Measurement and FEM Analysis of Three Dimensional Residual Stresses in Fillet Welds of Stainless and Mild Steel Clad Plates †

Ning-xu MA*, Hidekazu MURAKAWA, Ya-sheng WANG*** and Yukio UEDA******

Abstract

In this paper, the detailed residual stresses in stainless and mild steel clad plates made by rolling are measured by the layer removal method. Welding residual stresses in fillet welds of clad plates are then measured by experiment using inherent strain as a parameter and computed by FEM. Finally, the effects of restraint in the fillet welding of chemical tanks on welding residual stresses are analyzed.

KEY WORDS: (Measurement) (FEM) (Residual Stresses) (inherent Strain) (Fillet Welds) (Clad Plates) (Stainless Steel) (Mild Steel) (Restraint) (Chemical tanks)

1. Introduction

Clad materials are widely used in pressure vessels in nuclear power plant and chemical tanks since they have good strength and low cost and they can also offer good resistance to corrosion and wear. However, in making clad materials, large residual stresses may be induced at the interfaces and surfaces of clad layers. When the clad materials are used to make structural components by welding, residual stresses will also be produced in the clad materials. The residual stresses at the interfaces may be deeply related to the formation and propagation of laminate separation, weld cracking and fatigue cracking. Up to now, there are few reports on the research into the residual stresses in the clad materials[1]. In this paper, a clad plate (SUS/MB) rolled from stainless (SUS316L) and mild steel (MB410) is taken as an example. Firstly, the residual stresses in rolled SUS plate and SUS/MB clad plate are measured. Then, a fillet weld of a SUS/MB flange and a SUS web is taken out from the structure of chemical tanks which is shown in Fig.1(a) and the welding residual stresses in the fillet welds shown in Fig.1(b) are measured using inherent strain as a parameter[2]. Lastly, welding residual stresses are computed using thermal elastic plastic FEM and the effects of restraint in fillet welding of cargo holds of chemical tanks on welding residual stresses are investigated.

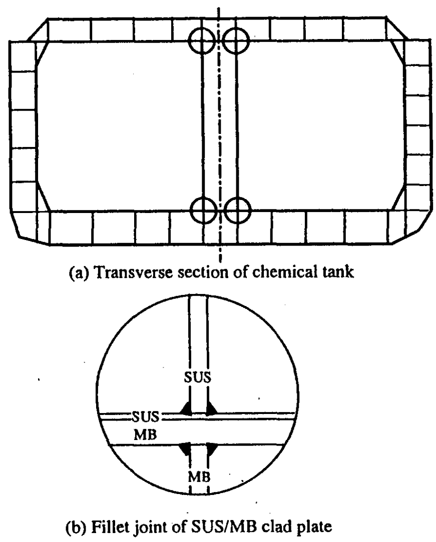

Fig.1 Application of clad plates and welded joints in chemical tanks

2. Measurement of Residual Stresses in Rolled SUS/MB Clad Plate and SUS Plate

2.1 Measuring Objects and Measuring Methods

The measuring objects are rolled SUS/MB clad plate

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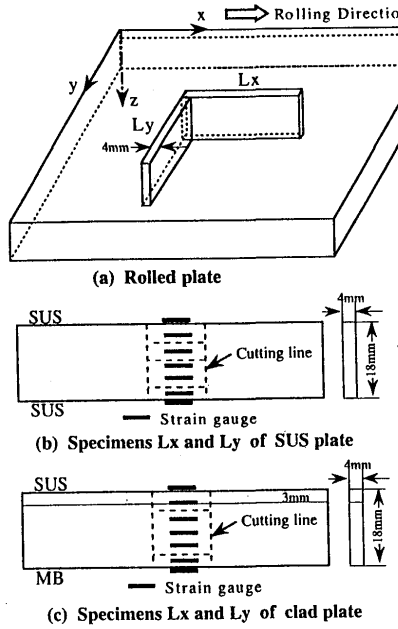


Fig. 2 A rolled SUS plate and a SUS/MB clad plate

and SUS plate shown in Fig.2. The thickness of clad plate is 3mm for the SUS layer and 15mm for the MB layer. The thickness of the SUS plate is 18mm.

In the measurement of residual stresses produced in the rolled plates, it is assumed that only two stress components σ_x and σ_y parallel and perpendicular to the rolling direction exist in the plate. It is also assumed that residual stresses σ_x and σ_y distribute uniformly in the rolling direction (x) and the transverse direction (y), and they change only in the thickness direction (z). To measure these two stress components σ_x and σ_y, thin specimens L_x and L_y, respectively, parallel to the x and y directions are sliced from the original plates as shown in Fig.2(a). The stress in specimens L_x and L_y is in a one dimensional stress state. i.e. in specimen L_x only stress σ_{Lx} and in specimen L_y only stress σ_{Ly} exist. The stresses σ_{Lx} and σ_{Ly} can be measured by the stress release method using strain gauges shown in Figs.2 (b) and (c). When σ_{Lx} and σ_{Ly} are measured, the stresses σ_x and σ_y in the original plates can be estimated by the following Equation.

$$\sigma_x = (\sigma_{Lx} + \upsilon\sigma_{Ly})/(1-\upsilon^2) \qquad (1a)$$

$$\sigma_y = (\sigma_{Ly} + \upsilon\sigma_{Lx})/(1-\upsilon^2) \qquad (1b)$$

where υ is Poisson ratio of materials.

Using the conventional stress release method and observed strains in the gauges shown in Figs. 2(b) and (c), the detailed distribution of stresses at the interface of clad plate can not be obtained. To measure the detailed distribution of residual stresses through the thickness, the layer removal method is proposed.

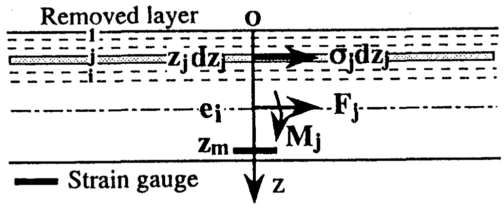


Fig. 3 Schematic representation of measurement of residual stress by the layer removal method with the aid of beam theory

2.2 Layer Removal Measuring Method

The layer removal method employs the changes of measured strain during the layer removing process and estimates the residual stress in removed layers by means of elasticity theory[1, 3].

When "q" layers are removed from the top surface shown in Fig.3, the stress in these "q" layers can be denoted by the stress vector $\{\sigma\}_q=\{\sigma_1, \sigma_2, ..., \sigma_q\}^T$. During removal of these "q" layers, stress changes observed at the z_m position can be measured "q" times, which are denoted by $\{\sigma^m\}_q=\{\sigma^m{}_1, \sigma^m{}_2, ..., \sigma^m{}_q\}^T$. The relationship between $\{\sigma\}_q$ and $\{\sigma^m\}_q$ is as follows,

$$[C]_{qxq}\{\sigma\}_q = \{\sigma^m\}_q \qquad (2)$$

where matrix [C] is a lower triangular matrix called the elastic response matrix between the vector of residual stresses and that of changes in released stress at the measuring point. The component C_{ij} of matrix [C] is equal to the observed stress change at the measuring point when "i" layers are totally removed and the unit stress component at the j-th layer $\sigma_j=1$ (j<i) is released. When the length of specimens L_x and L_y, shown in Fig.2, is long enough compared with their height, $[C]_{qxq}$ can be calculated by the following equation using beam theory [3].

$$C_{ij} = \frac{dz_j}{(t-z_i)} - \frac{dz_j(e_i - z_j)(z_m - e_i)}{(EI)_i} \qquad (3)$$

(j=1, 2,...,i), (i=1, 2,..., q)

dz_j = thickness of the j-th layer removed
z_j = z coordinate of the j-th layer removed
z_i = z coordinate of the i-th layer removed
e_i = Central coordinate of specimen after the i-th layer is removed.
$(EI)_i$= Bending stiffness of beam after the i-th layer is removed.
z_m = z coordinate of measuring point
t = height of specimen (thickness of original plate)

2.3 Distribution of Residual Stresses in SUS/MB Clad Plate and SUS Plate

Figure 4 shows the distributions of residual stresses σ_x and σ_y through the thickness of SUS plate measured directly by strain gauges when the specimens shown in Fig.2(b) were cut into small pieces following the cutting lines. Residual stresses σ_x and σ_y are compressive on the surfaces of SUS plate and tensile in the middle of the thickness.

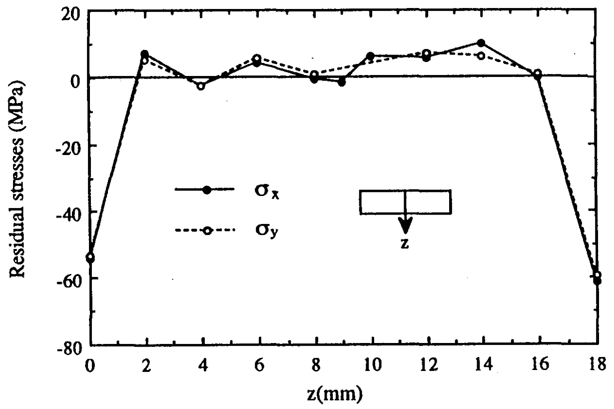


Fig. 4 Residual stress distribution through the thickness of a rolled SUS plate

Fig.5 shows the residual stress distributions through the thickness of SUS/MB clad plate. The solid circles and hollow circles are the average residual stresses measured by conventional stress release methods when the specimens shown in Fig. 2(c) were cut into small pieces following the cutting lines. On the SUS surface and the MB surface, tensile residual stresses σ_x and σ_y can be observed. At the interface of SUS/MB, residual stresses σ_x and σ_y show sudden changes. Tensile residual stresses are produced on the SUS side and compressive residual stresses on the MB side. The two stress components σ_x and σ_y have very similar distributions.

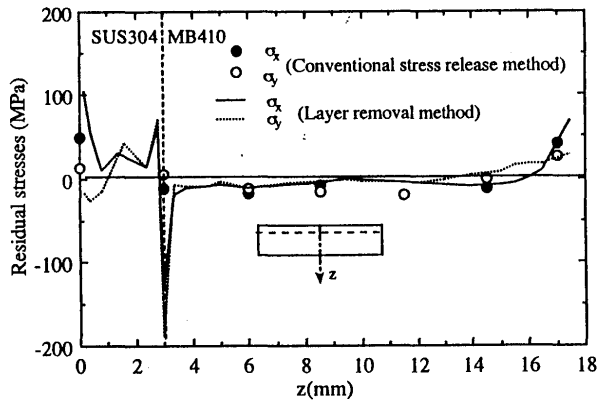


Fig. 5 Residual stress distributions through the thickness of a rolled SUS/MB clad plate

3 Measurement of Residual Stresses in Fillet Welds of A SUS/MB Clad Flange and A SUS Web

3.1 Measuring Object

The measuring object is a T-type fillet weld of a SUS/MB flange and a SUS web shown in Fig.6, which corresponds to the fillet welds of the chemical tank structure shown in Fig.1. The length of the fillet weld is 1000 mm, the width and thickness of the flange are 300 mm and 18 mm, respectively. Those of the web are 120 mm and 18 mm, respectively. Two fillet welds at left and right sides of the web were welded simultaneously. Therefore, residual stresses can be considered to be symmetrical with respect to the x-z plane (the y-axis). The welding conditions are also shown in Fig.6.

To measure welding residual stresses, thin specimens T, L_y (L_{y1}, L_{y2}) and L_z (L_{z1}, L_{z2}, L_{z3}), respectively, perpendicularly to welding direction (x), transverse direction of flange (y) and transverse direction of web (z), are cut off from the original fillet weld as shown in Figs. 6(b)-(d). The length and thickness of specimens L_y and L_z are 100 mm, 3 mm respectively. The thickness of specimen T is 8 mm. The positions of strain gauges are also shown in these figures.

3.2 Measuring Method Using Inherent Strain as A Parameter

When inherent strain is considered as a parameter or a source inducing residual stresses, the relationship among inherent strain $\{\varepsilon^*\}$, elastic strain $\{\varepsilon^e\}$ and residual stress $\{\sigma\}$ can be described as follows [1-2],

$$[H]\{\varepsilon^*\} = \{\varepsilon^e\} \quad (4)$$

$$\{\sigma\} = [D]\{\varepsilon^e\} \quad (5)$$

where [D] is the elastic matrix. [H] is the elastic response matrix which can be computed by elastic FEM assuming that a unit inherent strain component is applied to an element.

For a very long fillet weld, residual stresses distribute uniformly in the welding direction, except at the two ends of the joint[2]. The residual stresses existing in the transverse sections are σ_x, σ_y, σ_z and τ_{yz}.

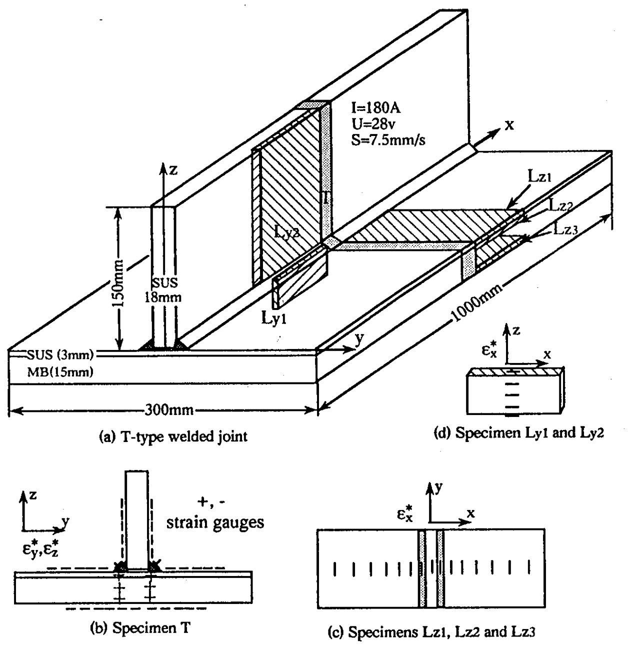


Fig. 6 A T-type fillet weld of SUS/MB plate and SUS plate, and specimens for welding residual stress measurement

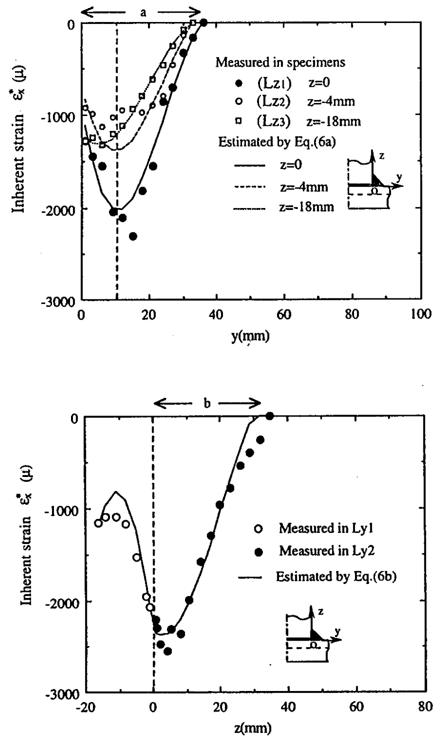


Fig. 7 Distribution of inherent strain ε^*_x in the transverse section of the fillet weld

Corresponding to these stress components, there are four inherent strain components ε^*_x ε^*_y, ε^*_z and ε^*_{yz} in the transverse sections. These inherent strain components can be separated into two parts as shown in Fig.6. One is the inherent strain ε^*_x which is the out-of-plane component in the transverse section, and the others are the inherent strains ε^*_y, ε^*_z and ε^*_{yz} in the plane of the transverse section. Welding residual stresses produced by out-of-plane inherent strain ε^*_x are denoted by $\{\sigma^A\}$ and those produced by in-plane inherent strains ε^*_y, ε^*_z and ε^*_{yz} are denoted by $\{\sigma^B\}$.

3.3 Measurement of residual stress $\{\sigma^A\}$ produced by ε^*_x

To measure the distribution of inherent strain ε^*_x in both transverse and thickness directions of a transverse section using a conventional method[2], many pieces of specimens L_y in the web and specimens L_z in the flange should be sliced from the original plates. To simplify the measurement using the function describing method for inherent strain distributions[4], only two pieces of specimens L_y (L_{y1}, L_{y2}) and three pieces of specimens L_z(L_{z1}, L_{z2}, L_{z3}) are sliced. Specimen L_{y1} is for measuring inherent strain ε^*_x through the thickness of the flange. L_{y2} is for measuring ε^*_x distribution in the transverse direction of the web. Specimens L_{z1} and L_{z2} are for measuring ε^*_x distribution at the two sides of the SUS/MB interface. L_{z3} is for measuring the distribution of ε^*_x on the bottom surface of the flange.

As a measuring procedure, firstly elastic strain ε^e_x in sliced thin speceimens L_y and L_z is measured by a stress release method using strain gauges, then inherent strain ε^*_x is estimated using equation (4) by FEM modeling of these thin speceimens[2]. The estimated inherent strain ε^*_x in the specimens L_z (L_{z1}, L_{z2}, L_{z3}) and that in the specimens L_y (L_{y1}, L_{y2}) are shown in Figs.7(a) and (b), respectively, denoted by solid and hollow points. In these figures, the parameters "a" and "b" present the widths of the inherent strain distribution zone in the transverse direction of the flange and the web, which are about 35 mm and 32 mm, respectively. Using these inherent strains measured in the specimens L_y (L_{y1}, L_{y2}) and L_z(L_{z1}, L_{z2}, L_{z3}), the inherent strain distribution in all of the transverse section can be described as a function[4] based on the following assumptions:

(1) The distribution of inherent strain ε^*_x in the web thickness direction is assumed to be uniform since the two sides of the web are welded simultaneously and only the average residual stresses through its thickness are discussed here.

(2) The inherent strain ε^*_x become zero beyond its existing zone. i.e. It is zero when z>b=32 mm in the web and y>a=35 mm in the flange.

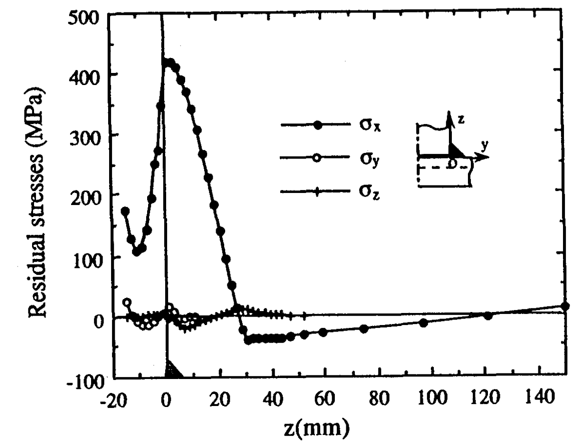


Fig. 8 Residual stress $\{\sigma^A\}$ produced by inherent strain ε^*_x

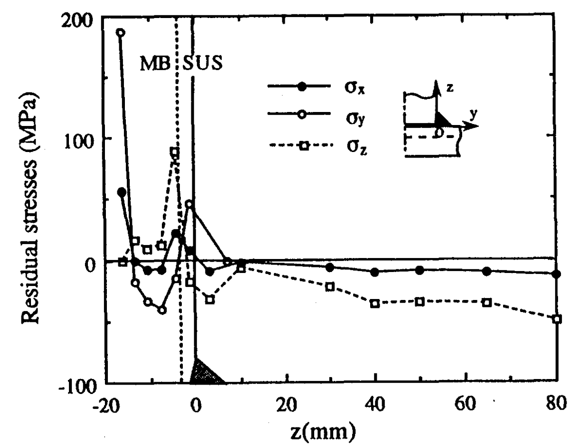


Fig. 9 Residual stress $\{\sigma^B\}$ produced by inherent strain $(\varepsilon^*_y, \varepsilon^*_z, \varepsilon^*_{yz})$

(3) The inherent strain distribution in its existing zone can be described by a polynomial function or a series function using the exponential function or the trigonometric function as a base function. However, these distribution functions have to have zero value at the boundary of the inherent strain existing zone. In this paper, very simple polynomial functions are used, and inherent strain distributions are expressed by the following equations.

$$\varepsilon^*_x(y,z) = \sum_{i=1}^{M}\sum_{j=1}^{N} A^*_{ij}(1-\frac{y}{a})^i(-\frac{z}{t})^{j-1} \text{ in Flang} \quad (6a)$$

$$\varepsilon^*_x(y,z) = \sum_{j=1}^{N} B^*_j(1-\frac{z}{b})^j \quad \text{in Web and WM} \quad (6b)$$

The y and z are the coordinates measured from the symmetrical axis and the flange top surface, respectively. The t is the flange thickness. M and N are the orders of y and z, respectively, in the polynomial functions. A^*_{ij} and B^*_j are unknown coefficients which can be determined using the measured inherent strains ε^*_x in specimens L_y (L_{y1}, L_{y2}) and L_z(L_{z1}, L_{z2}, L_{z3}) by the minimum square method. When M=N=1, a uniform distribution of inherent strain through the flange thickness and the linear distribution in the width directions of the flange and the web within the existing zone, can be expressed. When M=N=2, the linear distribution through the flange thickness can be described. In the case of M=N=3, the inherent strain distributions described by the functions are shown in Fig.7 by solid lines and very good results are obtained compared with the experimental ones.

When inherent strain ε^*_x described by Eq.(6) with M=N=3 is applied to the original fillet weld shown in Fig.6(a), the three dimensional residual stresses $\{\sigma^A\}$ can be computed by three dimensional elastic FEM and the results are shown in Fig.8.

3.4 Measurement of residual stress $\{\sigma^B\}$ produced by $(\varepsilon^*_y, \varepsilon^*_z, \varepsilon^*_{yz})$

Specimen T shown in Fig.6(b) is for measuring residual stress $\{\sigma^B\}$ in fillet weld produced by the inherent strains $(\varepsilon^*_y, \varepsilon^*_z, \varepsilon^*_{yz})$. Residual stresses in specimen T produced by these inherent strains are denoted by $\{\sigma^{Bo}\}$, which are in the plane stress state and can be directly measured by strain gauges. Using directly measured residual stress $\{\sigma^{Bo}\}$, the residual stress $\{\sigma^B\}$ can be easily calculated by following equation[2].

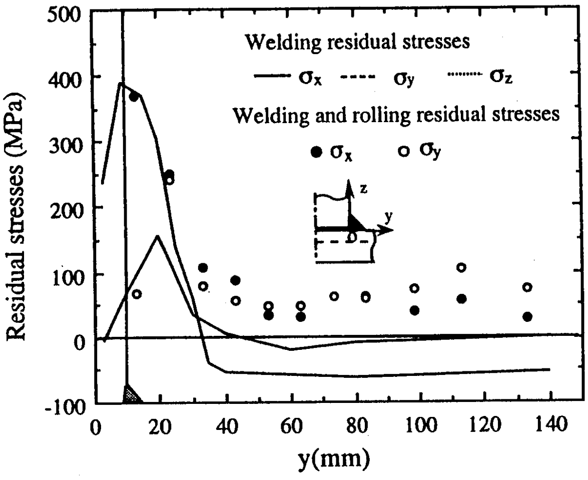
$$\sigma^B_x = \left(\sigma^{Bo}_y + \sigma^{Bo}_z\right) \times \frac{\upsilon}{(1-\upsilon^2)}, \quad \sigma^B_y = \frac{\sigma^{Bo}_y}{(1-\upsilon^2)}$$

$$\sigma^B_z = \frac{\sigma^{Bo}_z}{(1-\upsilon^2)} \qquad \tau^B_y = \frac{\tau^{Bo}_y}{(1-\upsilon^2)} \quad (7)$$

The distributions of residual stress $\{\sigma^B\}$ estimated by the above equation are shown in Fig.9.

3.5 Three dimensional residual stresses

The three dimensional welding residual stresses in the original fillet welds are the sum of stresses $\{\sigma^A\}$ and $\{\sigma^B\}$. Their distributions in the y and z directions are shown in Fig.10. The final residual stresses produced by welding and rolling are also presented by solid and hollow



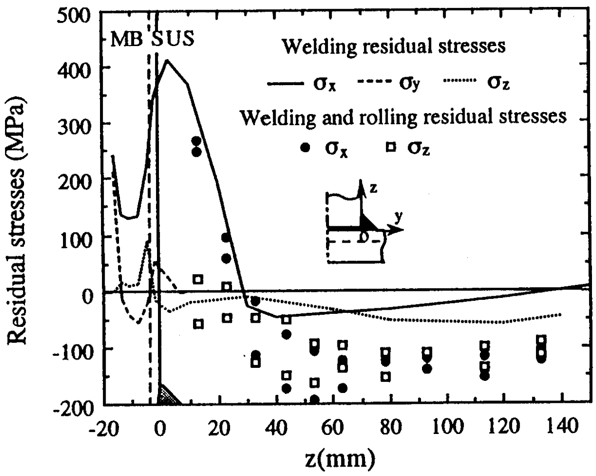


Fig. 10 Measured three dimensional residual stresses distributed in the transverse sections of filled welds of SUS/MB clad plates

points in this figure. Very large tensile stresses σ_x in the welded zone and σ_y near the fillet toe of the flange are observed. The transverse residual stress σ_y is tensile at the SUS layer and on the bottom surface of the flange. It becomes compressive in the center of the thickness. Compared with welding residual stresses σ_x and σ_y, residual stress σ_z is quite small. In the welded zone, final residual stresses are governed by welding stresses. Away from the welded zone, the final residual stresses are different from those due to welding. These differences are due to the residual stresses produced by rolling.

4 FEM Analysis of Welding Residual Stresses in Clad Fillet Welds And The Effects of Restraint

4.1 Analyzing conditions

In the previous sections, the measurement of three dimensional residual stresses are described. In this section, the thermal elastic plastic FEM is employed to analyze the detailed residual stresses at SUS/MB and the effects of restraint.

In the FEM analysis, generalized plane strain is assumed and only the transverse section is subdivided into an FEM mesh as shown in Fig.11. The welding heat

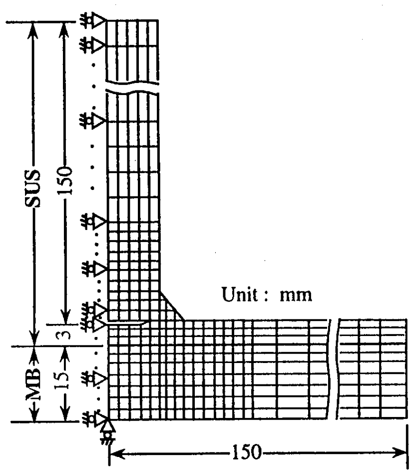


Fig. 11 Mesh division for the FEM analysis

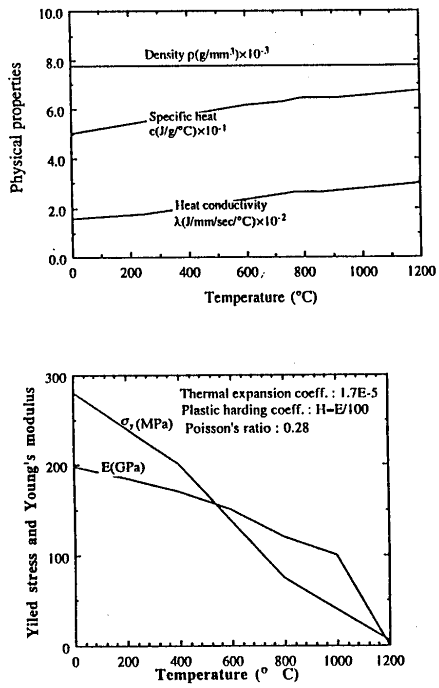


Fig. 12 Material properties and their temperature dependency for SUS316L

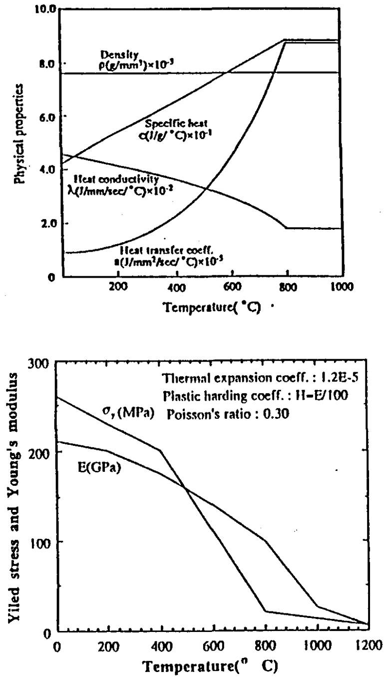


Fig. 13 Material properties and their temperature dependency for MB410

efficiency is assumed to be 60% in this analysis. The material properties of SUS316L and MB410 are shown in Figs.12 and 13, respectively.

4.2 Welding Residual Stresses in Clad Fillet Weld

The residual stresses computed by FEM are shown in Fig.14. The measured residual stresses are also displayed in this figure. Both results agree very well and FEM results are verified. At the interface of SUS and MB, a sudden change of stress component σ_y, which can not be easily measured by experiments, is observed.

4.3 Effect of Restraint on Welding Residual Stresses in Clad Fillet Weld

As shown in Fig.1, the fillet weld in a chemical tank structure may be welded with restraint conditions. To simulate these restraint conditions in T-type fillet welding, the nodal displacements in the z direction at the top of web and at the bottom of flange are set to be zero. In considering restraint conditions, the residual stresses computed by FEM are shown in Fig.15 where the restraint condition is schematically represented. It can be observed from Fig.15 that the large tensile three dimensional residual stresses σ_x, σ_y and σ_z are produced at the SUS side of the SUS/MB interface, a large tensile

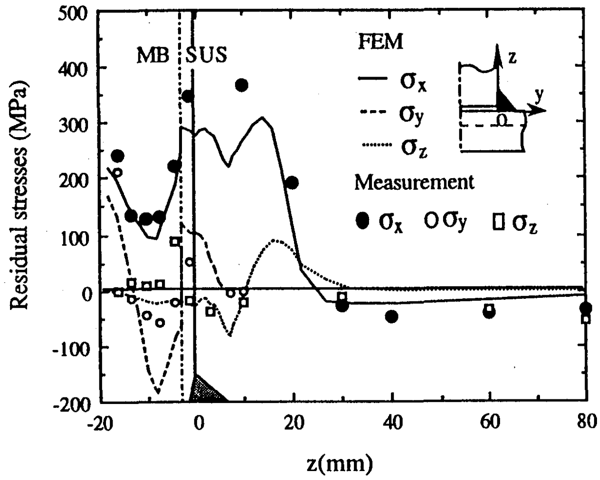


Fig. 14 Welding residual stresses in clad fillet welds computed by thermal elastic plastic FEM

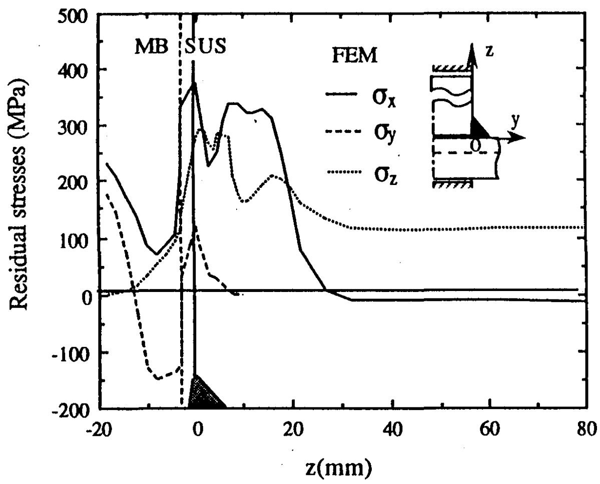


Fig. 15 Welding residual stresses in clad fillet welds under restraint conditions computed by thermal elastic plastic FEM

stress σ_z at the fillet toe of the web side. The large tensile residual stress σ_z perpendicular to the SUS/MB interface may be one of the reasons for laminate cracking.

5 Conclusions

(1) Residual stresses in SUS/MB clad plate produced by rolling are tensile on the two surfaces and compressive in the middle of the plate thickness. Large tensile residual stresses are produced at the SUS side of the SUS/MB interface and large compressive stresses at the MB side of the interface.

(2) Residual stresses in SUS plate are compressive on the two surfaces and tensile in the middle of the plate thickness.

(3) Welding residual stresses σ_x, σ_y are large tensile at the SUS layer. On the SUS surface near the fillet toe of the flange, a large tensile transverse residual stress σ_y is produced. This may have a detrimental effect on the fatigue cracking induced at the fillet toe.

(4) Welding residual stresses computed by FEM show very good agreement with those measured by experiments

(5) In considering restraint on the fillet welds of chemical tanks, not only the large tensile residual stresses σ_x, σ_y parallel to the SUS/MB interface, but also the large tensile residual stress σ_z perpendicular to the SUS/MB interface appear from the computation results. These large tensile residual stresses may be one of the reasons for laminate cracking.

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