Title	Measuring Methods for Three-Dimensional Residual Stresses with The Aid of Distribution Functions of Inherent Strain (Report II) : TL_yL_z-Method and T-Method for Measurement of 3-Dimensional Residual Stresses in Bead-on-plate Welds(Mechanics, Strength & Structural Design)
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Measuring Methods for Three-Dimensional Residual Stresses with The Aid of Distribution Functions of Inherent Strain (Report II)†

— TL_yL_z-Method and T-Method for Measurement of 3-Dimensional Residual Stresses in Bead-on-plate Welds —

Ning Xu MA* and Yukio UEDA**

Abstract

A distribution function of inherent strains on long bead-on-plate welds, which has 3 unknown parameters for each inherent strain component, is proposed. With the aid of the proposed distribution function of inherent strains, the measurement of 3-dimensional residual stresses can be made with the following procedures:

(1) 3 pieces of specimens T, L_y and L_z (named TL_yL_z-Method) are cut from the bead-on-plate weld and the inherent strain components are separated.

(2) Measurements are performed on the specimens T, L_y and L_z. Then, the inherent strain zones and the 3 unknown parameters for each inherent strain component are estimated.

(3) 3-dimensional residual stresses are computed by applying the inherent strains measured in step (2) in the original welded plate, whose stress is free.

When inherent strain distributes through the entire thickness of plate, the 3-dimensional residual stresses can be measured only by slicing one piece of specimen T (named T-Method).

To verify the TL_yL_z-Method and T-Method, numerical experiments and actual measurements were carried out respectively for mild steel and stainless steel bead-on-plate welds. The measured residual stresses by the new methods show very good accuracy compared with those computed by thermal elastic-plastic FEM analysis and direct measurements on the surfaces of the welded plate.

KEY WORDS: (Residual stresses) (Inherent strain) (Distribution function) (TL_yL_z-Method) (T-Method) (Measurement) (Bead-on-plate welds)

1. Introduction

It is well known that the measurement of 3-dimensional residual stresses is very important for estimation of fatigue strength and fracture of welded structures. Y.Ueda[1,2] proposed a general measuring theory for 3-dimensional residual stresses using inherent strain as a parameter. When the entire inherent strain distribution in an object is described by the individual inherent strain components in each finite element, many unknown inherent strain components have to be specified. If these are to be determined by experiment, too many elastic strains have to be observed. Further more, elastic strains at local areas such as weld toes and their detailed distribution through the thickness of plate can not be observed using conventional strain gauges, and it is very difficult to measure the local distribution of inherent strains and residual stresses. To solve these problems, a function method describing inherent strain distributions is proposed[3]. With parametric functions, inherent strain distributions can be expressed by a few unknown coefficients included in the functions. When these coefficients are determined by a few observed elastic strains, the inherent strain distributions can be estimated, and then the residual stress distributions can be computed.

In this paper, a very simple distribution pattern of inherent strains in an infinitively long bead-on-plate weld, is derived based on the results of thermal elastic-plastic analysis of FEM described in the previous report[3]. In the simple distribution pattern, there are only 3 unknown coefficients for each inherent strain component. With the aid of the proposed distribution pattern, two simple

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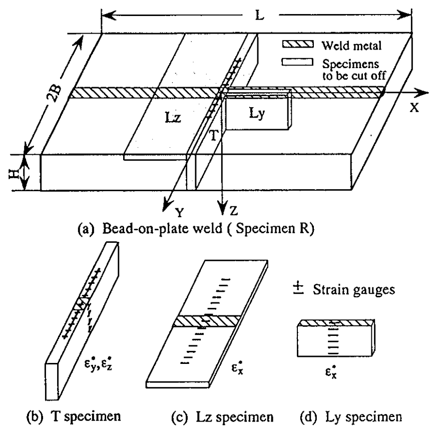


Fig.1 A bead-on-plate weld and specimens used in TLyLz-Method and T-Method

measuring methods for residual stresses are developed, In actual measurement, thin specimens which are sliced from the original welded plate shown in Fig.1 are used. When three kinds of specimens T, L_y and L_z are employed in measurements, the measuring method is called the TL_yL_z-Method. When only specimen T is used for measurements, the method is called the T-Method. To verify the validity and accuracy of the TL_yL_z-Method and the T-Method, both numerical experiments and actual measurements were carried out.

2. Distribution functions of inherent strains

2.1 Series function

In order to estimate residual stress distributions in transverse sections of a long weld, it is sufficient to consider only three components ε^*_x, ε^*_y and ε^*_z of inherent strain[3]. These inherent strain components are simply expressed by $\varepsilon^*_s(s=x,y,z)$. In the transverse sections, these inherent strains distribute only within the elliptical zones[3] shown in Fig.2. The size of ellipsis is expressed by radius $R_s(s=x,y,z)$, or by width $a_s(s=x,y,z)$ in the y axis and depth $b_s(s=x,y,z)$ in the z axis, and it varies with each of the inherent strain components ε^*_x, ε^*_y and ε^*_z. In Fig.2, the heat affected zone (HAZ) is also assumed to be elliptical shape and its size is expressed by $R_m(a_m,b_m)$, which is independent of inherent strain components ε^*_x, ε^*_y and ε^*_z. Inherent strain $\varepsilon^*_s(s=x,y,z)$ is uniform in the welding direction (x) and varies in the elliptical zones of the transverse section shown in Fig.2. The distributions of inherent strains in the elliptical zones can be expressed by the following series function using dimensionless polar coordinates (r, θ).

$$\varepsilon^*_s(x,y,z)=\sum_{i=1}^{M}\sum_{j=1}^{N} A^*_{sij}\,(1-\xi_s)^i\,\omega^{(j-1)} \quad (s=x,y,z) \qquad \text{(1a)}$$

$$\xi_s=\frac{r}{R_s} \qquad \omega=\frac{\theta}{\pi/2} \qquad (s=x,y,z) \qquad \text{(1b)}$$

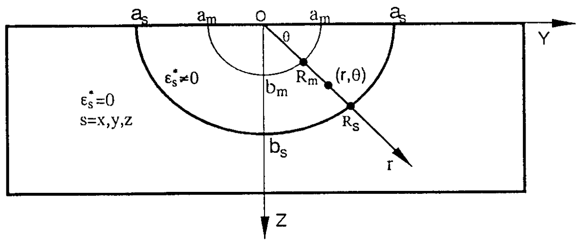


Fig.2 The shape of inherent strain zones in bead-on-plate welds

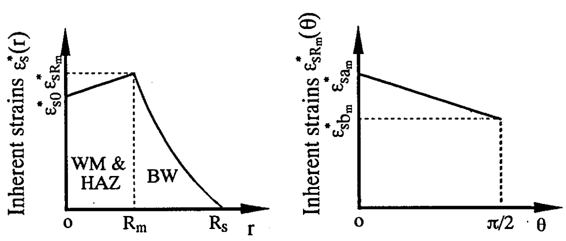


Fig.3 The distribution pattern of inherent strains in r and θ directions

where M and N are the orders of series, A^*_{sij} is the coefficient of the series functions.

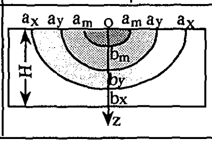
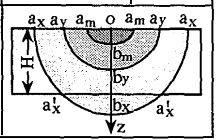
With increases in the order M and N of the series function, the total number $p_s(=M*N)$ of unknown coefficients and accuracy will increase. In actual measurements, according to the expected accuracy, measuring points corresponding to the total number $p_s(=M*N)$ of unknown coefficients, or M and N of the series function can be freely selected. When M and N are more than 2, or the total number $p_s(=M*N)$ of unknown coefficients is more than 4, the actually expected accuracy can be obtained[3].

2.2 Simple function

When M=N=2, the distributions of inherent strains show trapezoidal shape in the r direction and linearly in the θ direction. Furthermore, considering the differences of weld metal, HAZ and base metal, a very simple distribution pattern of inherent strains is proposed as shown in Fig.3. Inherent strains vary linearly in the r direction within the weld metal and HAZ, and decrease gradually out of the HAZ and become zero out side inherent strain zones. The distribution pattern can be described by a simple function shown in the following equation:

$$\left.\begin{array}{l} \varepsilon^*_s(r,\theta)=\begin{cases}(1-\frac{r}{R_m})\varepsilon^*_{s0}+\frac{r}{R_m}\varepsilon^*_{sR_m}(\theta) & (0\le r\le R_m)\\ \exp\left(\frac{-3(r-R_m)^2}{(R_s-R_m)^2}\right)\varepsilon^*_{sR_m}(\theta) & (R_m\le r\le R_s)\end{cases}\\ \varepsilon^*_{sR_m}(\theta)=(1-\frac{\theta}{\pi/2})\varepsilon^*_{sa_m}+\frac{\theta}{\pi/2}\varepsilon^*_{sb_m} \quad (0\le\theta\le\frac{\pi}{2}) \end{array}\right\} \; (s=x,y,z) \qquad (2)$$

Table 1 Separation and measurement of inherent strains by TLyLz-Method and T-Method

Methods	TLyLz Method			T Method (bx>H)	
Specimens	T	Ly	Lz	T	T(surfaces)
Zone of inherent strains	(a_m, b_m) $(a_y, b_y)=(a_z, b_z)$	b_m b_x	a_m a_x	(a_m, b_m) $(a_y, b_y)=(a_z, b_z)$	a_m (a_x, a'_x)
Values of inherent strains	$\{A^*_{yz}\}$	$\{A^*_x\}$		$\{A^*_{yz}\}$	$\{A^*_x\}$
Situations of TLyLz and T Methods					

In the newly proposed simple function, HAZ $R_m(a_m,b_m)$, inherent strain zones $R_s(a_s,b_s, s=x,y,z)$ and the values of inherent strains at point O, a_m and b_m expressed by $\{A^*\}_p=\{\varepsilon^*_{sO}, \varepsilon^*_{sam}, \varepsilon^*_{sbm}, s=x,y,z\}^T$ are the unknown parameters. To determine these unknown parameters by experiment, the specimens shown in Fig.1 and Table 1 are sliced from the original welded plate, inherent strain components are separated in each specimen, and then measured.

2.3 Separation of inherent strain components

As shown in Figs.1(b), (c) and (d), specimens T, L_y and L_z are the ones sliced from the original welded plate perpendicular to the weld line (x), in the transverse direction (y) and the thickness direction (z). These specimens are so thin that the plane stress state is satisfied. Therefore, inherent strain component ε^*_x does not produce any stresses in specimen T, and neither do the components ε^*_y and ε^*_z in specimens L_y and L_z.

When the welding condition changes, the size of inherent strain zones varies. Then, the measuring procedure of residual stresses can be classified into the following two cases, according to the relative size of depth bx of elliptical zone of inherent strain component ε^*_x and plate thickness H.

In the case of $b_x<H$, i.e. compared with plate thickness, welding heat input is relatively small, and inherent strains exist partially near the weld bead.

In the case of $b_x>H$, i.e. compared with plate thickness, welding heat input is relatively large, and inherent strain distributes through the entire thickness of plate.

Generally, to determine the sizes of inherent strain zones (a_x,bx), (a_y,b_y) and (a_z,b_z), three kinds of specimens (T, L_y, L_z) shown in Fig.1 will be employed in measurements, and this measuring method is called the TL_yL_z-Method. In the case of $b_x>H$, the inherent strain zone of component ε^*_x can be expressed by the widths a_x and a'_x respectively on top and bottom surfaces of the welded plate. This inherent strain zone within the plate can be considered as part of an ellipse whose depth b_x is larger than the plate thickness. Therefore, (a_x,b_x) or (a_x, a'_x) of the elliptical zone of inherent strain component ε^*_x can be measured on the top and bottom surfaces of the original welded plate. Thus, (a_y, b_y) and (a_z, b_z) of the elliptical zone of inherent strain components $(\varepsilon^*_y, \varepsilon^*_z)$ can be measured on specimen T. Because only one specimen T is needed in the case of $b_x>H$, the measuring method is simply referred as T-Method.

3. TL_yL_z-Method

3.1 Estimation of distribution zones of inherent strains

The distribution zones $(a_s,b_s, s=x,y,z)$ of inherent strains can be estimated from the changes of released elastic strain during cutting[1,2], or by applying the condition of minimizing errors in the resulting residual stresses[3]. In the former, all metals in the inherent strain zone have to be removed gradually by cutting. In the later, residual stresses at a sufficient number of points have to be observed in order to minimize the error of reproduced residual stresses. In this paper, a new simple method is proposed based on the shapes of stress distribution in both the y axis and the z axis of the coordinates, or in specimens T, L_y and L_z.

Inherent strain is defined as the source of residual stress, and their inter-relation can be expressed by the following equations.

$\{\sigma\}=[D](\{\varepsilon\}-\{\varepsilon^*\})$ within inherent strain zone (3a)

$\{\sigma\}=[D]\{\varepsilon\}$ out side inherent strain zones (3b)

where $\{\sigma\}$, [D], $\{\varepsilon\}$ and $\{\varepsilon^*\}$ are the residual stress, stress-elastic strain matrix, the total strain and inherent strain, respectively.

At the boundary of inherent strain zones, the value of inherent strain becomes zero, but the derivative of the inherent strain distribution functions is not generally zero. In other words, the stress distributions are continuous at the boundary, but their derivatives with respect to coordinates x, y and z may not be continuous at the boundary according to Eq.(3). Therefore, obvious changes or maximum or minimum values in stress distribution curves may appear at the points of the boundary. In order to clarify the response relation between inherent strain zones and distribution features of stresses, inherent strains distributed on the assumed elliptical zones, are applied to the bead-on-plate welds, and then a series of numerical computations are performed.

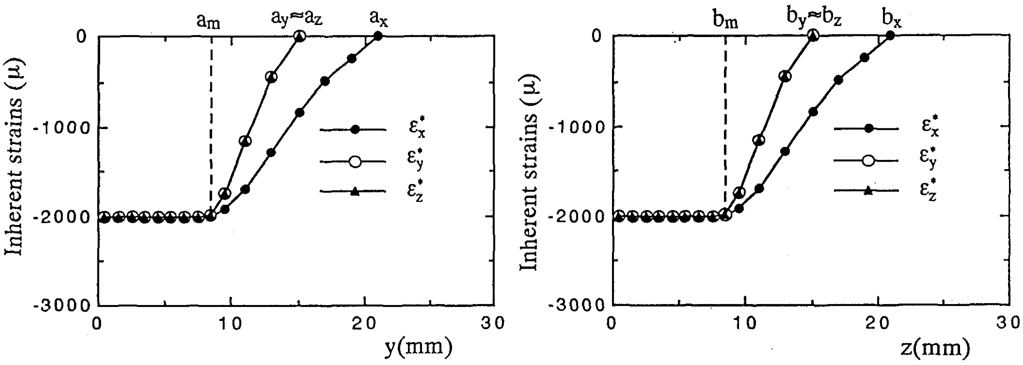


Fig.4 Assumed inherent strains and their distribution zonese

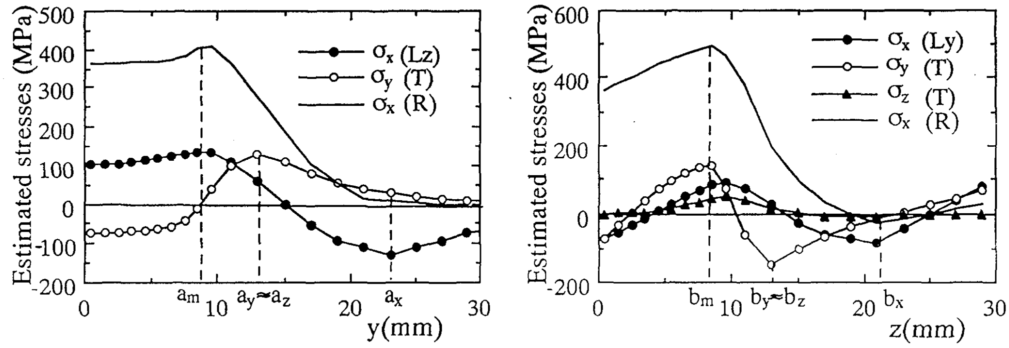


Fig.5 Residual stress distributions produced in specimens (R), (T), (Ly), (Lz) by assumed inherent strains shown in Fig.4

Fig.4 shows the assumed inherent strain distributions which are similar to the pattern shown in Fig.3 obtained from thermal elastic-plastic analysis. In Fig.4, (a_m,b_m), (a_x,b_x), (a_y,b_y) and (a_z,b_z) are the sizes of elliptical zones of HAZ, inherent strain components ε^*_x, ε^*_y and ε^*_z, respectively. Here, inherent strain zones (a_y,b_y) and (a_z,b_z) of components ε^*_y and ε^*_z are assumed to be the same. When these inherent strains are imposed on the original welded plate (R), sliced specimens (T), (L_y) and (L_z) respectively, the resulting stress distributions in these specimens are shown by Fig.5. Comparing Fig.4 with Fig.5, the relation of inherent strain zones and distribution features of stresses in specimens R, T, L_y and L_z can be summarized as follows:

1) (a_m,b_m) are corresponding to the width of linear distribution of stress component σ_x in the y and z directions respectively.

2) (a_x,b_x) are corresponding to the width from the origin O to the bending points in the compression side of stress component σ_x in the y and z directions, respectively.

3) a_y is corresponding to the width from the origin O to the maximum point in the tension side of stress component σ_y in the y direction. b_y is equal to the depth from the origin O to the maximum point in the compression side of component σ_y.

4) (a_z,b_z) are assumed to be the same as (a_y,b_y).

On the other hand, the shape and sizes of the HAZ can be more accurately determined by observing the macrostructure of welds.

3.2 Estimation of the value of inherent strains

When the inherent strain distributions are expressed by the functions shown in Eq.(2) and the inherent strain zones are determined according to the described feature of measured stress distributions, the values of inherent strains can be determined only by the following coefficients included in the functions,

$$\{A^*\}_p=\{\varepsilon^*_{xo}, \varepsilon^*_{xam}, \varepsilon^*_{xbm}, \varepsilon^*_{yo}, \varepsilon^*_{yam}, \varepsilon^*_{ybm}, \varepsilon^*_{zo}, \varepsilon^*_{zam}, \varepsilon^*_{xbm}\}^T \quad (4)$$

where p is the total number of unknown coefficients.

The relationship between p numbers of coefficients $\{A^*\}_p$ and m numbers of observed elastic strains $\{\varepsilon^e\}_m$ is defined by the following equation.

$$[G]_{mp}\{A^*\}_p=\{\varepsilon^e\}_m \quad (5)$$

where $[G]_{mp}$ is the elastic response matrix between $\{A^*\}_p$ and $\{\varepsilon^e\}_m$, and it can be computed by performing elastic analysis of FEM p times[3].

In the actual measurement, inherent strain components ε^*_x, ε^*_y and ε^*_z are separated by slicing thin specimens L_y, L_z and T shown in Fig.1 and Table 1. In this case, the coefficients of inherent strain components ε^*_y and ε^*_z existing in specimen T, and those of inherent strain component ε^*_x in specimens L_y

and L_z can be estimated, respectively. The coefficients of ε^*_x in specimens L_y and L_z, and ε^*_y and ε^*_z in specimen T are expressed by $\{A^*_x\}$ and $\{A^*_{yz}\}$, shown in the following equations:

$$\{A^*_x\}_p=\{\varepsilon^*_{xO}, \varepsilon^*_{xam}, \varepsilon^*_{xbm}\}^T$$
$$\{A^*_{yz}\}=\{\varepsilon^*_{yO}, \varepsilon^*_{yam}, \varepsilon^*_{ybm}, \varepsilon^*_{zO}, \varepsilon^*_{zam}, \varepsilon^*_{xbm}\}^T \quad (6)$$
$$\{A^*\}_p=\{A^*_x, A^*_{yz}\}^T$$

When these coefficients are estimated from measured elastic strains later, the elastic strain $\{\varepsilon^e\}$ and residual stress $\{\sigma\}$ at arbitrary positions can be computed by the following equation:

$$\{\varepsilon^e\}=[G]\{A^*\}_p \qquad \{\sigma\}=[D]\{\varepsilon^e\} \qquad (7)$$

where [D] is the strain-stress matrix composed of Young's modulus E and Poisson's ratio υ.

3.2.1 Estimation of $\{A^*_{yz}\}$

As shown in Fig.1(b), when elastic strains at the positions on the two axes y and z of specimen T are observed by strain gauges, $\{A^*_{yz}\}$ can be estimated using Eq.(5).

3.2.2 Estimation of $\{A^*_x\}$

The components ε^*_{xO} and ε^*_{xam} in $\{A^*_x\}$ can be estimated from the observed elastic strains on specimen L_z. However, according to the relative size b_y/H (by is the depth of the elliptical inherent strain zone, and H is the thickness of plate), the other component ε^*_{xbm} in $\{A^*_x\}$ can be determined as follows.

In the case of $b_x<H$, as inherent strain ε^*_x exists only in a part of specimen L_y, ε^*_{xbm} can be estimated from the observed elastic strains on specimen L_y in the same way as ε^*_{xO} and ε^*_{xam} on specimen L_z.

In the case of $b_x>H$, inherent strain ε^*_x distributes through the entire thickness of plate. Inherent strain ε^*_x distributing through thickness can be separated into linear part ε^*_{xL} and nonlinear part ε^*_{xN}[2], respectively, by slicing specimen L_y. Then ε^*_{xL} can be determined from inherent strains on the top and bottom surfaces of specimen L_y, which are equal to elastic strain changes occurring as a result of cutting off specimen L_y. The ε^*_{xN} is equal to the elastic strain in the specimen L_y, which can be measured when specimen L_y is cut into small pieces. The sign of inherent strain ε^*_{xL} and ε^*_{xN} is opposite to that of the observed elastic strains.

In the case of $b_x>H$, as inherent strain ε^*_x distributes through the entire thickness of plate, its distribution can be simple estimated from the measurement only on the top and bottom surfaces of the original welded plate R without furnishing specimens L_y and L_z. This measuring method is called T-Method, which is described in the following chapter.

4 T-Method

When the T-method is used, the distributions of inherent strain components ε^*_y and ε^*_z are determined from the measurement on specimen T as indicated above. The distribution of component ε^*_x can be estimated by the following procedures:

4.1 Measurement of (a_x, b_x)

As shown in Fig.5, from the distribution of observed residual stress σ_x or elastic strain ε^e_x on the top and bottom surfaces of the original welded plate R, the width, a_x, on the top surface of the inherent strain zone and the width, a'_x, on the bottom surface shown in Table 1 can be decided. From a_x and a'_x, the depth, b_x, of the elliptic inherent strain zone which is larger than the plate thickness H can be estimated by the following equation.

$$b_x=H/\sqrt{1-(a'_x/a_x)^2} \qquad (8)$$

4.2 Estimation of $\{A^*_x\}$

Once $\{A^*_{yz}\}$ of inherent strain components ε^*_y and ε^*_z, and the zone (a_x,b_x) of inherent strain component ε^*_x are decided from the measurements above, $\{A^*_x\}$ of inherent strain ε^*_x can be computed by substituting elastic strains $\{\varepsilon^e\}_m$ measured on the surfaces of the original welded plate R into Eq.(6) which is rewritten as follows.

$$[G]_{mp}\{A^*_x, A^*_{yz}\}_p{}^T=\{\varepsilon^e\}_m \qquad (9)$$

5 Measurement of Residual Stresses by TL_yL_z-Method and T-Method

5.1 Numerical Experiment

In this section, a numerical experiment is performed to verify the reliability of the TL_yL_z-Method and the T-Method, and residual stresses are computed by thermal elastic-plastic FEM. Then, the computed elastic strains which are considered as the measured data to which assumed errors are added. Using these data, inherent strains are estimated with the aid of the functions shown by Eq.(2) and residual stresses are reproduced.

5.1.1 Model in numerical experiment

The material employed in the numerical experiment is mild steel. The physical properties and mechanical properties are assumed to be the functions of temperature as shown in Figs.6 and 7. When the temperature is higher than T_m to be defined below shown in Fig.7, Young's modulus E and yield stresses σ_{yB} and σ_{yW} of the base metal and weld metal will become very small. Above Tm, the material will lose its stiffness and

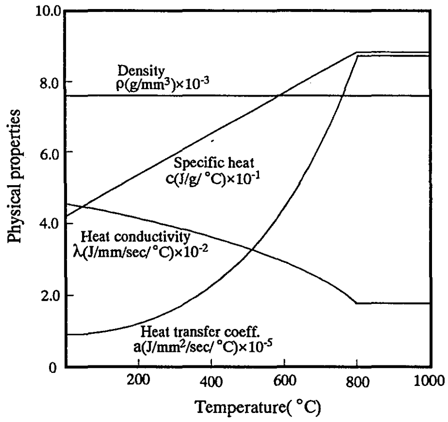


Fig. 6 Physical properties of mild steel

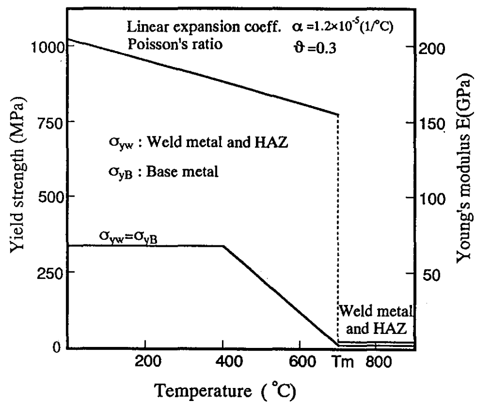


Fig. 7 Mechanical propperties of mild steel

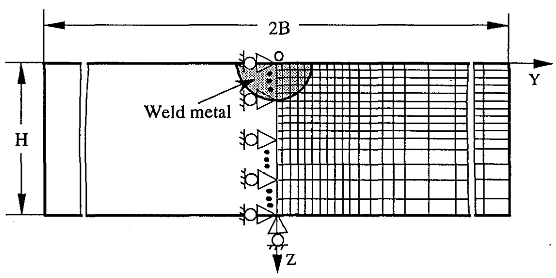
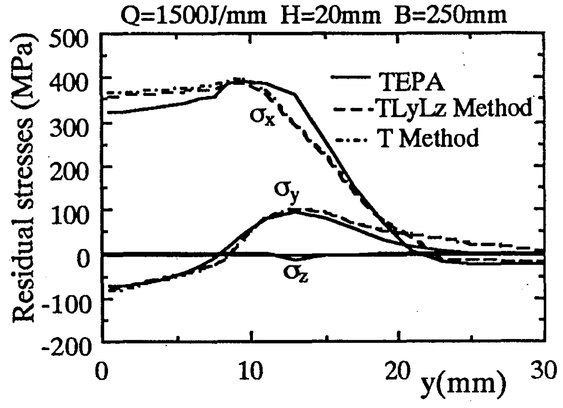


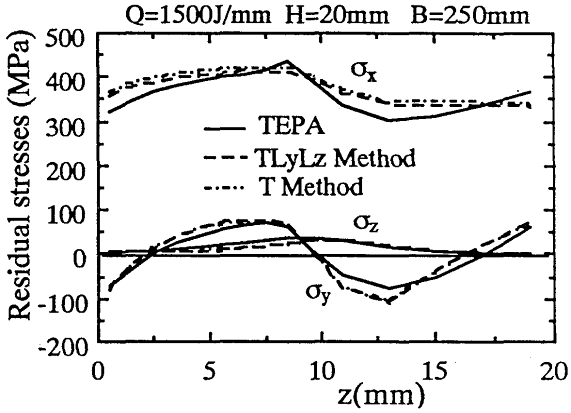
Fig. 8 Model of bead-on-plate weld and mesh division used in numerical experiment

exhibit no resistance to deformation. T_m shown in Fig.7 is called the mechanical melting temperature, For mild steel, T_m is about 700°C, which is approximately equal to that of the phase transformation point Ac_1. Therefore, the zone where the maximum temperature attained in the thermal cycle was equal to or higher than T_m is called HAZ.

The model to be analyzed is a very long bead welded plate. When residual stresses and inherent strains, distributed in the transverse section (except near the two ends), are to be discussed, the problem can be simplified as a plane deformation or general plane strain problem[3,4]. For this reason, the heat conduction in the welding direction is neglected in this study. The mesh



(a) Residual stresses in transverse direction (y)



(b) Residual stresses through the thickness (z)

Fig. 9 Residual stresses in bead-on-plate weld by TLyLz-Method and T-Method based on numerical experimente
(TEPA : Thermal Elastic-Plastic Analysis)

division employed in FEM analysis for both heat conduction and stress analysis is shown in Fig.8.

5.1.2 Accuracy of TL_yL_z-Method and T-Method

To verify the accuracy of TL_yL_z-method and T-Method, First, the residual stresses and elastic strains are computed by thermal elastic-plastic analysis of FEM. The computed elastic strains $\varepsilon^e{}_y$ and $\varepsilon^e{}_z$ are assumed as the measured ones on specimen T, and elastic strain $\varepsilon^e{}_x$ distributed in the y and z axes is assumed as the observed data in specimens L_z and L_y, respectively. The assumed observation errors are from -40μ to 40μ. These errors are assumed to be in a normal distribution, the average error and the standard deviation of the errors are 0 and 16.5μ respectively.

For bead-on-plate welding with Q=1500J/mm, H=20mm and B=250mm, computed residual stresses by TEPA (Thermal Elastic-Plastic Analysis) are shown in Fig.9 by solid lines. The broken lines and the chain lines in Fig.9 are the results estimated by the TL_yL_z-Method and the T-Method, respectively. The residual stresses estimated by the TL_yL_z-Method and the T-Method are in good agreement with those by TEPA.

5.2 Actual measurement

The actual measurement of residual stresses in a bead-on-plate weld was done by the TL_yL_z-Method. The length L, a half width B and thickness H of the welded plate were 1000mm, 125mm and 18.5mm, respectively. The material of plate was SUS316L stainless steel. The bead-on-plate is made by semi-automatic CO_2 welding. Material properties of SUS316L and welding conditions are shown in Tables 2 and 3, respectively. For this welding condition and plate thickness, the inherent strain distribution belongs to the case of $b_x>H$ represented in Table 1.

5.2.1 Measured results on specimens T, L_y and L_z

Following the procedures described in chapter 3, the specimens T, L_y and L_z were cut from the original welded plate shown in Fig.1. The thickness of specimens T, L_y and L_z were 8mm, 4mm and 4mm, respectively. Strain gauges attached to these specimens are shown in Fig.10. The strain gauges of 2mm gauge length were used.

The measured residual stresses σ_x, σ_y and σ_z in specimens T, L_y and L_z are shown in Fig.11. These for σ_x, σ_y and σ_z are marked by ●, ○ and ▲, respectively. From the measured residual stresses in Fig.11, the sizes (a_m, b_m), (a_x,b_x) and (a_y, b_y) of the inherent strain zones were determined, Then, by substituting these measured data into Eq.(5), the coefficient $\{A^*\}_p$ which describes the inherent strain distributions, was estimated. The estimated inherent strain distributions are shown in Fig.12. As shown in Fig.12(b), the inherent strain component ε^*_x distributes through the entire thickness of plate, and the inherent strain components ε^*_y and ε^*_z distribute partially in the thickness direction.

Using the inherent strains shown in Fig.12, residual stresses in specimens T, L_y and L_z are reproduced. The reproduced residual stresses are shown in Fig.11 by solid lines. The reproduced stresses are in good agreement with the measured ones.

Table 2 Mechanical properties of SUS316L

Young's modulus	Poisson's ratio	Yield strength	Tensile strength
19700(MPa)	0.28	180(MPa)	490(MPa)

Table 3 Welding conditions (CO2 Welding)

Current(A)	Voltage (V)	Speed(cm/min)
170	28	45

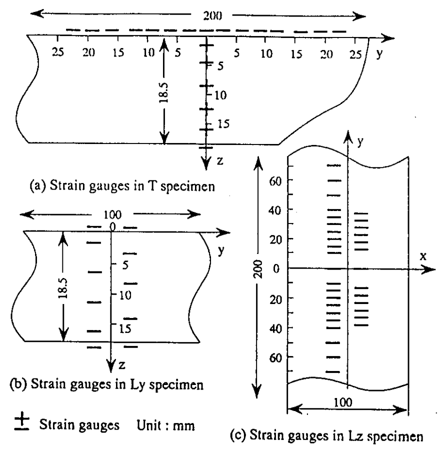


Fig.10 Location of strain gauges in specimens T, Ly and Lz

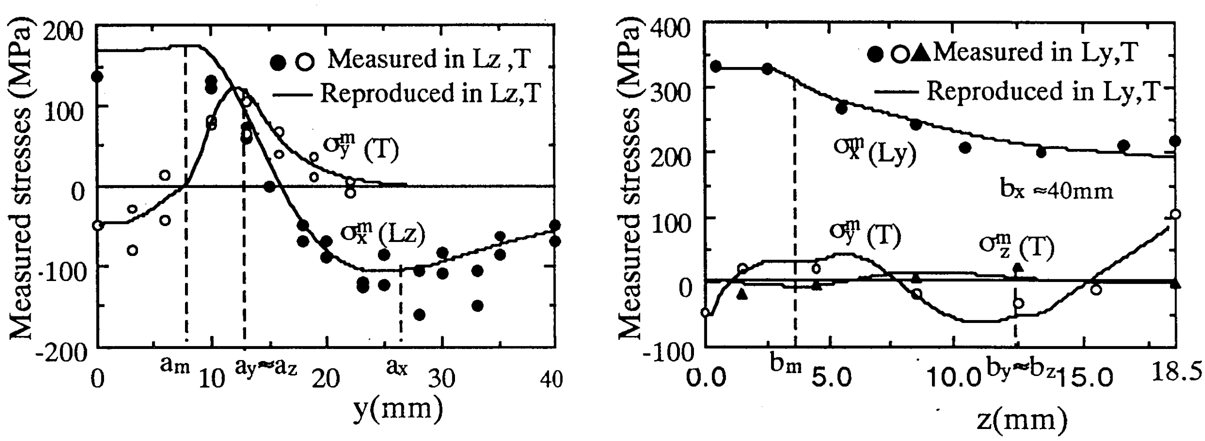


Fig.11 Measured and reproduced residual stress in specimens T, Ly and Lz

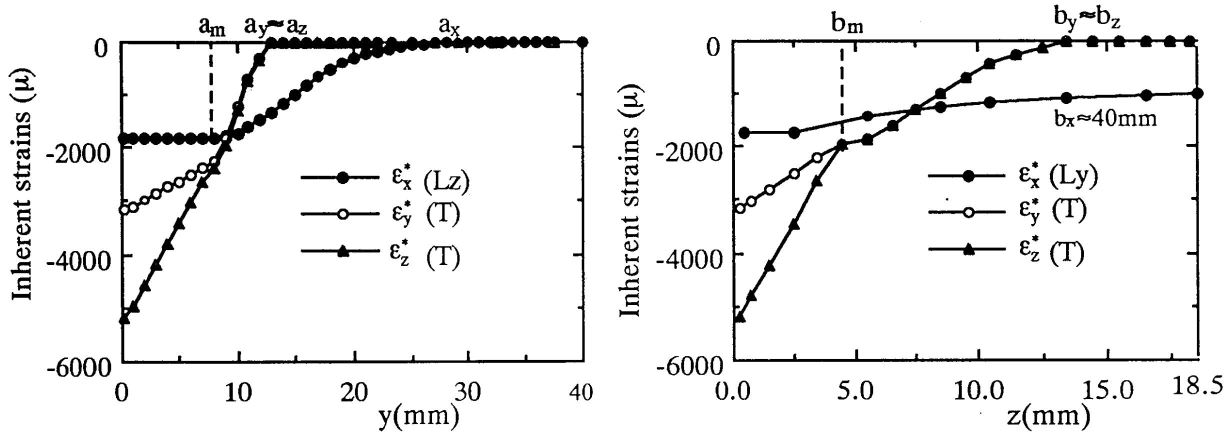


Fig.12 Inherent strain distributions estimated with the aid of functions

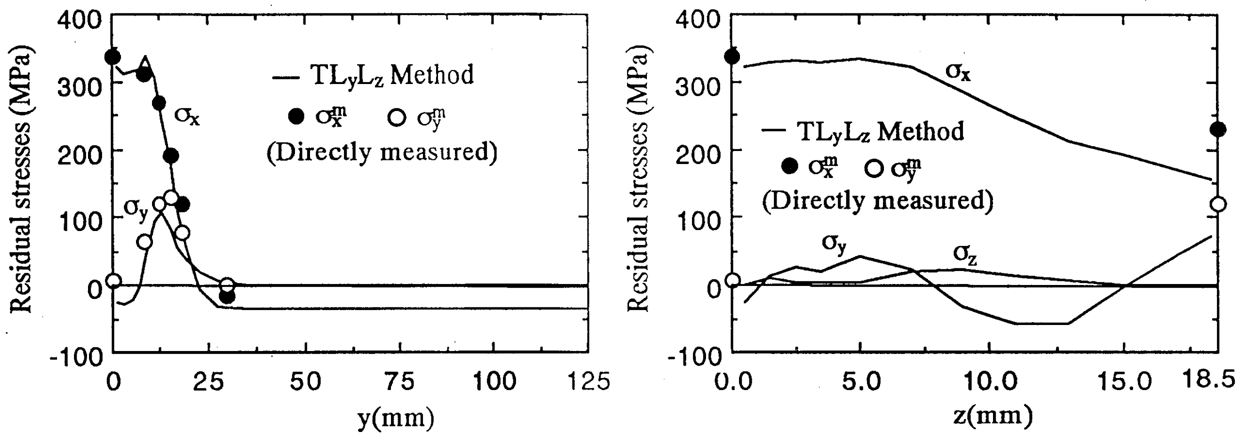


Fig.13 Residual stress distributions in stainless bead-on-plate weld measured by TLyLz-Method

5.2.2 3-dimensional residual stresses in the original welded plate

By applying the inherent strains measured above into the original welded plate R, the 3-dimensional residual stresses were computed by performing 3-dimensional elastic analysis of FEM. The distributions of residual stresses on the top surface and thickness directions of the middle transverse section are shown in Fig.13. The marks and indicate the residual stresses components $\sigma^m{}_x$ and $\sigma^m{}_y$ on the surface of the original welded plate R directly measured by strain gauges. The residual stresses measured by the TL_yL_z-Method show very good accuracy compared with those directly measured by strain gauges.

6. Conclusions

The main results obtained in this paper are summarized in the following:

(1) A simple distribution pattern of inherent strains in a bead-on-plate weld, which has only 3 unknown parameters for each of the inherent strain components, is proposed.

(2) The relationship between the inherent strain zones and the features of residual stress distributions are clarified by numerical experiments.

(3) The TLyLz-Method and the T-Method for measurement of local and overall distributions of three dimensional residual stresses in bead-on-plate welds with the aid of functions for inherent strains, are developed.

(4) The validity of the TL_yL_z-Method and the T-Method was verified by numerical experiment using the thermal elastic-plastic analysis of FEM.

(5) 3-dimensional residual stresses in a bead-on-plate weld of stainless steel are measured by the TLyLz-Method, and the accuracy of the method was ascertained in comparison with the stresses directly observed on the surfaces of the welded plate by conventional strain gauges. By using this newly proposed method, the necessary number of strain measurements is greatly reduced for practical use.

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