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Measurement of Three Dimensional Residual Stresses in Rolled Clad Plates and Welded Joints of a Chemical Tank Structure†

MA Ninshu *, MURAKAWA Hidekazu**, LUO Yu*** and DENG Dean****

Abstract

To evaluate the safety of welded joints in a chemical tank before manufacture, the rolling residual stress in steel plates and welding residual stress in welded joints need be measured. In this paper, firstly, the rolling residual stresses in a stainless plate (SUS304) and a clad plate (SUS304/MB410) used in a chemical tank are measured. Then, the welding residual stresses in a simple bead-on-plate weld and a practical filled weld are measured by the inherent strain method. Lastly, the total residual stresses in the welded joints are discussed.

KEY WORDS: (Three Dimensional Residual Stress), (Rolled Clad Plates), (Measurement)

1. Introduction

Clad steel is widely used in pressure vessels and chemical tanks because it has advantages of both the strength and resistance to corrosion. On the other hand, since the base metal and the clad metal have different physical and mechanical properties, residual stresses are often induced by the cladding process and the following welding process. The residual stresses may induce interface peeling at the clad plates, fatigue cracking, stress corrosion cracking during service.

Figure 1 shows a chemical tank in which stainless steel (SUS304), high strength steel (MB410) and thermally rolled clad steel (SUS304/MB410) are used. Before production, residual stresses in a fillet welded joint, shown in Fig. 1, need to be measured. In this paper, firstly, the rolling stresses in both a stainless steel plate (SUS304) and a clad steel plate (SUS304/MB410) are carried out by the layer removal method³ and conventional stress release method. Then, the residual stresses in a simple bead-on-plate weld and in a practical fillet joint with a clad plate are measured based on the inherent strain method²⁻⁴. Lastly, the total residual stress states are discussed.

2. Measurement of rolling stress in a stainless plate and a clad plate

2.1 Measurement specimens

Figures 1 and 2 show a stainless plate (SUS304) and a clad plate (SUS304/MB410) made by thermal rolling. The thicknesses of the SUS304 layer and MB410 layer of the clad plate are 3mm and 15mm, respectively. The Young’s modulus and Poisson’s ratio for SUS304 and MB410 are 198000MPa, 0.28 and 206000MPa, 0.3, respectively.

The rolling stress has two components \( \sigma_x \) and \( \sigma_y \), which are parallel and perpendicular to the rolling direction, respectively, as shown in Figs. 2-3. By cutting off two thin specimen Lx and Ly, two stress components \( \sigma_x \) and \( \sigma_y \) can be separated. The stresses in specimen Lx and in specimen Ly are described by \( \sigma_{Lx} \) and \( \sigma_{Ly} \). The rolling stresses \( (\sigma_x, \sigma_y) \) in the original clad plate can be calculated from the stresses \( (\sigma_{Lx}, \sigma_{Ly}) \) in specimen \( (Lx, Ly) \) by Eq. (1),

\[
\sigma_x = \frac{\sigma_{Lx} + \nu \sigma_{Ly}}{1 - \nu^2}, \quad \sigma_y = \frac{\sigma_{Ly} + \nu \sigma_{Lx}}{1 - \nu^2}
\]  

where \( \nu \) is Poisson’s ratio.
If localized stress distribution at the cladding interface is neglected, the rolling stresses \( \sigma_{Lx} \) and \( \sigma_{Ly} \) can be directly measured using strain gauges attached on specimens \( Lx \) and \( Ly \) shown in Fig. 2(b) and Fig. 3(b) by the conventional mechanical stress release method. To measure the local stress and detail distribution through the thickness of the clad plate, a layer removal method is employed for specimens \( Lx \) and \( Ly \), which will be described in detail below.

2.1 Rolling residual stresses measurement by layer removal method

(1) Assumption

If it is assumed that the stress in specimen \( Lx \) or \( Ly \) distributes uniformly in the longitudinal direction and varies only in the thickness direction \( (z) \), as shown in Fig. 4, the elastic beam theory can be applied to estimate the residual stresses.

(2) Measuring procedure

Step 1: A strain gauge is attached to the specimen \( Lx \) and \( Ly \) at the position \( z_m \) near the lower surface shown in Fig. 4.

Step 2: Thin layers with 0.2mm are removed by milling gradually from the SUS304 side. During milling, a cooling oil is used to prevent the temperature rising.

Step 3: After each layer is removed, the strain at measuring position \( z_m \) must be measured.

(3) Measuring equations

When \( i \) layers are removed, the stresses \( \sigma_{1}^{Lx}, \sigma_{2}^{Lx}, \ldots, \sigma_{i}^{Lx} \) of these \( i \) layers will be released. If the size of j-th layer \( (1 \leq j \leq i) \) is \( dz_j \) and the specimen thickness is unit, the released force on the j-th layer should be \( \sigma_{j}^{Lx}dz_j \). This force at the j-th layer can be expressed by the force \( F_j \) and the moment \( M_j \) acting on a neutral axis.

\[
F_j = \sigma_{j}^{Lx}dz_j, \quad M_j = F_j(e_i - z_j) = \sigma_{j}^{Lx}dz_j(e_i - z_j), \quad (j = 1 \sim i)
\]

Where, \( e_i \) and \( z_j \) are the coordinate of the neutral axis after \( i \) layers are removed and coordinate of the j-th layer, respectively.

After \( i \) layers are all removed, the axial force \( F \) and moment \( M \) acting on the neutral axis can be calculated by Eq. (3).

\[
F = \sum_{j=1}^{i} F_j = \sum_{j=1}^{i} \sigma_{j}^{Lx}dz_j, \quad M = \sum_{j=1}^{i} M_j = \sum_{j=1}^{i} \sigma_{j}^{Lx}dz_j(e_i - z_j)
\]

If the measured strain at position \( z_m \) is \( \varepsilon_{i}^{m} \) after \( i \) layers are removed, the relation between measured strain \( \varepsilon_{i}^{m} \) and released stresses \( \sigma_{j}^{Lx} \quad (j=1 \sim i) \) can be derived by elastic beam theory.

\[
\varepsilon_{i}^{m} = \frac{F}{(h - z_i - dz_i/2)E_m} - \frac{M(z_m - \varepsilon_i)}{(EI)_i}
\]

\[
= \sum_{j=1}^{i} \frac{\sigma_{j}^{Lx}dz_j}{(h - z_i - dz_i/2)E_m} - \frac{(z_m - \varepsilon_i)\sum_{j=1}^{i} \sigma_{j}^{Lx}dz_j(e_i - z_j)}{(h - z_i - dz_i/2)E_m}
\]

where, \( h, z_m, E_m \) are the thickness of the clad plate, the coordinate and Young’s modulus of the material at the strain gauge position, respectively. \( (EI)_i \) is bending stiffness of the beam after \( i \) layers are removed.

If Eq. (4) is written in vector form, the following equations can be created.

\[
\varepsilon_{i}^{m} = \{\varepsilon_{i1}, \varepsilon_{i2}, \ldots, \varepsilon_{ii}\} \{\sigma_{1}^{Lx}, \sigma_{2}^{Lx}, \ldots, \sigma_{i}^{Lx}\}^T
\]

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If, totally, $q$ layers are removed in the experiment and the strain is measured after each layer is removed, the following equations can be obtained.

$$
i = 1, \quad \varepsilon_i^m = \{c_{i1}, 0, ..., 0\} \{\sigma_{i1}^L, \sigma_{i2}^L, ..., \sigma_{iq}^L\}^T$$

$$
i = 2, \quad \varepsilon_i^m = \{c_{i1}, c_{i2}, ..., 0\} \{\sigma_{i1}^L, \sigma_{i2}^L, ..., \sigma_{iq}^L\}^T$$

$$
\vdots \quad i = q, \quad \varepsilon_i^m = \{c_{iq}, c_{iq2}, ..., 0\} \{\sigma_{i1}^L, \sigma_{i2}^L, ..., \sigma_{iq}^L\}^T
$$

If Eq. (7) is written in the form of a matrix, the following measuring equation can be obtained.

$$
[C]_{q \times q} \{\sigma_i^L\}_q = \{\varepsilon_i^m\}_q
$$

where, $[C]$ is the elastic response matrix between measured strains and released stresses by the layer removal method.

### 2.3 Rolling residual stresses in a clad plate (SUS304/MB410)

The measured rolling stresses $(\sigma_x, \sigma_y)$ and their distributions through the thickness of the clad plate are shown in Fig. 5. The marks (•, ○) are the stresses $(\sigma_x, \sigma_y)$ directly measured by strain gauges using conventional stress release methods. The overall distribution of residual stresses measured by the layer removal method agrees well with that by the conventional stress release method. The maximum stress values on the surfaces and the clad interface by the layer removal method are larger than those by the conventional stress release method.

Two stress components $(\sigma_x, \sigma_y)$ have a similar distribution shape and are slightly different in their values. The rolling stresses $(\sigma_x, \sigma_y)$ are tensile on the SUS304 layer and lower surface of MB410 layer. The local stresses $(\sigma_x, \sigma_y)$ at the clad interface are tensile on the side of SUS304 and compressive on the side of MB410.

### 2.4 Rolling residual stresses in a stainless plate (SUS304)

The rolling residual stresses in a SUS304 plate measured by the conventional stress release method are shown in Fig. 6. The rolling residual stresses $\sigma_x$ and $\sigma_y$ are compressive on the top surface and bottom surface of the SUS304 plate. They are quite different from the stresses in the SUS304/MB410 clad plate shown in Fig. 5.
(2) Measuring equations of inherent strain method

The general relationships among inherent strain \( \varepsilon^* \), elastic strain \( \varepsilon^e \) and welding residual stress \( \sigma \) can be expressed by the following equations,

\[
[H]\{\varepsilon^*\} = \{\varepsilon^e\} \tag{9}
\]
\[
\{\sigma\} = [D]\{\varepsilon^e\} \tag{10}
\]

Where, \([H]\) is the elastic response matrix between inherent strain and elastic strain and \([D]\) is elastic stress-strain matrix of material defined by Young’s modulus and Poisson’s ratio.

Equations (9-10) for all specimens shown in Fig. 7 have the same form. The value of elastic strains \( \varepsilon^e \) and the components \( H_{ij} \) of matrix \([H]\) will be different between the specimens. The elastic strain \( \varepsilon^e \) in each specimen can be measured. The matrix \([H]\) for each specimen can be created by elastic FEM computation. The component \( H_{ij} \) is equal to the elastic strain at the measuring element when unit inherent strain is applied to the FEM model as an initial strain.

(3) Separation of inherent strain components

To measure welding stresses in the transverse section using the inherent strain method, one piece of T-specimen (transverse section specimen), three pieces specimens Lz (Lz1, Lz2, Lz3) and one piece specimen Ly as shown in Figs. 7 (a), (b) and (c) are cut off from the original bead-on-plate weld. The specimens Lz1, Lz2 and Lz3 are used for the stress measurements on SUS304 layer, MB410 layer and bottom layer of the clad plate, respectively. The strain gauges attached on each specimen are schematically represented in the figures. The inherent strain components existing in specimen T and in specimens Lz, Ly are \( \{\varepsilon^*, \varepsilon^e_z, \gamma^e_{yz}\} \) and \( \varepsilon^*_x \), respectively, which are the same as those in the original bead-on-plate weld. The welding residual stresses \( \{\sigma\} \) can be divided into two parts \( \{\sigma^A\} \) and \( \{\sigma^B\} \) as shown in Eq. (11), which are produced by the transverse inherent strain components \( \{\varepsilon^*_y, \varepsilon^*_z, \gamma^e_{yz}\} \) and the longitudinal component \( \varepsilon^*_x \) in the welding direction (x), respectively.

\[
\{\sigma\} = \{\sigma(\varepsilon^*_y, \varepsilon^*_z, \gamma^e_{yz})\} + \{\sigma(\varepsilon^*_x)\} = \{\sigma^A\} + \{\sigma^B\} \tag{11}
\]

3.2 Welding residual stresses \( \{\sigma^A\} \) due to inherent strains \( \{\varepsilon^*_y, \varepsilon^*_z, \gamma^e_{yz}\} \)

If the overall distribution inherent strains \( \{\varepsilon^*_y, \varepsilon^*_z, \gamma^e_{yz}\} \) are measured in the specimen T, the overall distribution of residual stresses \( \{\sigma^A\} \) can be estimated. If the residual stresses only at the particular positions are necessary, the residual stresses \( \{\sigma^A\} \) can be determined by transferring the measured stresses \( \{\sigma^T\} \) on specimen T to the original welded joint using following equation.

\[
\sigma^A_i = \frac{\sigma_i^T + u\sigma^T_{zy}}{1 - u^2}, \quad \sigma^A_z = \frac{\sigma^T_z + uv^T_{yy}}{1 - u^2}, \tag{12}
\]

where, \( u \) is Poisson’s ratio.

The residual stresses \( \{\sigma^A\} \) and their distributions on the SUS304 surface (y) and through thickness (z) are shown in Fig. 8. The transverse residual stress \( \sigma^A_y \) is tensile on both the top surface and the bottom surface of the weld zone. The value of transverse residual stress \( \sigma^A_y \) is larger than the values of longitudinal residual stress \( \sigma^A_x \) and residual stress \( \sigma^A_z \) in thickness direction.

3.3 Welding residual stresses \( \{\sigma^B\} \) due to inherent strain \( \varepsilon^*_x \)
To estimate the distribution of residual stresses \( \{ \sigma^B \} \) by the inherent strain method, the distribution of inherent strain \( \varepsilon_x^* \) has to be determined. The inherent strain distribution in the transverse direction (y) and in the thickness direction (z) can be estimated by Eq. (9) using the measured elastic strain \( \varepsilon_x^* \) in Ly and Lz specimens.

The measured residual stress \( \sigma_{ix}^i = E \times \varepsilon_x^i \) in specimens Lz \( (L_{z1}, L_{z2}, L_{z3}) \) and its distribution in the y-direction are shown in Fig. 9 by marks ●, ○, □. The parameters \( a_1, a_2, a_3 \) shown in Fig. 9 are the half width of inherent strain zone in the y-direction, which are corresponding to the positions of the peak compressive residual stresses in the y-direction of the specimens \( L_{z1}, L_{z2}, L_{z3} \), respectively. The width of inherent strain zone can be expressed by \( a(z) \), where \( z \) is the z-coordinate. The distributions of inherent strain \( \varepsilon_x^* \) in the y-direction of specimens \( (L_{z1}, L_{z2}, L_{z3}) \) estimated by Eq. (9) are shown in Fig. 10, which has a simple distribution shape compared with the residual stress \( \sigma_x^r \).

The reproduced residual stresses in specimens \( L_{z1}, L_{z2}, L_{z3} \) by inherent strain \( \varepsilon_x^* \) are also plotted in Fig. 9. The residual stresses are accurately reproduced by the inherent strain method.

The distribution of inherent strain \( \varepsilon_x^* \) in the z-direction of specimen Ly consists of a linear part \( \varepsilon_{ixL}^*(z) \) and a non-linear part \( \varepsilon_{ixN}^*(z) \) described as below,

\[
\varepsilon_x^*(z) = \varepsilon_{ixL}^*(z) + \varepsilon_{ixN}^*(z) = c_1 + c_2z + \varepsilon_{ixN}^*(z) \equiv \varepsilon_x(0, z)
\]

(13)

where, \( c_1 \) and \( c_2 \) are the coefficients of linear inherent strain \( \varepsilon_{ixL}^*(z) \).

The linear inherent strain \( \varepsilon_{ixL}^*(z) \) is equal to the released strain when specimen Ly is cut off. It can be measured by attaching the two strain gauges respectively on the top surface and the bottom surface of specimen Ly before cutting off from the original bead-on-plate weld.

The non-linear part \( \varepsilon_{ixN}^*(z) \) is equal to the released strain, which can be measured by attaching new strain gauges on the specimen Ly. The measured inherent strains \( \varepsilon_x^r(z) \) and their distributions in the thickness direction (z) are shown in Fig. 11.

To determine the distribution of welding residual stresses \( \{ \sigma^B \} \), the distribution of inherent strain \( \varepsilon_x^* \) has to be known. Here, a function defined by Eq. (14) is adapted to describe the inherent strain distribution on the transverse section,

\[
\varepsilon_x(y, z) = \varepsilon_x(0, z)[1 - \frac{y}{a(z)}][1 + A_i(\frac{y}{a(z)}) + A_i(\frac{y}{a(z)})^2]
\]

(14)

where, \( c_1, c_2 \) are the coefficients of linear inherent strain \( \varepsilon_{ixL}^*(z) \).

The reproduction of inherent strain \( \varepsilon_x^* \) and its distribution in the y-direction are shown in Fig. 12.
where, \( a(z) \) is the half width of the inherent strain zone and varies slightly in the z-direction. Coefficients \( A_x \) and \( A_z \) can be determined by function fitting using inherent strains already measured in specimens \( L_{z1}, L_{z2}, L_{z3} \) as shown in Fig. 10 and Fig. 11. Figure 12 shows the residual stresses \( \{ \sigma^B \} \) and their distributions through thickness estimated by applying inherent strain \( \epsilon^*_z \) expressed by Eq. (4) to the original bead-on-plate weld. As shown in Fig. 12, the residual stress \( \sigma_z \) is dominantly larger compared with the residual stress components \( \sigma_y \) and \( \sigma_z \).

3.4 Welding residual stresses in original bead-on-plate weld

The residual stresses, sum of \( \{ \sigma^A \} \) and \( \{ \sigma^B \} \), and their distributions along the SUS304 surface (y) and through thickness (z) are shown in Fig. 13. \( \sigma_z \) (weld), \( \sigma_y \) (weld), \( \sigma_z \) (weld) in Fig. 13 are the welding residual stresses only. The marks ●, ○, □ are the total residual stresses, the sum of welding residual stresses and rolling residual stresses. The welding residual stress \( \sigma_z \) (weld) is tensile on the top surface and bottom surface of the welded zone. The welding residual stress \( \sigma_y \) (weld) is very small. The residual stress state is two directional tensile on the surfaces of the weld zone.

The total tensile residual stresses (●, ○, □) on the SUS304 surface shown Fig. 13 have larger tensile values than those of welding stresses because the in-rolling residual stresses are tensile on the surface of the clad plate.

4. Measurement of residual stresses in fillet welds with clad plates

4.1 Fillet welded joint

Figure 14(a) shows a fillet welded joint with a clad plate (SUS304/MB410) and a stainless plate (SUS304). To measure the welding residual stress, specimen T and specimens \( L_z \) (Lz1, Lz2, Lz3), Ly shown in Fig. 14(b) and Fig. 14(c), respectively, are prepared.

4.2 Separation of inherent strain components and residual stresses

By cutting off the specimen T and the specimens \( L_{z1}, L_{z2}, L_{z3}, L_y \), the inherent strain components \( \epsilon^*_{y}, \epsilon^*_{z}, \epsilon^*_{y}, \gamma^*_{y} \) in the original fillet welded joint can be separated into two parts, which are transverse components \( \epsilon^*_{y}, \epsilon^*_{y}, \gamma^*_{y} \) in specimen-T and longitudinal component \( \epsilon^*_{y} \) in specimens \( L_{z1}, L_{z2}, L_{z3}, L_y \). Therefore, the residual stresses can be divided into two parts \( \{ \sigma^A \} \) and \( \{ \sigma^B \} \), which are produced by the transverse inherent strain components \( \epsilon^*_{y}, \epsilon^*_{y}, \gamma^*_{y} \) and the component \( \epsilon^*_{y} \) in welding direction (x), respectively.

4.3 Measurement of residual stresses \( \{ \sigma^A \} \) by inherent strains \( \{ \epsilon^*_{y}, \epsilon^*_{y}, \gamma^*_{y} \} \)

The welding residual stresses \( \{ \sigma^A \} \) measured in specimen-T and transferred by Eq. (12) are shown in Fig. 15. A large tensile stress \( \sigma_z \) near the fillet weld zone on the surface of SUS304 layer of clad flange can be observed in Fig. 15(a). A large tensile stress \( \sigma_z \) occurs at the SUS304 side of the SUS304/MB410 interface.

Fig. 14 A fillet weld and specimens for measurement of welding residual stresses
4.4 Measurement of residual stresses \( \{ \sigma^R \} \) by inherent strain \( \varepsilon_x^* \)

Inherent strain \( \varepsilon_x^* \) and its distribution in specimens \( L_{z1}, L_{z2}, L_{z3}, L_y \) can be estimated by Eq. (9) using measured elastic strain in these specimens. The inherent strain \( \varepsilon_x^* \) distributing in flange and web of the middle transverse section can be separately expressed by the functions defined as below,

In flange

\[
\varepsilon^*_x(y,z) = \sum_{i=1}^{N} \sum_{j=1}^{M} A_{ij}^f(1-\frac{y}{a})(1-\frac{z}{b})
\]  

(15)

In web

\[
\varepsilon^*_x(y,z) = \sum_{j=1}^{M} A_{j}^w(1-\frac{z}{b})
\]  

(16)

Where, \( a (=35\text{mm}) \) is the half width of the inherent strain zone in the flange and \( b (=30\text{mm}) \) is the width of the inherent strain zone in the web. Coefficient \( A_{ij}^f, A_j^w \) can be predicted by function fitting using inherent strains already measured in specimens \( L_{z1}, L_{z2}, L_{z3} \) and \( L_y \).

Figure 15 shows the welding residual stresses \( \{ \sigma^{weld} \} \) due to inherent strain \( \varepsilon_x^* \) expressed by Eq. (15) and Eq. (16).

4.5 Residual stresses in fillet welded joint

The welding residual stress distributions \( \sigma^{(weld)} \) in y-direction and z-direction measured in a fillet welded joint by the inherent strain method are shown in Figs. 18 (a) and (b), respectively. The marks \( \bullet, \circ, \square, \blacksquare, \square \) and \( \ast \) in Fig. 18 are the total residual stresses, sum of rolling residual stresses and welding residual stresses on the surfaces of flange and web measured by strain gauges directly\(^{11}\). The welding
residual stresses \((\sigma_x, \sigma_y)\) are tensile in the fillet weld zone and compressive away from the weld zone. However, the total residual stresses \(\sigma_x(weld & roll)\) and \(\sigma_y(weld & roll)\) away from the weld zone on the SUS304 surface of SUS304/MB410 clad flange are tensile. This is because the rolling residual stresses on SUS304 layer are tensile. The total residual stresses \(\sigma_x(weld & roll)\) and \(\sigma_y(weld & roll)\) away from the weld zone on SUS304 web are compressive. Therefore, the fillet weld zone and SUS304 surface of the clad plate may be weaker in resisting stress corrosion. To improve the corrosion resistance of SUS/MB clad steel, a higher grade of stainless steel is recommended.

5 Conclusions
(1) Layer removal method is proposed and adapted for the measurement of rolling residual stresses in the SUS304/MB410 clad plate.
(2) Rolling residual stresses are tensile on the SUS304 layer of the SUS304/MB410 clad plate.

Fig. 18 Welding Residual stresses and rolling residual stresses in fillet weld with clad plate

However, the total residual stresses \(\sigma_x(weld & roll)\) and \(\sigma_y(weld & roll)\) away from the weld zone on the SUS304 surface of SUS304/MB410 clad flange are tensile. This is because the rolling residual stresses on SUS304 layer are tensile. The total residual stresses \(\sigma_x(weld & roll)\) and \(\sigma_y(weld & roll)\) away from the weld zone on SUS304 web are compressive. Therefore, the fillet weld zone and SUS304 surface of the clad plate may be weaker in resisting stress corrosion. To improve the corrosion resistance of SUS/MB clad steel, a higher grade of stainless steel is recommended.

5 Conclusions
(1) Layer removal method is proposed and adapted for the measurement of rolling residual stresses in the SUS304/MB410 clad plate.
(2) Rolling residual stresses are tensile on the SUS304 layer of the SUS304/MB410 clad plate.
(3) Rolling residual stresses are compressive on the surface of the SUS304 stainless plate.
(4) Welding residual stresses are tensile in the weld zone of bead-on-plate weld and fillet weld.
(5) The total residual stresses, sum of rolling residual stresses and welding residual stresses, are tensile on the SUS304 layer of the SUS304/MB410 clad plate after bead–on-plate welding and fillet welding.

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