyond them is termed the base metal.

2.1.1 Butt welding [6,7]

When the welds and the base metal are cut off after welding and cooling down to room temperature, the situation is shown in **Fig.1.** The welds shrink and the base metal adjacent to the

† Received on December 1st, 2003

* Professor

Transactions of JWRI is published by Joining and Welding Research Institute of Osaka University, Ibaraki, Osaka 567-0047, Japan

welds expands. However, the base metal restricts the free shrinkage of welds because the welds and the base metal are continuous. Therefore, residual stress is generated. **Figure 2** shows the schematic representation of residual stress distributions.

The stress component of the welding direction, σ_x, generated in the welds is equal to the yield stress of the deposited metal (Fig.2 (a)). On the other hand, the distribution of σ_x generated in the base metal is not simple. It is generally separated into three parts depending upon the bending rigidity (the width of the plate) of the plate (**Fig.3**).

The stress component perpendicular to the weld line, σ_y, is largely compressive at the edges of the welds, and is slightly tensile in other parts (Fig.2(b)). However, in the case where welding length becomes longer, σ_y is not generated at the center parts.

2.1.2 Multi-pass welding [8,9)]

The production mechanism of residual stress in welding direction is not largely different from that described in 2.1.1. Here, the production mechanism of residual stress with several built-up passes and the characteristics of the residual stress distribution through the thickness are described.

z is in thickness direction.

Figure 4 shows residual stress obtained by FEM analysis [8)].
Figure 5 shows transient and residual stress along the thickness of the stress component σ_y perpendicular to the weld line.

In multi-pass welding, stress generated in the former pass is redistributed after once melted by the heat of the next pass. Then, the base metal and already welded layer restrict the shrinkage by cooling of weld metal.

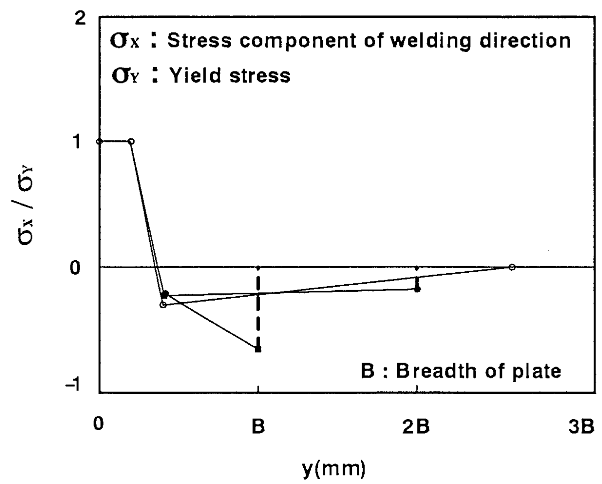


Fig.3 Features of residual stress generated by butt welding.

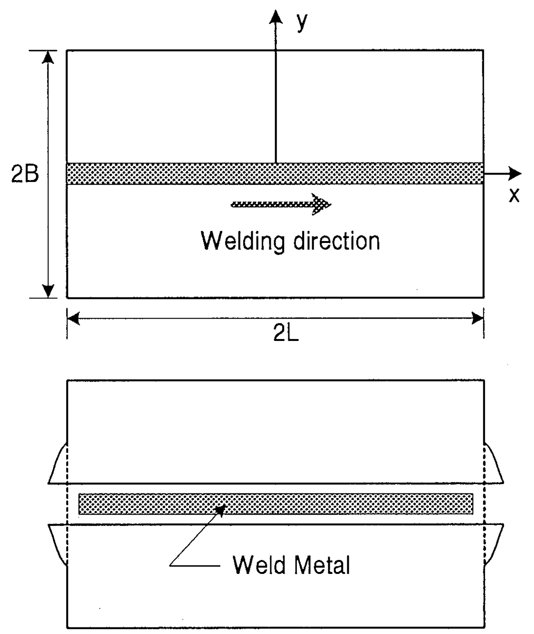
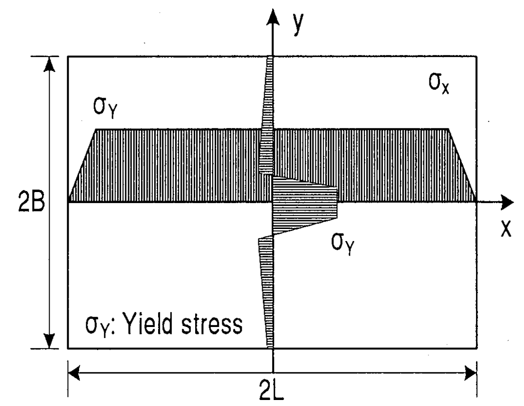
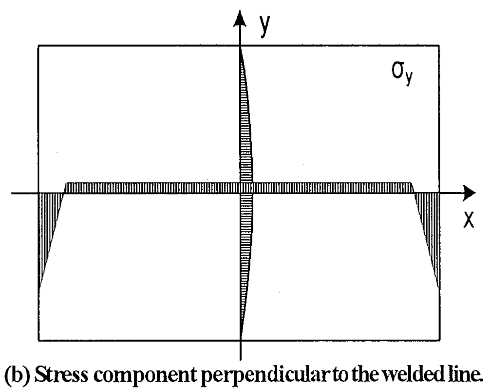


Fig.1 Production concept of residual stress generated by butt welding.



(a) Stress component of welding direction.



(b) Stress component perpendicular to the welded line.

Fig.2 Schematic representation of residual stress distributions of butt welded joints.

As the characteristics of σ_x and σ_y, the maximum tensile stress is generated at about 10 mm within the thickness from the upper surface (Fig.5). This is because the material (beyond 10 mm in the inner parts, including the deposited metal and HAZ) largely shrinks and because the mechanical restriction for the inner part of the thickness is severe compared with the surface of the welds. The above-mentioned behavior is repeated during welding through the last pass. Therefore, the shapes of the stress distributions along the thickness after several built-up passes do not largely change (Fig.5).

On the other hand, a bending moment applies at the cross section because the source of the shrinkage comes up to the top of the neutral axis following the built-up layer. Then, σ_y on the lower surface is tensile (Fig.5).

The stress component σ_z along the thickness is small.

Although the residual stress distribution does not change with reinforcement, the location generating the maximum tensile stress moves a little to the upper surface.

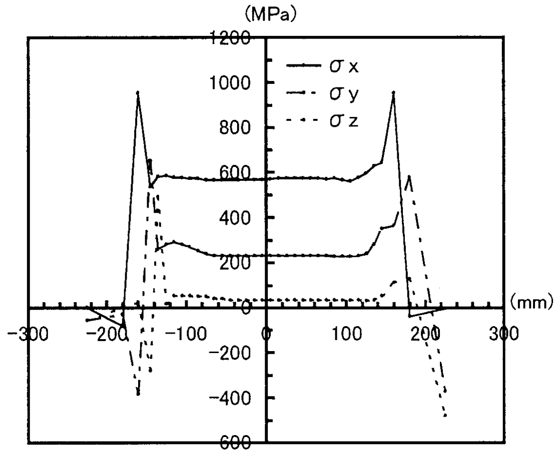
2.2 Solid-state bonding [10)]

There are several methods of solid-state bonding. Among them, the diffusion bonding of circumferences at uniform temperatures in a furnace is considered first. Next, friction welding in the case where a temperature gradient exists along the axial direction, mutual differences in the production mechanism of residual stress are described. In friction welding, although flashes are produced, it is considered that flashes do not influence residual stress in joints generated by welding. Therefore, flashes are ignored here [11)].

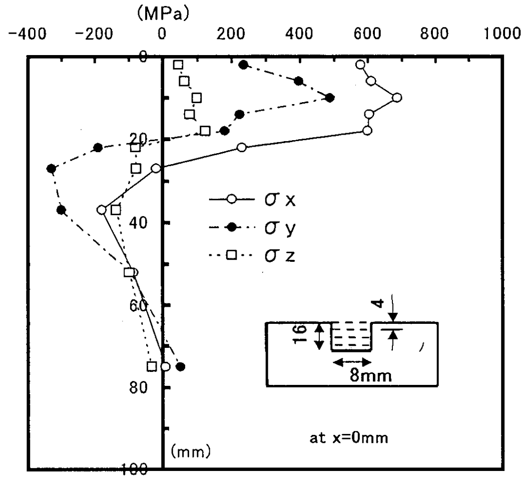
2.2.1 Similar materials [12)]

The dotted line in **Fig.6(a)** expresses the state at the point when the welds joined in a furnace cool down to the temperature, T_m, at which yield stress of the materials becomes quite small in comparison with yield stress at room temperature. In the cooling process after the temperature, T_m, the joined materials behave as a unit. In diffusion bonding, when the weld cool down to room temperature, it uniformly shrinks like as expressed by a solid line. Naturally, residual stress is not generated though the distortion is produced.

In friction welding, a temperature gradient exists along the axial direction. In this case, the shrinkage in a radial direction is



(a) Along the weld line.



(b) Through the thickness.

Fig.4 Distributions of residual stress generated by multi-pass repair welding of thick plate.

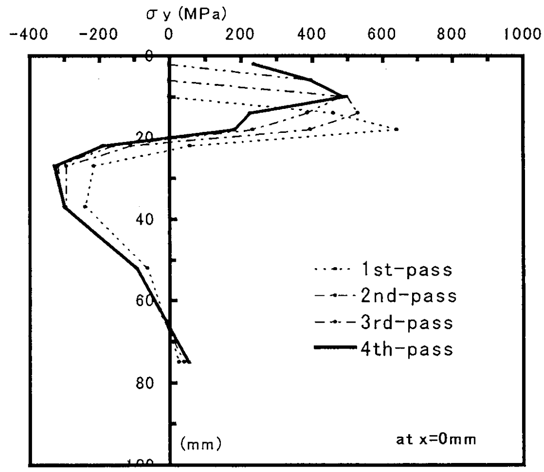


Fig.5 Transient stress distributions with multi-pass repair welding of thick plate.

different from that in the axial direction (The difference between the dotted line and the solid line is not constant (**Fig.7(a)**.). Owing to this, residual stress is generated. Although this point is different from diffusion bonding, the absolute value of residual stress is not large.

2.2.2 Dissimilar materials [11,13]

In diffusion bonding, although the temperature of a specimen in the furnace is constant, the magnitude of the linear expansion coefficient for each material is different. Therefore, if the specimen is cooled down independently without bonding, the shrinkage of each material is different as expressed by a solid line in **Fig.6(b)**. Owing to the differences in shrinkage, residual stress is generated.

In friction welding, a temperature gradient exists along the axial direction as mentioned in 2.2.1. Moreover, the temperature of each material is different. So, the shrinkage of each material is different in the radial direction. Stress caused by the shrinkage difference (**Fig.7(b)**) is added. The influence on the production of residual stress by the shrinkage difference is larger than the influence by the temperature gradient along the axial direction.

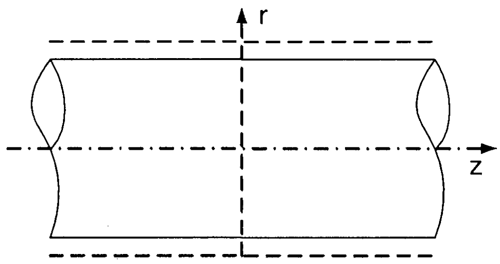
In dissimilar materials bonding, residual stress is necessarily generated. As the characteristics of residual stress, the component σ_r in a radial direction and the component σ_θ in circumferential direction become tensile in a substrate whose thermal shrinkage (the product of a linear expansion coefficient and a bonding temperature) is large, and becomes compressive in a substrate whose thermal shrinkage is small. The stress component σ_z generated in the axial direction is largely tensile at the periphery adjacent to the interface.

The production mechanism of residual stress in an ideal situation is described above. However, in actual welding or joining, residual stress is generated as the result of the elastic-plastic behavior in which thermal expansion and shrinkage are closely interrelated. For residual stress generated by welding or joining the main causes may be roughly divided into three. These are, the methods of welding or joining (the magnitude of heat input and bonding temperature, etc.), the properties of materials (a physical constants and the mechanical properties, etc.) and rigidity of the welding objects (a size of the welding objects, etc.)

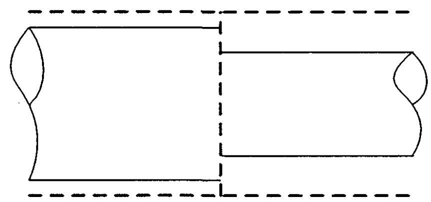
3. Prediction of Residual Stress

For the requirements to predict residual stress, it is known that restraint stress (residual stress) can be obtained from the restraint intensity of the joints [14]. Many studies have been carried out with considering the restraint intensity as a mechanical measure. So, the significance as a mechanical measure of the restraint intensity is described. Next, the thermal elastic-plastic analysis is performed for the problems of welding/joining and the obtained results are introduced below.

Phase transformation is ignored here [15].

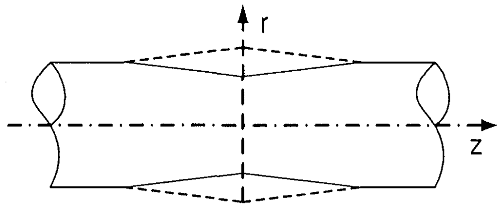


(a) Similar materials.

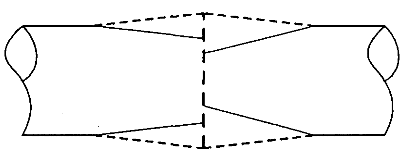


(b) Dissimilar materials.

Fig.6 Production concept of residual stress generated by solid-state bonding.



(a) Similar materials.



(b) Dissimilar materials.

Fig.7 Production concept of residual stress generated by friction welding.

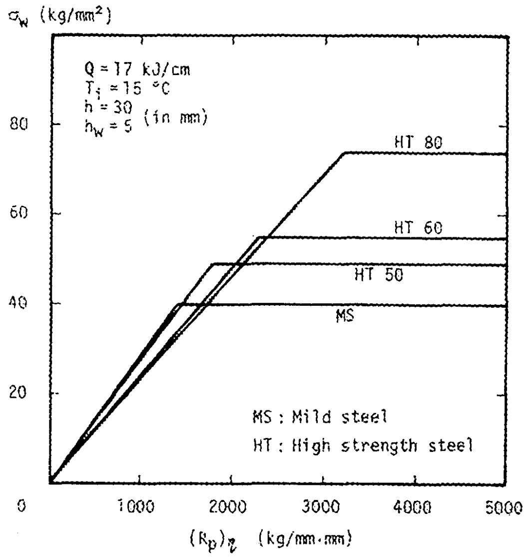


Fig.8 Relation between restraint intensity and restraint stress.

3.1 Restraint intensity and restraint stress (residual stress)

In the one-dimensional restraint state (RRC test), it was shown from investigating the process of shrinkage due to welding that restraint stress (residual stress) of the joints σ_w could be divided into inherent shrinkage and rigidity (restraint intensity) of the welding objects [14]. Restraint intensity R_p is defined as the force per unit welding length necessary to shrink the root gap of the joint by one unit .

In the one-dimensional restraint state, restraint intensity and restraint stress are directly related in the elastic region irrespective of the kind of steel (**Fig. 8**). So, it follows that restraint intensity instead of restraint stress can be used as a mechanical measure.

In two-dimensional and three-dimensional restraint states, restraint intensity is used as a mechanical measure by analogy with the one-dimensional restraint state without a detailed investigation. However, it was elucidated that inherent shrinkage and restraint intensity could not be divided in two-and three-dimensional restraint states[16]. Therefore, it was conducted that restraint intensity was only rigidity of the welding objects and could not used as a mechanical measure. On the other hand, the applicability and the utility of restraint intensity as a simple mechanical measure were shown, too[16].

3.2 Thermal elastic-plastic analysis based on FEM

In the case of welding, the temperature changes from the melting temperature to the room temperature. Accompanying this, the mechanical properties of materials largely change. Therefore, the analysis should be carried out with considering the material non-linearity. Furthermore, in the case of a thin plate, geometrical non-linearity should be considered.

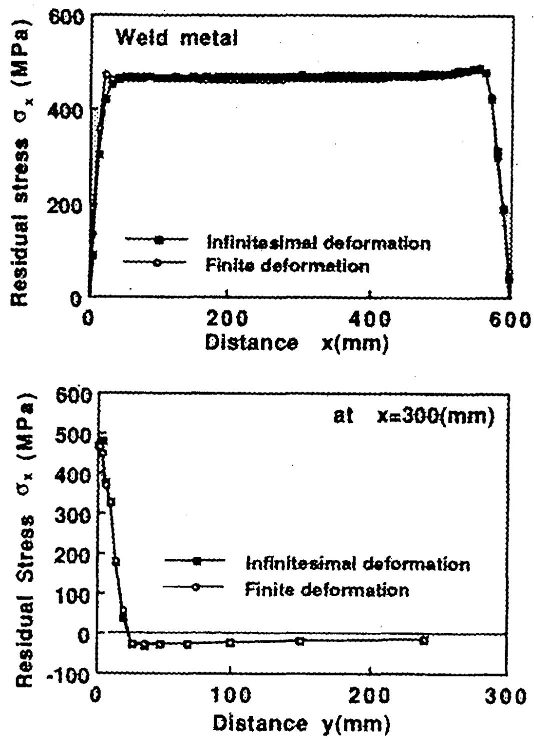


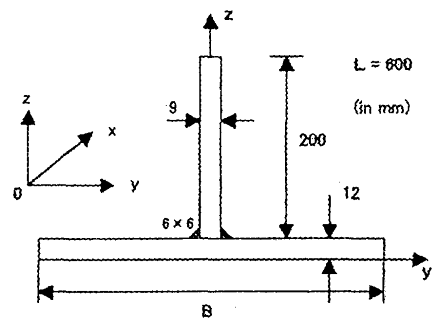
Fig.9 Comparison of the results obtained by infinitesimal deformation theory and finite deformation theory.

In the case of welding, a temperature history corresponds to the external force in the structure mechanics. Although thermal conduction in welding is not referred to, it is important for understanding the mechanical behavior of welding to know the temperature dependency of physical constants of materials, because a temperature history is equivalent to the external force in welding/joining. Concerning thermal conduction, see the references [1-3,17].

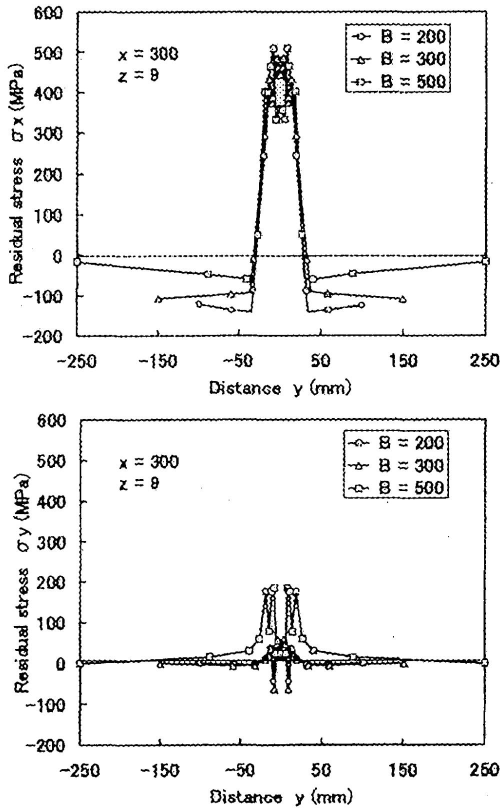
For the problems of welding/joining, some results obtained by using the thermal elastic-plastic analysis program based on FEM developed by the author and his colleagues are introduced below.

3.2.1 Butt welding for rectangular plate [18]

Figure 9 shows the results for butt welding of rectangular plate obtained by using a 2D-program based on the infinitesimal deformation theory and the finite deformation theory, respectively.



(a) Component geometry.



(b) Residual stress distributions.

Fig.10 Distributions of residual stress generated by fillet welding.

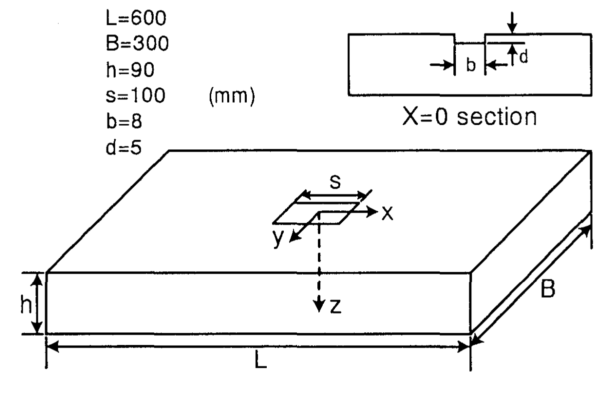
In the prediction of residual stress, both of these programs produce the same results.

3.2.2 Fillet welding [19]

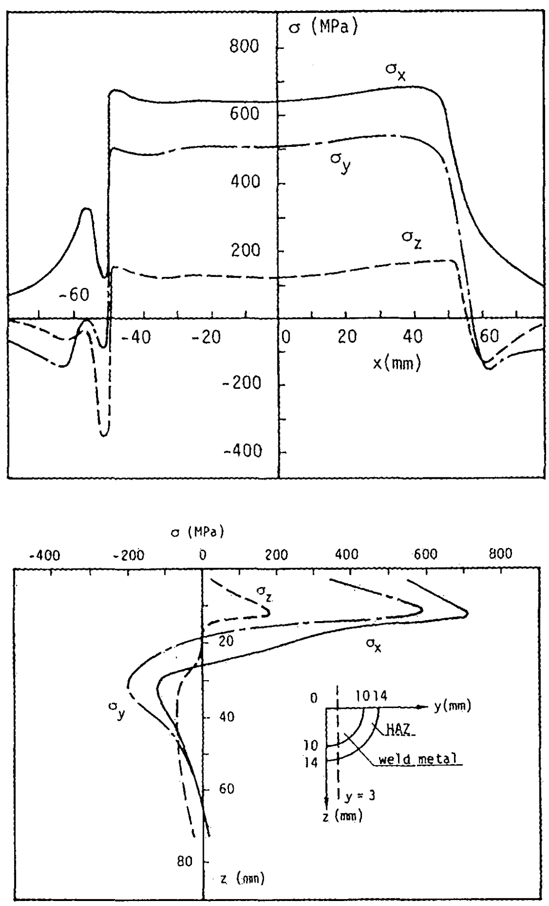
Figure 10(a) shows the model for analysis. Material is mild steel. Heat input is 12(kJ/mm), welding speed is 6(mm/s). The case in which one pass welding is performed in 600(mm) along x-direction at the same time on right and left sides is shown.

Figure 10(b) shows the residual stress distribution obtained by using a 3D-program.

The residual stress distribution has the same tendency in butt welding. The stress component along the weld line σ_x is large under the weld metal and it shows various forms at the compressive part depending on the plate width. The stress component perpendicular to the weld line σ_y is small in the whole region.

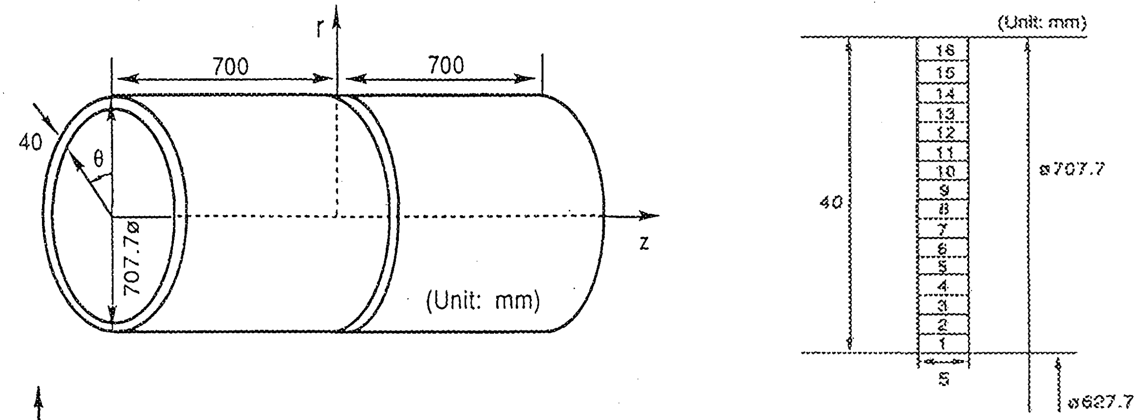


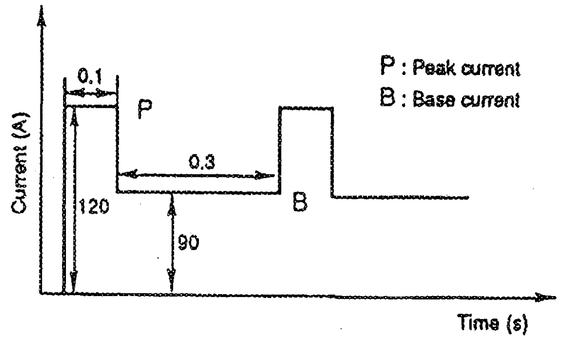
(a) Component geometry.



(b) Residual stress distributions.

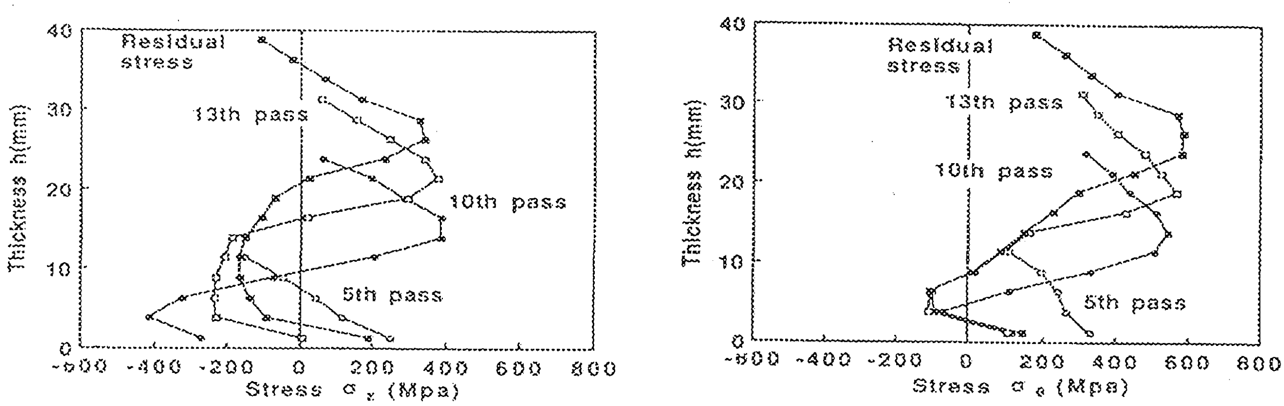
Fig.11 Distributions of residual stress generated by repair welding of thick plate.





Pass	Current P/B (A)	Voltage P/B (V)	Welding speed (cm/min)
1	120/90	7.3	6
2	200/120	7.3	8
3-16	240/150	8.5	8

(a) Component geometry and welding sequence.



(b) Transient and residual stress distributions.

Fig.12 Distributions of transient and residual stress generated by multi-pass pipe welding.

3.2.3 Repair welding in thick plate [20]

Figure 11(a) shows the model for analysis. Material is mild steel. One pass welding is performed in the groove of the model. Heat input is 3.4(kJ/mm), welding speed is 6(mm/s).

Figure 11(b) shows the residual stress distribution obtained by using a 3D-program.

Noting the shape of the distributions of σ_x and σ_y through the thickness, maximum tensile stress is generated at around 10mm inner from the upper surface same as residual stress generated in multi-pass welding (Fig.4(b)). σ_z through the thickness is small.

3.2.4 Multi-pass welding of pipe [9]

Figure 12(a) shows the model for analysis and the welding conditions. Rectangular pulse TIG welding is performed and material is stainless steel SUS304. **Figure 12(b)** shows transient and residual stress obtained by using an axi-symmetric program. The characteristics and the production mechanism were already described in the section 2.1.2.

3.2.5 Friction welding [11-13]

Figure 13 shows the model for analysis.

(a) Similar materials [12]

In order to elucidate the characteristics of residual stress generated by friction welding of similar materials (pure titanium),

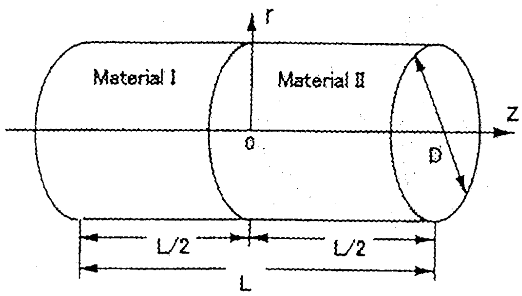


Fig.13 Component geometry and coordinate system.

axi-symmetric thermal elastic-plastic analysis is performed. Diameter D and length L of the model are D=13 and L = 80 (mm), respectively.

Figure 14 shows residual stress generated adjacent to the bonded line.

Although the yield stress of the base metal is 340 (MPa) at room temperature, the generated residual stress is small. σ_z at the edge adjacent to the bonded line is compressive and is not large.

(b) Dissimilar materials [11,13]

Materials are pure titanium and pure aluminum for industrial use. As the size of the model, D is 13 and L is 80 (mm).

Figure 15 shows residual stress generated adjacent to the bonded line [13].

σ_r and σ_θ are tensile in aluminum whose thermal shrinkage is larger than titanium and are compressive in titanium whose thermal shrinkage is smaller than aluminum. Large tensile σ_z is generated at the edge adjacent to the bonded line.

4. Prediction of Residual Stress in Constructing of Large Steel Structures

Although the results obtained by using the thermal elastic-plastic analysis program developed by the author and his colleagues in the previous sections were introduced, the CPU time for analysis was not mentioned. In recent years, computers have made remarkable progress. However, it takes a few days for analysis with some problems. Thermal elastic-plastic analysis by FEM requires a lot of CPU times. The distribution and the magnitude of residual stress changes because the size of the welding objects is different although the kind of steels and the welding conditions are same. Therefore, it is economically

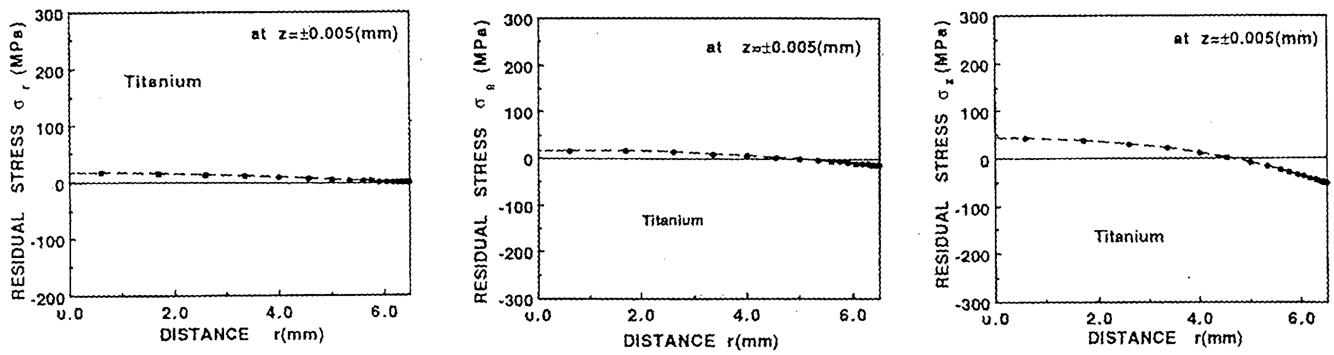


Fig.14 Residual stress in titanium /titanium friction welds.

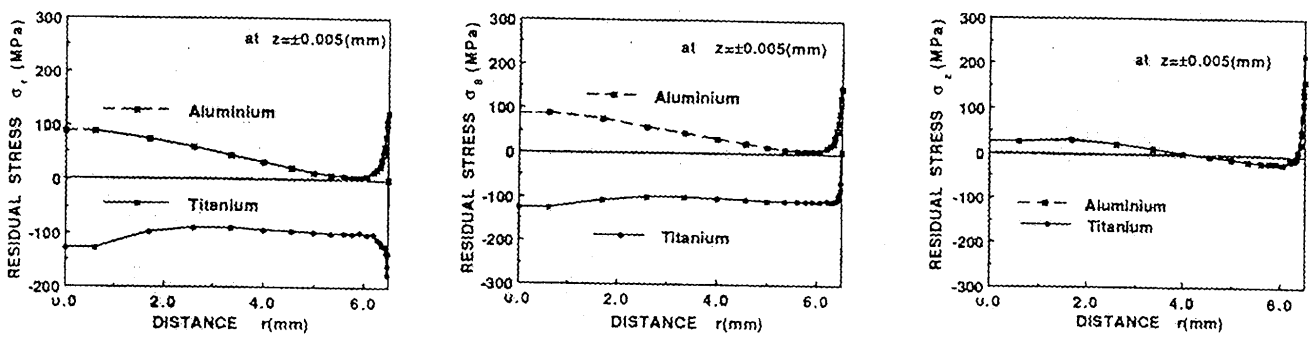


Fig.15 Residual stress in titanium/aluminum friction welds.

impossible that thermal elastic-plastic analysis can be performed on all problems. This is one reason why the prediction of residual stress is not easy.

One direction is proposed to solve this kind of problem. It was shown that residual stress changes because rigidity (the size etc.) of the welding objects is different although the source of residual stress (called inherent strain) is the same [6]. This has a very important meaning.

If it is assumed that inherent strain can be predicted for a change in the kind of steels and the welding conditions and a data base can be made, residual stress generated through the whole process in constructing the welded structures can be predicted by FEM elastic analysis by applying inherent strain to each joint[21]. That is, not residual stress in welding on each member but welding residual stress during construction of large steel structures such as bridges, ships, pressure vessels and so on can be predicted. These kinds of studies are being carried out in Japan.

5. Remark

There are various kinds of commercial programs for the prediction of residual stress generated by welding/joining. The commercial programs have the merit that input of the data is easy and a beautiful view of the output can be obtained, different from the program developed by the author. Therefore, the commercial programs have been frequently used in the fields of welding /joining. My candid opinion is described for the use of these commercial programs.

It seems that the users who trust that the obtained results are always correct have increased. This is a dangerous tendency. It is necessary to recognize that the commercial programs have no means of evaluating correctness of the results. That is, the evaluation of obtained results depends on the experience and the judgment of the users. The users should recognize this.

In using the commercial programs, it should be checked whether the obtained results shown in Fig.2 satisfy the equilibrium conditions expressed in the following equation (the basic item).

$$\int_{-B}^{B} \sigma_x dy = 0,\ \int_{-L}^{L} \sigma_y dx = 0$$

It should be always checked that the program is correctly used, by comparing the analytical solution or the experimental results. This is a necessary condition when using the commercial programs as tools for structural design. If the commercial programs are used with this attention, they can be powerful tools in engineering fields.

Residual stress generated by the thermal sprayed coating is not considered, but information. Concerning it can be found in the references [22, 23].

References

1) SATOH K, MUKAI N, TOYODA M: Welding Engineering, Rikougaku-sya, (1979) (in Japanese).

2) SATOH K, UEDA Y, FUJIMOTO F: Welding distortion and residual stress, Sanpou-syuppan, (1979) (in Japanese).

3) Handbook of Welding and Joining, Maruzen, (1990) (in Japanese).

4) FUJIMOTO F: Analysis of welding residual stress and distortion, Sanpou-syuppan, (1997) (in Japanese).

5) MURAKAWA H: Welding residual stress and distortion, J. of JWS, 67-3(1998), 26-42 (in Japanese).

6) UEDA Y, KIM Y-C, YUAN MG: A Predicting method of welding residual stress using source of residual stress, Quarterly J. of JWS, 6-1(1988), 59-64 (in Japanese).

7) KIM Y-C, PARK JU, HORIKAWA K: Effects of welding conditions on out-of-deformation and residual stress produced by welding, Steel construction engineering, 5-17(1998), 85-91 (in Japanese).

8) NAKAMURA T.: Mechanical characteristics of multi-pass repair welds in thick plate, Graduation thesis of Osaka Univ. (1988) (in Japanese).

9) KIM Y-C, PARK JU, HIRAOKA K: Reduction and control of residual stress generated by welding of pipe, Proc. of Welded Structures Symposium 99, (1999), Osaka, Japan, December (1999), 286-291 (in Japanese).

10) KIM Y-C: Joining of ceramics/ceramics and ceramics/metals (2) Mechanics in solid-state welds , J. of JWS, 65-4(1996), 319-323 (in Japanese).

11) KIM Y-C, FUJI A, T NORTH: Residual stress and plastic strain in AISI304L stainless steel/titanium friction welds, Materials science and Technology, 11-4(1995), 383-388.

12) HAYASHI T.: Joints characteristics of dissimilar materials friction welds, Master thesis of Osaka Univ., (1996) (in Japanese).

13) KIM Y-C, PARK JU, FUJI A, T NORTH, HORIKAWA K: Features of residual stress and plastic strain in titanium/aluminum friction welds, J. of High Temperature Society, 21-5(1995), 202-208 (in Japanese).

14) SATOH K, MATSUI S: Development of reaction stress and weld cracking under restraint,
J. of JWS, 36-10 (1967), 1096-1109 (in Japanese).

15) UEDA Y, KIM Y-C, CHEN C, TANG YM: Mathematical treatment of phase transformation and analytical calculation method of restraint stress-strain,
Quarterly J. of JWS, 2-1(1984), 89-97 (in Japanese).

16) UEDA Y, FUKUDA K, KIM Y-C, KOKI R: Characteristics of restraint stress-strain of the slit weld in a finite rectangular plate and the significance of restraint intensity as a dynamical factor,
J. of JWS, 51-8(1982), 636-643 (in Japanese).

17) UEDA Y, NAKACHO K, KIM Y-C, MURAKAWA H: Fundamentals of thermal elastic-plastic-creep analysis and measurement of welding residual stress (I),
J. of JWS, 55-6(1986), 336-348 (in Japanese).

18) KIM Y-C, PARK JU, IMOTO I, HORIKAWA K: Effects of initial imperfection on welding distortion and residual stress,
Proc. of Welding Structural Simposium 95, July (1995), Osaka, 239-246 (in Japanese).

19) KIM Y-C, CHANG KH, HORIKAWA K: Effects of welding conditions on out-of-plane deformation and residual stress in fillet welding,
Steel Construction Engineering, 6-21(1999), 77-82 (in Japanese).

20) UEDA Y, KIM Y-C, GARATANI K, YAMAKITA T: Mechanical characteristics of repair welds in thick plate,
Quarterly J. of JWS, 4-3(1986), 533-539 (in Japanese).

21) UEDA Y, NAKACHO K, KIM Y-C, MURAKAWA H: Fundamentals of thermal elastic-plastic-creep analysis and measurement of welding residual stress (III),
J. of JWS, 55-8(1986), 458-465 (in Japanese).

22) KIM Y-C, CHANG KH, HORIKAWA K: Characteristics of residual stress produced by $MoSi_2$ plasma thermal spraying and its production mechanism,
Quarterly J. of JWS, 16-1(1998), 82-86 (in Japanese).

23) KIM Y-C: What residual stress generated by thermal sprayed coating?, J. of High Temperature Society, Vol.27, Supplement (2001), 244-249 (in Japanese).