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Measurement of Residual Stresses in Explosively Clad Steels And A Method of Residual Stress Reduction †

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Abstract

In this paper, a new layer removal method for measurement of local residual stress through the thickness of clad plates is developed using inherent strain which is considered a source of residual stress. Using the new method, residual stresses in explosively clad plates of Ni/SUS304 and Zr/Zr/Ta/SUS304 are measured. Then, residual stresses remaining in a pipe joint piece cut from the explosively clad plate are estimated by an elastic analysis using inherent strain. Furthermore, the validity of a mechanical stress reduction method by applying axial compressive load to the pipe joint piece, is investigated by elastic-plastic FEM analysis.

KEY WORDS: (Residual Stresses) (Inherent Strains) (Layer-Removal Method) (Stress Reduction Method) (Explosively Clad Plates) (Pipe Joint Piece) (Ni/SUS304) (Zr/Zr/Ta/SUS304)

1. Introduction

For the production of clad steels, explosive bonding is more efficient than welding and rolling because of less limitation in material matching and high productivity. Therefore, many kinds of clad materials which offer good resistance to corrosion, high temperature and wear, can be easily made by explosive bonding. The clad materials are widely used in pressure vessels, chemical tanks and pipe lines. As with conventional welding processes, a high temperature thermal cycle together with plastic deformation occurs in a narrow zone of the interface between the clad plates during explosive bonding, and large residual stresses are produced near the interfaces. Because the residual stresses through the thickness, including interfaces, of clad plates are quite localized, the measurement of them becomes very difficult by conventional stress release methods using strain gauges[1]. To measure these local residual stresses, the layer removal method is generally employed[2-6]. However, using traditional layer removal methods, only residual stresses in the original clad plate can be measured, and residual stresses in the joints which are cut from the original plate can not be estimated.

In this paper, residual stresses are measured by the layer removal method using inherent strain as a parameter since this does not change when specimens are cut from the original object to be measured. The actual measurements were carried out on clad plates of Ni/SUS304 and Zr/Zr/Ta/SUS304, and the residual stress distribution through the thickness, including the interfaces, of these clad plates were investigated. Then, residual stresses in the pipe joint furnished by these clad plates are estimated using the inherent strain parameter and the method of residual stress reduction is discussed.

2 Measuring Method for Residual Stresses Using Inherent Strain

The components to be measured were the explosively clad plates of Ni/SUS304 (2mm, 20mm) and Zr/Zr/Ta/SUS304 (10mm, 4.5mm, 1mm, 50mm) shown in Figs.1 and 2, respectively. Because the explosive bonding process completes the bonding almost instantaneously in the width of the clad plates and does in very high speed in the bonding direction, the distribution of residual stresses in the bonded plates can be assumed uniform along the explosive direction (x) and transverse direction (y), except at the edges of plates. Therefore, the residual stresses vary only in the thickness direction (z) of clad plate, and likewise the inherent strains. To measure the residual stresses using inherent strains, specimens L_x and L_y are sliced from the original clad plates as shown in Figs.1 and 2. The detail measuring procedures are described in the following sections.

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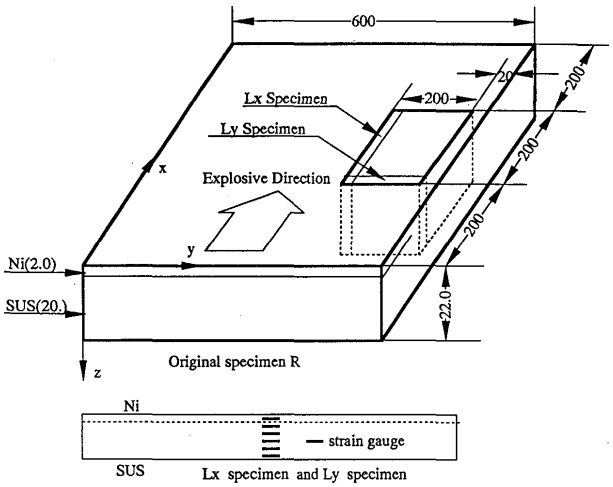


Fig.1 Ni/SUS304 clad plate and specimens in the measurement of residual stresses

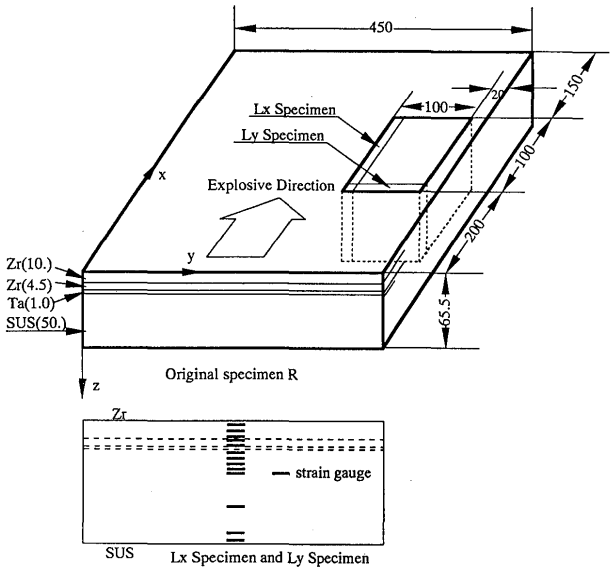


Fig.2 Zr/Zr/Ta/SUS304 clad plate and specimens in the measurement of residual stresses

Table 1 Mechanical properties of clad materials

Materials	SUS	Ni	Zr	Ta
Young's modulus(GPa)	195.0	206.9	99.3	181.0
Poisson's ratio	0.27	0.31	0.35	0.35

2.1 Relationship between Residual Stress and Inherent Strain

The relationships between inherent strain, elastic strain and residual stress may be expressed as follows[7,8]:

$$\{\varepsilon^e\} = [H]\{\varepsilon^*\} \quad (1)$$

$$\{\sigma\} = [D]\{\varepsilon^e\} \quad (2)$$

where $\{\varepsilon^*\}$, $\{\varepsilon^e\}$ and $\{\sigma\}$ are the vectors of inherent strain, elastic strain and residual stress. [H] and [D] are the elastic response matrix and elastic strain-stress matrix, respectively. Matrix [D] is composed of Young's modulus and Poisson's ratio for the material. The values of Young's modulus and Poisson's ratio of the explosively clad materials are shown in Table 1. Matrix [H] can be computed by performing elastic FEM analysis if elastic strains are calculated by imposing unit inherent strain as the initial strain in the analyzed object[7,8].

Once inherent strain $\{\varepsilon^*\}$ is known, elastic strain $\{\varepsilon^e\}$ can be computed by performing FEM analysis, and then residual stress $\{\sigma\}$ can be obtained by substituting elastic strain $\{\varepsilon^e\}$ into Eq.(2). Conversely, when elastic strain $\{\varepsilon^e\}$ is measured, the inherent strain $\{\varepsilon^*\}$ can also be determined. The inherent strain produced by welding or explosive bonding exists only in a limited region such as the region near the weld metal or near the interfaces of the clad materials, and it does not change in specimens which are taken from the original component if plastic strains are not produced by cutting[7]. From this fact, it is deduced that, when FEM is employed, the total components of inherent strain in the elements where inherent strain exists are much less than those for elastic strain or residual stress. Therefore, in order to determine all the components of inherent strain, the necessary number of elastic strains to be measured can be greatly reduced compared with direct measurement of elastic strains or residual stresses.

2.2 Components of Inherent Strain and Residual Stress

For the explosively clad plates shown in Figs.1 and 2, it is assumed that only two components σ_x and σ_y of residual stress exist. Thus, σ_x and σ_y distribute uniformly in the x and y directions, and vary only in the thickness direction z. Corresponding to these stress components σ_x and σ_y, only two inherent strain components ε^*_x and ε^*_y need be considered. The inherent strain components do not change with the coordinates x and y. They are functions of the coordinate z in the thickness direction. To measure these two components of inherent strain, specimens L_x and L_y parallel to the x and y directions respectively, are sliced. Specimens L_x and L_y are so thin that the residual stress in each one is in the plane stress state. This implies that the residual stress in specimen L_x is only σ_x which is produced by only ε^*_y, and so σ_y in the specimen L_y is produced by ε^*_y. For this reason, the inherent strain components ε^*_x and ε^*_y are separated by slicing specimens L_x and L_y from the original clad plates.

2.3 Measurement of Inherent Strain Components

As described above, to estimate inherent strain, elastic strain has to be measured first. In the conventional stress relieving method, a small block is

cut from the specimen and the relieved elastic strain in the block can be measured. In this paper, to measure the local residual stress, especially near the interfaces of the explosively clad materials, a layer removal method is employed, and the measuring procedure is described as follows:

(1) Measuring Procedures

Step 1: Strain gauges are attached to the specimens L_x and L_y as shown in Figs.1 and 2.

Step 2: Each layer of 0.2mm thickness is removed by milling from the clad material side of specimens L_x and L_y (i.e.Ni side for Ni/SUS and Zr side for Zr/Zr/Ta/SUS). During milling, a cooling oil is used to prevent the temperature rising. After each thin layer is milled, elastic strain changes $\{\Delta\varepsilon^e\}$ at all the points shown in Figs.1 and 2, are measured. According to the theory of elasticity, the strain change at one measuring point is sufficient to estimate the inherent strain distribution. Because some measuring errors in the observed elastic strain changes directly influence the results, more measuring points are used to improve the accuracy in this measurement. When n layers are removed, the total elastic strain changes observed at each measuring point can be expressed by $\{\Delta\varepsilon^e\}_m$, whose total number, m, is more than the total number, n, of removed layers.

(2) Computation Procedures

When elastic strain changes are measured, the inherent strain and residual stress can be computed by the following procedures:

Firstly, specimens L_x and L_y are divided into finite elements whose size corresponds to the thickness of the removed layers.

Secondly, the inherent strain in removed layer, i, is expressed by ε^*_i. If a total of n layers are removed, the inherent strain distribution can be expressed by the inherent strain vector $\{\varepsilon^*\}_n$ in which there are n components. The relationship between inherent strain $\{\varepsilon^*\}_n$ and total elastic strain changes $\{\Delta\varepsilon^e\}_m$ can be derived as follows[9]:

$$[\Delta H]_{mn}\{\varepsilon^*\}_n = \{\Delta\varepsilon^e\}_m \quad (3)$$

Because errors may occur in the measurements, the left and right sides of Eq.(3) are not exactly equal if $\{\varepsilon^*\}_n$ is assumed to be exact. The difference $\{e\}_m$ between them is defined by following equation:

$$\{e\}_m=[\Delta H]_{mn}\{\varepsilon^*\}_n - \{\Delta\varepsilon^e\}_m \quad (4)$$

According to the condition which minimizes the sum of the squares of the difference $\{e\}_m$, the inherent strain $\{\varepsilon^*\}_n$ can be computed by

$$[\Delta H]^T_{nm}[\Delta H]_{mn}\{\varepsilon^*\}_n = [\Delta H]^T_{nm}\{\varepsilon^e\}_m \quad (5)$$

where $[\Delta H]$ can be computed by FEM and can also be derived from beam theory.

2.4 Estimation of Residual Stresses

Generally, once inherent strain $\{\varepsilon^*\}_n$ is estimated by Eq.(5) and then applied to the specimens L_x and L_y and the original clad plates, the residual stresses in each of the specimens L_x and L_y and in the clad plates, can be numerically computed by FEM.

In contrast with the general procedure of computation of residual stress in clad plate using inherent strain, the following simple method is proposed in the case where the length and width of the clad plate are large compared with its thickness. In such special cases, the deformation produced by the inherent strain is linear in the thickness, that is ε_x and ε_y distribute linearly respectively on yz and xz cross-sections (except near the edges of the clad plate), and are then defined as plane deformations in the two directions. The plane deformation coincides with the plane strain in the measurement of residual stresses, which was proven previously by the authors[8]. Thus, the relationship between residual stresses σ_{Lx} and σ_{Ly} respectively in the specimens L_x and L_y, and residual stresses σ_x and σ_y in the original clad plate can be derived as follows.

$$\sigma_x=(\sigma_{Lx}+\upsilon\sigma_{Ly})/(1-\upsilon^2) \quad (6a)$$

$$\sigma_y=(\sigma_{Ly}+\upsilon\sigma_{Lx})/(1-\upsilon^2) \quad (6b)$$

where υ is Poisson's ratio.

3 Measured Residual Stresses

3.1 Residual Stresses in Ni/SUS304 Clad Plate

3.1.1 Inherent Strain and Residual Stress in Specimens L_x and L_y

Inherent strain ε^*_y estimated by the beam theory and also FEM using the observed elastic strain changes in specimen L_y, is shown in Fig.3. Because the length-width ratio of specimens L_x and L_y used in the experiments is about 9/1, the estimated inherent strain show no difference according to the beam theory and FEM. The inherent strain and residual stress distributions in both specimens L_x and L_y are shown in Figs.4 and 5, respectively. The overall distributions of ε^*_x and ε^*_y, or σ_x and σ_y are similar, and the maximum tensile residual stresses are produced near the interface, their values are about 300-400MPa. When attention is paied to the local distribution, more difference can be found on the top surface and in the Ni plate. On the surface, residual stress σ_y is tensile, while σ_x is compressive. In the Ni clad plate, obvious anisotropy can be found. One of the reasons for the anisotropy may be the local plastic

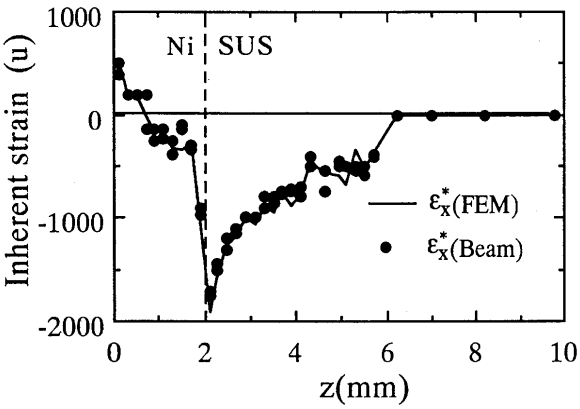


Fig.3 Distribution of inherent strain ε^*_x through the thickness of Ni/SUS clad plate

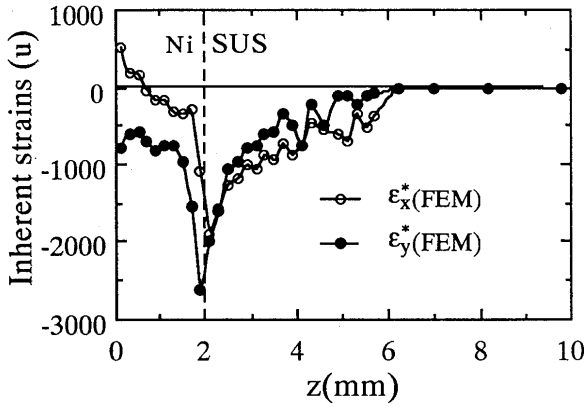


Fig.4 Inherent strain distributions measured in the specimens L_x and L_y of Ni/SUS clad plate

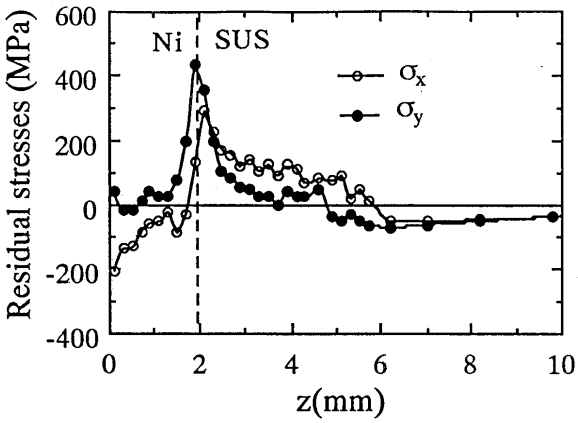


Fig.5 Residual stress distributions in the specimens Lx and Ly of Ni/SUS clad plate

deformation of Ni plate which was bended in explosive direcion (x) during the explosive bonding process.

3.1.2 Residual Stresses in Original Clad Plate

Residual stresses in original Ni/SUS clad plate are estimated using inherent strain ε^*_x and ε^*_y measured in specimens L_x and L_y. The distribution of residual stresses σ_x and σ_y through the thickness of the clad plate

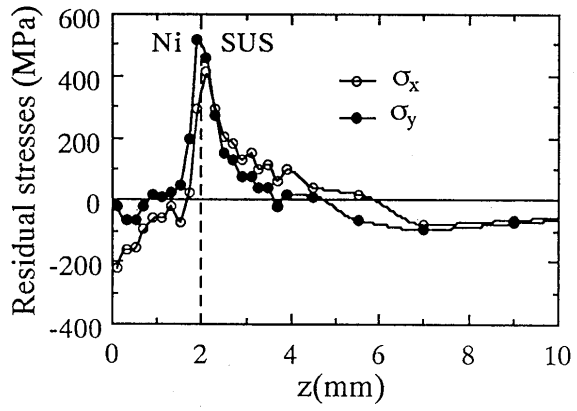


Fig.6 Residual stress distributions through the thickness of Ni/SUS clad plate

is represented in Fig.6. The distribution of residual stress in the original clad plate is similar to the distributions in specimens L_x and L_y. The residual stresses near the interface of Ni/SUS and on the top surface in the original clad plate are larger than those in the specimens L_x and L_y. This is the difference between plane strain state for the original clad plates and plane stress state for the specimens L_x and L_y, whose relationship was shown in Eq.(6).

3.2 Residual Stresses in Zr/Zr/Ta/SUS304 Clad Plate

3.2.1 Inherent Strain Distribution

As the length-width ratio of specimens L_x and L_y in the experiment is 2/1, as shown in Fig.2 (and should be much longer to satisfy the size condition of the beam theory), the FEM is only employed in the calculation of inherent strains and residual stresses. The estimated inherent strains ε^*_x and ε^*_y in multi-clad plates are shown in Fig.7. The overall distributions of ε^*_x and ε^*_y are similar, but different in detail. This implies the anisotropy of the distributions. The distribution of inherent strain ε^*_y is limited in a more narrow zone near the interface, and the maximum magnitude becomes larger in comparison with that of ε^*_x.

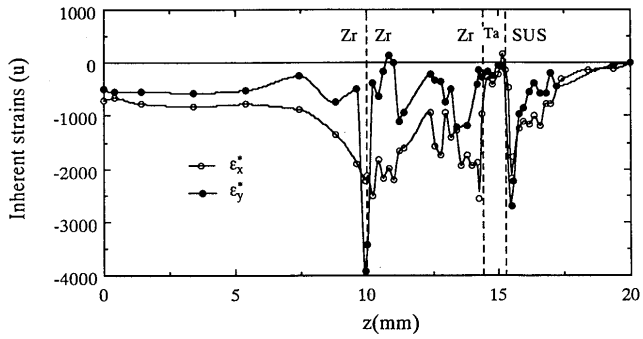


Fig.7 Inherent strain distrbutions measured in the specimens L_x and L_y of Zr/Zr/Ta/SUS clad plate

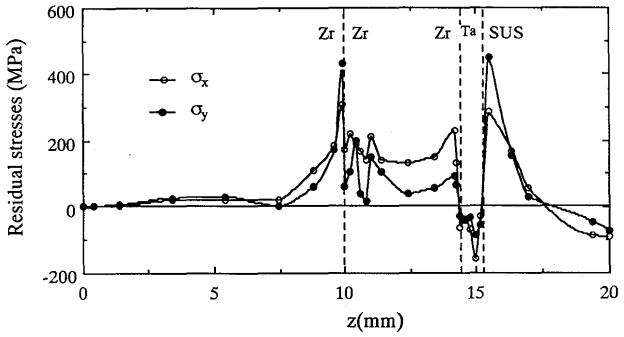


Fig.8 Residual stress distributions through the thickness of Zr/Zr/Ta/SUS clad plate

3.2.2 Residual Stress Distribution

Fig.8 shows the distribution of residual stresses σ_x and σ_y through the thickness of the original Zr/Zr/Ta/SUS304 clad plate computed from the above inherent strains. From Fig.8, it can be observed that residual stresses concentrate almost in the vicinity of the interfaces. Especially, at the Zr/Zr interface and the SUS side of Ta/SUS interface, very large tensile residual stresses are produced by explosive bonding.

4 Residual Stresses in Pipe Joint Pieces Cut from Clad Plate and The Mechanical Reduction Method of Residual Stress

4.1 Residual Stresses in Pipe Joint Pieces

As shown in Fig.9, a pipe joint piece, cut from the Ni/SUS304 clad plate, is to be used to join Ni pipe and SUS304 pipe, which experience different working temperatures in nuclear pipe lines. The residual stresses in the pipe joint piece can be easily computed using the same inherent strain measured in the original clad plate. As shown in Fig.3, the measured inherent strain components ε^*_x and ε^*_y are only slightly different in their distributions. To simplify the analysis, isotropic inherent strains are assumed in the pipe joint. According to this assumption, residual stresses in the pipe joint can be computed by axisymmetric elastic FEM. The computed residual stress distributions in the r direction of the SUS side of Ni/SUS interface are shown in Fig.10. On the inner surface of the pipe joint piece, very large tensile residual stress σ_θ is observed. This large tensile stress has a very detrimental effect on stress corrosion cracking.

4.2 Mechanical Stress Reduction Method

Because the mechanical properties of clad materials, such as thermal expansion coefficient, yield stress and Young's modulus, are quite different, the residual stresses in the clad pipe joint can not be effectively reduced by

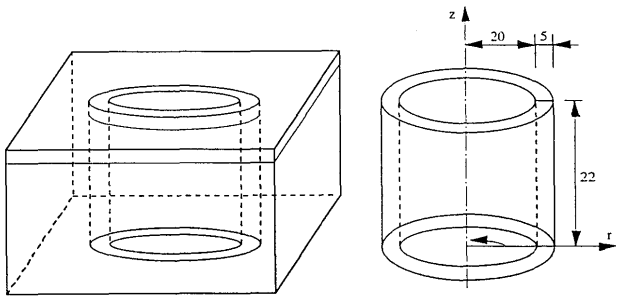


Fig.9 Pipe joint piece cut from the Ni/SUS clad plate

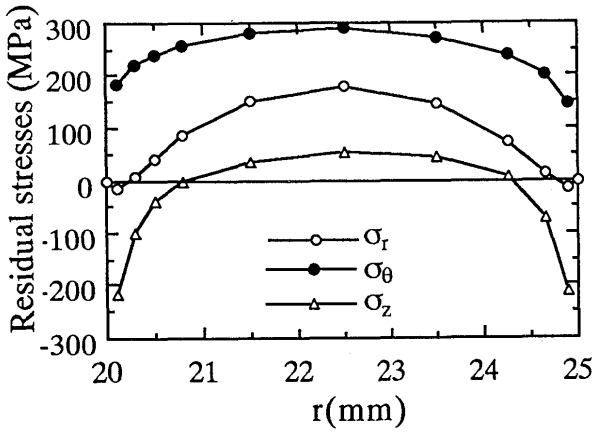


Fig.10 Resiual stresses in pipe joint piece cut from Ni/SUS clad plate

conventional heat treatment. In this paper, the validity of the mechanical stress reduction method is examined by elastic-plastic analysis of FEM. The principle of mechanical stress reduction method is to produce plastic deformation in the higher stress zone by mechanical loads. First, the compressive axial load is applied to the pipe piece, and then released. The maximum load is less than the yield point for material Ni whose yield stress is lower than SUS304. Next, the tensile axial load is applied.

The residual stresses in these two cases are obtained by elastic-plastic analysis of FEM, as shown in Figs.11 and 12, respectively. When the compressive load is applied, the maximum residual stress is reduced to about 60MPa, and the residual stresses on the inner surface of the pipe are almost zero. When tensile load is applied, the residual stresses are not reduced as shown in Fig.12.

To investigate the mechanism of stress reduction, the stress cycles during the loading and releasing processes are computed. The history of stress states on the inner surface is shown in Figs.13(a) and (b). In the case of compressive loading, the plastic deformation is produced during the loading process, and the residual stress is reduced after the load is released. However, in the case of tensile loading, only elastic deformation can be observed

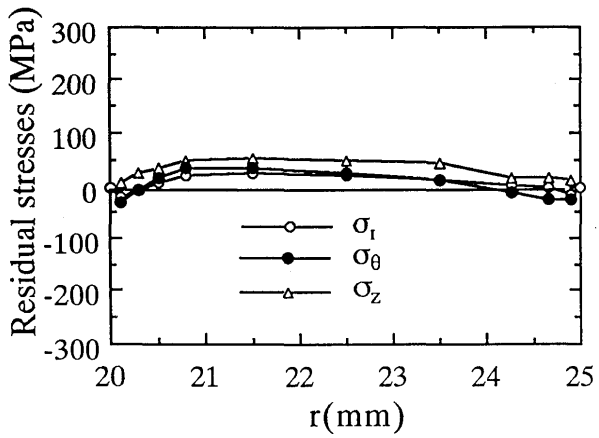


Fig.11 Resiual stresses in pipe joint piece after applying axial compressive load

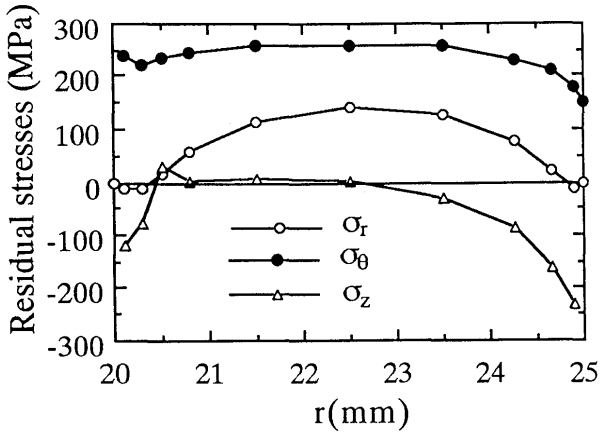
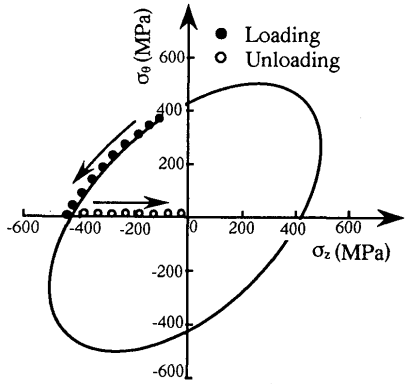
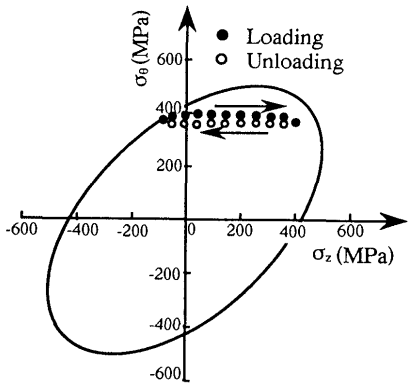


Fig.12 Resiual stresses in pipe joint piece after applying axial tensile load



(a) Applying axial compressive load



(b) Applying axial tensile load

Fig.13 History of stress states at the Ni/SUS interface of inner surface of pipe joint piece during loading cycle

in both loading and unloading processes shown in Fig.13(b).

5 Conclusions

In this paper, a new layer removal method is developed using inherent strain to measure the residual stresses, including the local distributions, at the interfaces of explosively clad plates. Actual measurements were performed on the two clad plates and the residual stresses in a pipe joint piece cut from the original clad plate were also estimated by the measured inherent strains. Further more, a mechanical reduction method for residual stress in the pipe joint piece of dissimilar metals is proposed. The main results obtained in this paper are as follows:

(1) Very large tensile stresses at the interface of the Ni/SUS304 clad plate and at the Zr/Zr and the Ta/SUS interfaces of the Zr/Zr/Ta/SUS304 clad plate, are observed by the actual measurement.

(2) Both longitudinal and transverse residual stress components are similar in overall distributions, and slight anisotropy can be observed.

(3) When a pipe joint piece is cut from the explosively clad plate, very large tensile residual stresses at the interface on the inner surface are observed. When an axial compressive load is applied to the pipe joint piece, the residual stresses can be reduced almost to zero.

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