Measurement of Three-dimensional Welding Residual Stresses due to Electron Beam Welding†

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Abstract

In this research, T-edge *method and* L_z *method, in which inherent strains are dealt as parameters, are applied to measurement of three-dimensional welding residual stresses produced by electron beam welding (*EBW*). Accuracy of the measured residual stresses are discussed. As a result, characteristics of three-dimensional residual stress distributions due to* EBW *are described.*

The main conclusions are as follows:

1) *Validity and availability of* T-edge *method, developed in order to save time and expense for measurement, are demonstrated by showing the fact that the accuracy of three-dimensional welding residual stress distributions measured by this method is very high.*
2) *Study on accuracy of residual stresses in a long welded joint measured by* T-edge *method and* L_z *method suggested that residual stresses produced by* EBW *should never be uniform along the weld line, though continuous welding is applied in both cases under the same restraint condition.*
3) *Residual stress in the welding direction,* σ_x*, produced in the weld metal distributed in the plate thickness direction varies from spot to spot in magnitude and distributes complicatedly. Since melting region is very narrow in* EBW*, mechanical restraint condition of the weld metal becomes so severe that the same large tensile residual stress as in* HAZ *is produced in the weld metal.*
4) *Residual stresses produced in the weld metal perpendicular to the weld line,* σ_y*, and in the plate thickness direction,* σ_z*, show peculiar distributions; i.e.,* σ_y*, is compressive on the top and bottom surfaces and tensile in the middle of the plate thickness, and* σ_z*, is compressive in the plate thickness direction. The same stress distributions appear when instantaneous plane heat source is placed in the cross section of a plate. In case of* EBW*, it may be assumed that instantaneous heat source is placed in the cross section, though no such assumption as moving plane heat source is placed continuously along the weld line can be made.*

KEY WORDS: (Measurement of Residual Stress) (Welding Residual Stress) (Electron Beam Welding) (Inherent Strain) (T-edge Method) (L_z Method) (Relaxation Method)

1. Introduction

In laser welding, electron beam welding, etc., which use high energy density heat source as welding heat source is, heat input is extremely small in comparison with that of arc welding but deep melt is produced. Owing to the small heat input, welding deformation is small and metallurgical change is limited to a narrow region. It is reported from the view-points of accuracy of the size of products and metallurgy that high quality welded joints can be obtained by these weldings[1].

In order to discuss the safety of a whole welded structure, it is necessary to know correctly not only welding deformation but also welding residual stresses which have various effects on fatigue strength, brittle fracture strength, etc. Especially, it is considered that high energy density heat source of a small heat input makes the mechanical restraint condition severe to the narrow melting region. At present, however, no report has been presented on measurement of three-dimensional welding residual stresses produced in a welded joint processed with high energy density heat source. Therefore, the characteristics of their distributions have been unknown.

In this research, three-dimensional residual stress distributions produced by electron beam welding for a long weld length of a thick plate are measured. Applied to the measurement are the two measuring methods of residual stresses in which inherent strains are dealt as parameters, i.e., a measuring method of three-dimensional residual stresses using only a thinly sliced plate perpendicular to the weld line (hereafter called T-edge method)[2] and L_z method[3]. Applicability of T-edge method developed to economize time and cost required for measurement of residual stresses is demonstrated. The results by the two methods are compared and their accuracy investigated. In the result, the characteristics of three-dimen-

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sional residual stress distributions produced by electron beam welding are also described.

2. Measurement of Three-dimensional Welding Residual Stresses and Their Accuracy

It is considered that if continuous welding is applied under uniform restraint in the welding direction, welding residual stresses distribute uniformly along the weld line except the starting and finishing weld ends and their vicinities. In this case, inherent strains, the source of residual stresses, are also considered to be uniform along the weld line. Here, uniformly distributed three-dimensional welding residual stresses produced by electron beam welding are actually measured.

2.1 Material of specimen and welding condition

Chosen as material of the specimen is SM 50. Its chemical composition and mechanical properties are shown in **Table 1**. Specimen R', the measuring object of residual stresses, is shown in **Fig. 1** (a) with its size (*670* × *200* × *49* (in mm)) and the coordinate system and a position to take out Specimen R.

Electron beam welding is applied to Specimen R' along the x-axis, that is the middle line ($y = 0$ mm), by the full penetrating bead-on-plate method after initially produced residual stresses are annealed. The welding conditions are shown in **Table 2**. The cross-sectional macrostructure is outlined in Fig. 1.

Table 1 Chemical composition and mechanical property

Chemical compositions (%)					Mechanical properties (MPa)		Thickness (mm)
C	Si	Mn	P	S	σ_Y	σ_U	
0.15	0.36	1.39	0.018	0.006	363	520	49

σ_Y : Yield strength, σ_U : Tensile strength

Table 2 Welding condition of electron beam welding

Beam voltage (kv)	Beam current (mA)	Welding speed (mm/min)
50	450	150

2.2 Measuring method and procedure

Leaving out the detail of the measuring theory, the measuring procedures of T-edge method[2] and L_z method[3], in which inherent strains are dealt as parameters, are explained briefly below.

The following assumptions are made for observation of residual stresses.

1) Cutting is accompanied by elastic change of strains and does not produce any new inherent strains.
2) When continuous welding is applied to Specimen R' along the x-axis, among inherent strain components ϵ_x^*, ϵ_y^*, ϵ_z^*, γ_{yz}^*, γ_{zx}^*, γ_{xy}^*, the source of residual stresses, γ_{zx}^* and γ_{xy}^* can be neglected[4], since they produce unsymmetric stresses in the portion inside from the starting and finishing weld ends by the length of plate thickness. In this middle portion, inherent strains, ϵ_x^*, ϵ_y^*, ϵ_z^* and γ_{yz}^*, are uniform along the weld line being the functions of only y and z in a cross-section.
3) Stresses remaining in a thinly sliced plate are in the plane stress state. That is, inherent strains perpendicular to the plate surface do not produce any stresses.

On these assumptions, Specimen R (*160* × *200* × *49* (in mm)) is cut out from Specimen R' (Fig. 1 (b)). Using this Specimen R, inherent strains, the source of residual stresses, $\{\epsilon^*\} = \{\epsilon_x^*, \epsilon_y^*, \epsilon_z^*, \gamma_{yz}^*\}^T$, are estimated being divided into longitudinal inherent strain component $\{\epsilon_x^*\}$ and cross-sectional inherent strain component $\{\epsilon_c^*\} = \{\epsilon_y^*, \epsilon_z^*, \gamma_{yz}^*\}^T$, which can be expressed as,

$$\{\epsilon^*\} = \{\epsilon_x^*\} + \{\epsilon_c^*\} \qquad (1)$$

Each inherent strain component is estimated separately, then residual stresses measured. Estimation of inherent strains and the following elastic analyses are conducted by the finite element method using Young's modulus $E = 206$GPa and Poisson's ratio $\nu = 0.3$.

2.2.1 *T-edge method*

Shown below is the measuring procedure (T-edge method) of three-dimensional welding residual stresses produced in a portion where residual stresses distribute uniformly except the starting and finishing weld ends and their vicinities. This method uses only a thinly sliced plate perpendicular to the weld line of Specimen R which is cut out from the portion where residual stresses are uniform.

(a) Cutting sequence of Specimen R and strains to be observed

After strain gages are attached to the edge surface (cross section) of Specimen R (Fig. 1 (b)), a thin plate, Specimen T, is cut out from Specimen R (Fig. 1 (c)). Relaxed strains by this cutting are observed. Elastic strains with the opposite sign of the observed strains are considered to have relaxed before the cutting and designated as $\{_m\epsilon_R\}$. Specimen T is further divided into pieces, and elastic strains $\{_m\epsilon_T\}$ and residual stresses $\{_m\sigma_T\}$ remaining in Specimen T are observed. Consequently, elastic strains $\{_m\epsilon_3\}$ and residual stresses $\{_m\sigma_3\}$ produced in the edge surface of Specimen R can be observed directly as,

$$\{_m\epsilon_3\} = \{_m\epsilon_R\} + \{_m\epsilon_T\}$$
$$\{_m\sigma_3\} = [D]\{_m\epsilon_3\} \qquad (2)$$

where, $[D]$ = elastic stress-strain matrix

The source of residual stresses $\{_m\sigma_3\}$ and the corresponding strains $\{_m\epsilon_3\}$ produced on the edge surface of Specimen R is the inherent strain component $\{\epsilon^*\}$

$= \left\{\epsilon_x^*, \epsilon_y^*, \epsilon_z^*, \gamma_{yz}^*\right\}^T$ (assumption (2)). The source of the stresses $\left\{{}_m\sigma_T\right\}$ and elastic strains $\left\{{}_m\epsilon_T\right\}$ remaining in the thinly sliced Specimen T is only the cross-sectional inherent strain component $\left\{\epsilon_c^*\right\} = \left\{\epsilon_y^*, \epsilon_z^*, \gamma_{yz}^*\right\}^T$ and not the longitudinal inherent strain component $\left\{\epsilon_x^*\right\}$ (assumption (3)).

Briefly stated in the following are the estimating method and procedure of the most probable value of the cross-sectional inherent strain component, $\left\{\hat{\epsilon}_c^*\right\}$, and that of the longitudinal component, $\left\{\hat{\epsilon}_x^*\right\}$.

(b) Estimating method and procedure of cross-sectional inherent strain component, $\left\{\hat{\epsilon}_c^*\right\}$

Strain gages are attached to Specimen T on the both sides at the same positions. Specimen T is then cut into pieces to observe elastic strains remaining in Specimen T. The average of elastic strains observed at the same position on the both sides is taken as a directly observed value $\left\{{}_m\epsilon_T\right\}$ at the position. Using this $\left\{{}_m\epsilon_T\right\}$, the most probable value of cross-sectional inherent strain component $\left\{\hat{\epsilon}_c^*\right\} = \left\{\hat{\epsilon}_y^*, \hat{\epsilon}_z^*, \hat{\gamma}_{yz}^*\right\}^T$ is estimated by two-dimensional elastic analysis.

(c) Estimating method and procedure of longitudinal inherent strain component, $\left\{\hat{\epsilon}_x^*\right\}$

The most probable value $\left\{\hat{\epsilon}_c^*\right\}$ of cross-sectional inherent strain component estimated from Specimen T is imposed in Specimen R uniformly along the weld line (x-axis), so that three-dimensional elastic analysis is conducted and elastic strains $\left\{\hat{\epsilon}_c\right\}$ produced by only $\left\{\hat{\epsilon}_c^*\right\}$ on the edge surface of Specimen R are calculated. Difference between this $\left\{\hat{\epsilon}_c\right\}$ and the directly measured value of elastic strain $\left\{{}_m\epsilon_3\right\}$ produced on the edge surface is obtained as,

$$\left\{{}_m\epsilon_3\right\} - \left\{\hat{\epsilon}_c\right\} = \left\{\Delta\epsilon\right\} \qquad (3)$$

The difference $\left\{\Delta\epsilon\right\}$ corresponds to the strain component $\left\{\epsilon_y, \epsilon_z, \gamma_{yz}\right\}^T$ produced only by the longitudinal inherent strain component $\left\{\epsilon_x^*\right\}$ on the edge surface of Specimen R. Considering this $\left\{\Delta\epsilon\right\} = \left\{\epsilon_y, \epsilon_z, \gamma_{yz}\right\}^T$ as a new observed value of strain, which is produced by only the longitudinal inherent strain component in Specimen R, the most probable value $\left\{\hat{\epsilon}_x^*\right\}$ of inherent strains may be estimated by using three-dimensional elastic analysis.

Imposing thus estimated most probable value of inherent strains, $\left\{\hat{\epsilon}^*\right\} = \left\{\hat{\epsilon}_x^*, \hat{\epsilon}_y^*, \hat{\epsilon}_z^*, \hat{\gamma}_{yz}^*\right\}^T$ in the original Specimen R', three-dimensional elastic analysis is conducted to obtain three-dimensional residual stresses produced at any position in the portion free from the influence of the starting and finishing weld ends, i.e. the portion where residual stresses are considered to distribute uniformly.

With this method, it is unnecessary any more to take time and labor on preparing many Specimens L_z, attaching strain gages, subdividing Specimens L_z and observing relaxed strains, all of which are required by the L_z method. That is to say, the time and cost for measurement of residual stresses are greatly saved.

2.2.2 L_z method

In L_z method, a thin plate perpendicular to the weld line (Specimen T) and n pieces of thin plates parallel to the weld line (Specimens L_z) are cut out as shown in Fig. 1 (b′). Specimen T is attached with strain gages on the both sides and cut into small pieces so as to observe elastic strains in Specimen T (Fig. 1 (c′)). The observed values of strains are used for estimation of the most probable value of cross-sectional inherent strain, $\left\{\hat{\epsilon}_c^*\right\} = \left\{\hat{\epsilon}_y^*, \hat{\epsilon}_z^*, \hat{\gamma}_{yz}^*\right\}^T$ (in the same way as in the afore-mentioned T-edge method). Giving only the estimated cross-sectional inherent strain component $\left\{\hat{\epsilon}_c^*\right\}$ to the original Specimen R', three-dimensional elastic analysis is conducted. Consequently, three-dimensional residual stress component $\left\{\sigma^A\right\}$ produced in Specimen R' only by $\left\{\hat{\epsilon}_c^*\right\}$ is obtained.

As for the portion where residual stresses are considered to be distributed uniformly along the weld line, two-dimensional stresses (plane stresses) remaining in Specimen T, $\left\{\sigma^{AO}\right\}$, are directly measured and substituted into Eq. (4) for estimation of three-dimensional residual stress component $\left\{\sigma^A\right\}$ produced by only cross-sectional inherent strain component $\left\{\epsilon_c^*\right\}$ (see reference

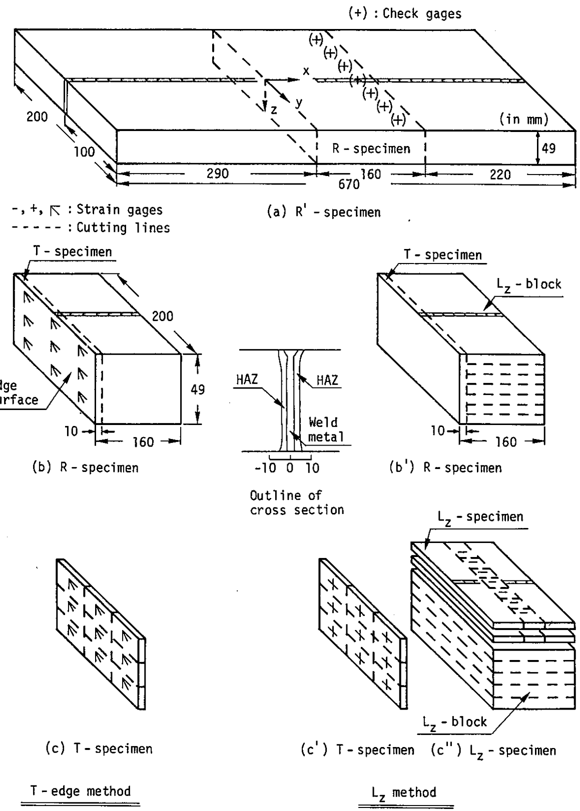

Fig. 1 Experimental model, location of strain gages, cutting lines and procedure for T-edge and L_z method.

4) for detailed verification). That is to say, when stresses in the plane stress state are observed and converted into ones in the plane strain state, three-dimensional residual stress component $\{\sigma^A\}$ produced by only cross-sectional inherent strain component $\{\epsilon_c^*\}$ can be obtained.

$$\sigma_x^A = \sigma_x^{AO} / (1-\nu^2)$$
$$\sigma_y^A = \sigma_y^{AO} / (1-\nu^2)$$
$$\sigma_z^A = \nu(\sigma_x^{AO} + \sigma_y^{AO}) / (1-\nu^2) \quad (4)$$

In the next, elastic strains remaining in n pieces of Specimens L_z are observed directly by strain gages attached in the middle of each Specimens L_z (Fig. 1 (c'')). Using the observed strain values, two-dimensional elastic analysis is conducted, and the most probable value $\{\hat{\epsilon}_x^*\}$ of longitudinal inherent strain component is estimated. As a matter of course, $\{\hat{\epsilon}_x^*\}$ is estimated for each n pieces of Specimens L_z. Then, distributing only $\{\hat{\epsilon}_x^*\}$ in Specimen R', three-dimensional elastic analysis is conducted, so that three-dimensional residual stress component $\{\sigma^B\}$ produced in Specimen R' by only $\{\hat{\epsilon}_x^*\}$ can be calculated. As a result, three-dimensional residual stresses $\{\sigma\}$ can be obtained as the sum of $\{\sigma^A\}$ and $\{\sigma^B\}$ as follows:

$$\{\sigma\} = \{\sigma^A\} + \{\sigma^B\} \quad (5)$$

2.3 Results of measurement and its accuracy

Comparing the three-dimensional welding residual stress distributions produced by electron beam welding measured by the above mentioned two measuring methods and discussing their accuracy, the practicability of T-edge method is demonstrated.

2.3.1 Results of measurement by T*-edge method and its accuracy*

The most probable value of inherent strains $\{\hat{\epsilon}^*\} = \{\hat{\epsilon}_x^*, \hat{\epsilon}_y^*, \hat{\epsilon}_z^*, \hat{\gamma}_{yz}^*\}^T$ estimated from Specimen R is imposed in the measuring object R', and three-dimensional elastic analysis is conducted. Distributions of three-dimensional welding residual stresses $\{\hat{\sigma}\}$ are shown by solid lines in **Fig. 2.** Here, the accuracy of measured three-dimensional welding residual stress distributions produced by electron beam welding may be evaluated as follows:

Residual stresses and the corresponding elastic strains, of which source is the total inherent strain components, can be observed directly by strain gages attached on the edge surface of Specimen R, and those on the top and bottom surfaces of Specimen R. That is, elastic strains $\{_m\epsilon_y, {}_m\epsilon_z, {}_m\gamma_{yz}\}^T$ can be observed on the edge surface of Specimen R and $\{_m\epsilon_x, {}_m\epsilon_y, {}_m\gamma_{xy}\}^T$ on the top and bottom surfaces of Specimen R or R'.

On the other hand, three-dimensional elastic analysis is conducted distributing the estimated most probable value

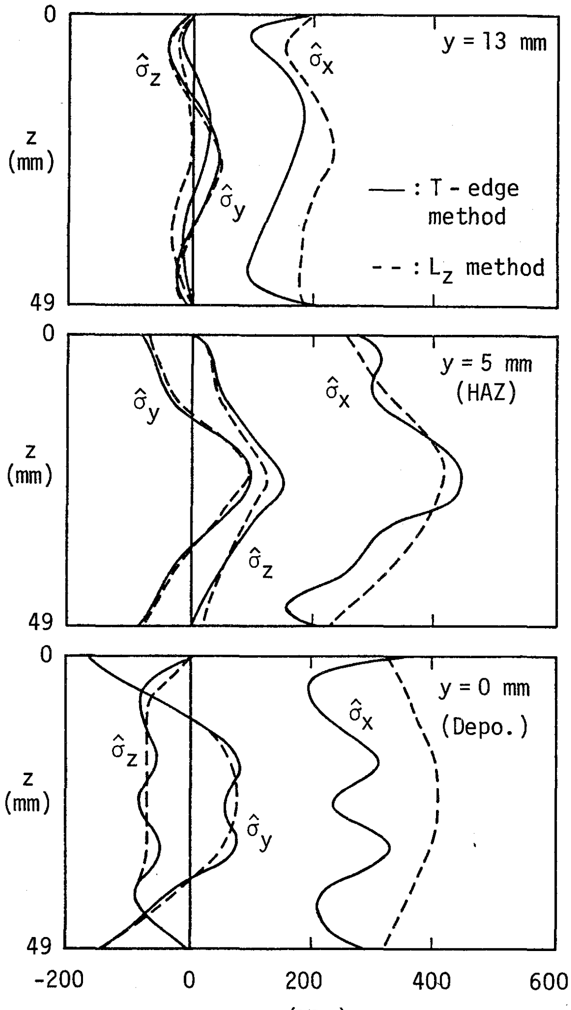

Fig. 2 Three-dimensional welding residual stress distributions on cross section due to electron beam welding.

$\{\hat{\epsilon}^*\}$ of inherent strain in Specimen R, so that the most probable value $\{\hat{\epsilon}\}$ of elastic strain and that $\{\hat{\sigma}\}$ of three-dimensional welding residual stress produced on the edge surface of Specimen R and the top and bottom surfaces of Specimen R or R' are calculated. Accuracy of the whole measured values can be evaluated directly by comparing these most probable values, $\{\hat{\epsilon}\}$, $\{\hat{\sigma}\}$, with the directly observed strains $\{_m\epsilon\}$ and stresses $\{_m\sigma\}$ respectively. It is also possible to evaluate the accuracy of measurement by using the unbiased estimate $\hat{s}_\epsilon$ of the standard deviation of the most probable value for observed elastic strains and that for residual stresses $\hat{s}_\sigma$.

Elastic strains $\{_m\epsilon_y, {}_m\epsilon_z\}^T$ observed directly on the edge surface of Specimen R in this experiment and their most probable value $\{\hat{\epsilon}_y, \hat{\epsilon}_z\}^T$ are shown in **Fig. 3** respectively by "○" and "●", and solid lines. Unbiased estimate of elastic strain is $\hat{s}_\epsilon$ = *77μ* and that of residual stress $\hat{s}_\sigma$ = *24.5* MPa.

Consequently, it has been shown that T-edge method is accurate to measure three-dimensional welding residual

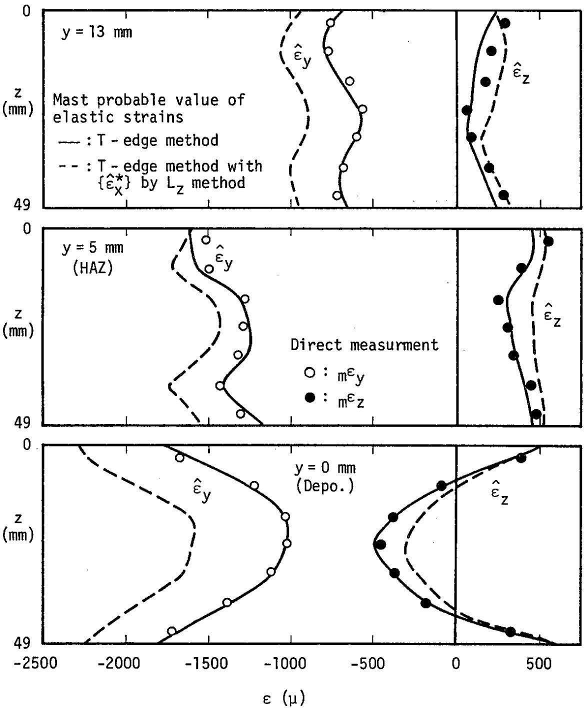

Fig. 3 Elastic strain distributions on edge surface of Specimen *R*.

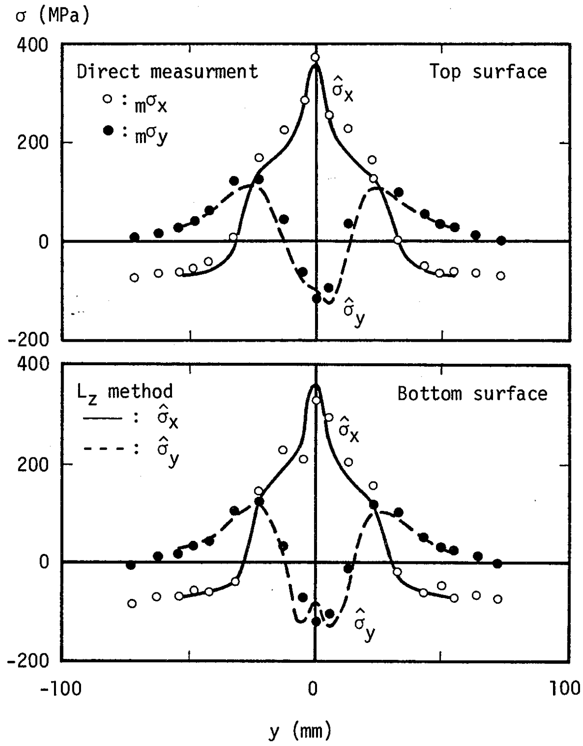

Fig. 4 Welding residual stresses on top and bottom surfaces of Specimen *R'*.

stress distributions produced by electron beam welding.

2.3.2 Result of measurement by L_z *method and its accuracy*

Seven pieces of Specimens L_z were used to measure three-dimensional residual stresses produced by electron beam welding using Specimen R taken from the same Specimen R'. Their distributions measured are shown by broken lines in Fig. 2.

The accuracy of residual stress distributions measured by L_z method may be evaluated as follows:

Shown in **Fig. 4** are the longitudinal residual stresses $\hat{\sigma}_x$ and ones perpendicular to the weld line $\hat{\sigma}_y$ measured by L_z method, and ${}_m\sigma_x$ and ${}_m\sigma_y$ which are directly observed by strain gages (check gages (Fig. 1 (a)): not for measurement of residual stresses but only for investigation of accuracy of measured residual stresses) attached on the top and bottom surfaces of Specimen R'. Though the measured values, $\hat{\sigma}_x$ and $\hat{\sigma}_y$, are quite independent of the observed ones, ${}_m\sigma_x$ and ${}_m\sigma_y$, they correspond to each other well. Since the accuracy of residual stresses by L_z method is the same on the top and bottom surfaces as well as in the inside of Specimen R', it is considered that residual stresses in the inside are also accurate.

3. Characteristics of Three-dimensional Welding Residual Stress Distributions

In this chapter, distributions of three-dimensional welding residual stresses produced by electron beam welding measured by T-edge method and L_z method are compared and their characteristics clarified.

3.1 Comparison of welding residual stress distributions measured by the two methods

Shown in Fig. 2 are the three-dimensional welding residual stress distributions in the plate thickness direction produced by electron beam welding measured by the two measuring methods. Cross-sectional residual stresses, σ_y and σ_z, measured by the two methods correspond well each other. While different longitudinal residual stress σ_x was measured by the different method. This difference is remarked in the weld metal ($y = 0$ mm).

Two-dimensional elastic analysis is conducted by giving to Specimen T the most probable value $\{\hat{\epsilon}_c^*\} = \{\hat{\epsilon}_y^*, \hat{\epsilon}_z^*, \hat{\gamma}_{yz}^*\}^T$ of cross-sectional inherent strain component chosen out of the total inherent strain component $\{\hat{\epsilon}^*\} = \{\hat{\epsilon}_x^*, \hat{\epsilon}_y^*, \hat{\epsilon}_z^*, \hat{\gamma}_{yz}^*\}^T$ which is the source of residual stresses. Stresses obtained by this analysis correspond well to those $\{\sigma^{AO}\}$ observed directly in Specimen T. The unbiased estimate for directly observed stresses is $\hat{s}_\sigma = 9$MPa. Therefore, it is considered that the difference between the two methods in the magnitude and distribution of longitudinal stress component σ_x attributes not to the cross-sectional inherent strain component $\{\epsilon_c^*\}$ but to the longitudinal inherent strain component $\{\epsilon_x^*\}$.

The most probable value of inherent strain $\{\hat{\epsilon}^*\} = \{\hat{\epsilon}_x^*, \hat{\epsilon}_c^*\}^T$ estimated by T-edge method has already been shown to be accurate in the previous chapter. Giving $\{\hat{\epsilon}_x^*\}$ estimated from seven pieces of Specimens L_z to stress-free Specimens L_z, two-dimensional elastic analysis is conducted, so that the most probable value $\{\hat{\epsilon}_x\}$ of elastic strain is obtained. Using the unbiased estimate $\hat{s}_\epsilon$ of the standard deviation for the directly observed elastic strains $\{{}_m\epsilon_x\}$, the accuracy of the estimated longitudinal inherent strain component $\{\hat{\epsilon}_x^*\}$ is evaluated. The maximum value of unbiased estimate $\hat{s}_\epsilon$ is $\hat{s}_\epsilon = 21\mu$ and the average in seven specimens 18μ. Therefore, $\{\hat{\epsilon}_x^*\}$ estimated from Specimens L_z is considered to be accurate.

Here, assuming that $\{\hat{\epsilon}_x^*\}$ obtained by L_z method is more accurate than that by T-edge method, only $\{\hat{\epsilon}_x^*\}$ chosen out of inherent strain components estimated by T-edge method is replaced by $\{\hat{\epsilon}_x^*\}$ estimated by L_z method. Then, it is regarded that inherent strains in Specimen R are composed of $\{\hat{\epsilon}_x^*\}$ estimated by L_z method and cross-sectional inherent strain component $\{\hat{\epsilon}_c^*\}$ estimated by T-edge method. Imposing those $\{\hat{\epsilon}_x^*\}$ and $\{\hat{\epsilon}_c^*\}$ to Specimen R, three-dimensional elastic analysis is conducted. Analyzed elastic strains in the edge surface of Specimen R are shown by broken lines in Fig. 3 where marks ○ and ● represent the directly observed values and solid lines the results by T-edge method.

Although $\{\hat{\epsilon}_x^*\}$ estimated in Specimens L_z is accurate as already mentioned, there is a great gap of 600μ between the analyzed $\hat{\epsilon}_y$ and the directly observed ${}_m\epsilon_y$ at $y = 0$ mm (Fig. 3), suggesting that the measured longitudinal stress component σ_x differs in magnitude and distribution not owing to the measuring method but depending on the measuring position varying along the weld line (x-axis). That is, in case of electron beam welding, residual stresses are nowhere uniform along the weld line even though continuous welding is applied for a long weld length under presumably constant welding and restraining conditions.

3.2 Characteristics of welding residual stress distributions and their production mechanism

The characteristics of residual stress distributions produced by electron beam welding are described on the basis of the measured results and the above mentioned study.

Longitudinal stresses σ_x are great in tension on the top and bottom surfaces ($z = 0$ and 49 mm) near the weld metal ranging from the center of the weld line to one quarter of the plate width; that is, $y = \pm 25$ mm (Fig. 4). Longitudinal stresses σ_x in the plate thickness direction are also tensile but distribute complicatedly depending on the position. This implies that, in case of electron beam welding, the heat source along the weld line is not uniform though the cross-sectional macrostructure (Fig. 1) suggests that the heat source is placed instantaneously in plane. Moreover, the mechanical restraint condition of the weld metal is severe because the melting region is extremely narrow, and the same large tensile residual stresses as in HAZ are produced in the weld metal.

Stresses perpendicular to the weld line, σ_y, are compressive on the top and bottom surfaces of the weld metal ($y = 0$ mm) and tensile in the middle plate thickness, whereas stresses in the plate thickness direction, σ_z, are uniformly compressive along the plate thickness (Fig. 2). Since these distributions correspond to those produced by imposing narrow instantaneous plane heat source in the cross section, their production mechanism can be estimated from the distributions of σ_y and σ_z in the plate thickness direction as follows:

When narrow instantaneous plane heat source is imposed in the cross section, the weld metal cools rapidly and starts to shrink due to the heat conduction to the y-z plane and the heat transfer from the top and bottom surfaces. In this case, shrinkage occurs in the middle plate thickness later than at the top and bottom surfaces. Consequently, stress σ_y become tensile in the middle plate thickness and compressive at the top and bottom surfaces. It follows from this that, unlike general multipass layer weldings, electron beam welding in which melting region is extremely narrow characterizes the distribution of σ_y compressive at the top and bottom surfaces and that of σ_y symmetric with respect to the middle plate thickness in the plate thickness direction.

On the other hand, excluding the weld metal, the distributions of stresses perpendicular to the weld line, σ_y, and those in the plate thickness direction, σ_z, in the HAZ and the base plate are similar to the actually measured three-dimensional welding residual stress distributions[5] produced by the conventional electroslag welding by which a thick plate can be welded with a single layer. Contrary to this, σ_y in the weld metal produced by electroslag welding is tensile on the top and bottom surfaces and slightly compressive in the middle plate thickness. This difference attributes to the difference in shrinking process; that is, the cooling stage of a joint differs between electron beam welding and electroslag welding in which the width of weld metal is *10* to *20* times as wide as that in the former. Residual stresses produced by electroslag welding also distribute symmetrically with respect to the middle plate thickness in the plate thickness direction.

4. Conclusions

In this research, two measuring methods in which inherent strains are dealt as parameters (T-edge method and L_z method) are applied to measurement of three-dimensional welding residual stress distributions produced by electron beam welding. Results of measurement by these methods and their accuracy are comparatively investigated, and the characteristics of residual stress distributions produced by electron beam welding described.

The main conclusions are as follows:

1) Demonstrating good accuracy of three-dimensional welding residual stress distributions measured by T-edge method, the validity and practicability of T-edge method developed for economization of time and cost required for measurement of residual stresses were proven.
2) It is considered that electron beam welding produces nowhere uniform residual stresses along the weld line even though continuous welding is applied for a long weld length under constant welding and restraining conditions.
3) Longitudinal residual stress σ_x varies from position to position in magnitude along the weld line, distributing complicatedly. Since the melting region is narrow with extremely small heat input, the mechanical restraint of the weld metal becomes so severe that σ_x becomes largely tensile in the weld metal as well as in HAZ.
4) Stress perpendicular to the weld line, σ_y, in the weld metal is compressive on the top and bottom surfaces and tensile in the middle plate thickness, and stress σ_z in the plate thickness direction is compressive and almost uniform in the plate thickness direction. Since the measured stress distributions in the cross section are similar to these appear when instantaneous plane heat source is imposed, it may be regarded that the heat source of electron beam welding is imposed instantaneously in the longitudinal cross section. However, judging from the fact that the measured longitudinal stress distribution is not uniform, it is hard to consider that moving plane heat source is imposed continuously along the weld line.

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