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A Predicting Method of Welding Residual Stress Using Source of Residual Stress (Report IV) †

— Experimental Verification for Predicting Method of Welding Residual Stresses in T-joints Using Inherent Strains —

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Abstract

In this paper, a predicting method of welding residual stress in a T-joint using inherent strain (the source of residual stress) is verified by experiments. The measured inherent strains are compared with the results of thermal elasto-plastic analysis and the simplified formulae proposed by some of the authors.

The released strains along the welding direction of T-joints are measured by strain gauges, and inherent strains are calculated from the released strains. The stress equilibrium across the cutting plane during releasing strains by cutting should be maintained in order to accurately determine the inherent strains. The measured inherent strains in T-joints agree well with the results of thermal elasto-plastic analysis and also with those by estimating formulae which are represented within the scatter of the inherent strain distribution. The proposed predicting method of welding residual stresses using the inherent strains is experimentally validated.

KEY WORDS: (Source of Residual Stress) (Inherent Strain) (Welding Residual Stress) (T-joint) (Strain Measurement) (Predicting Method)

1. Introduction

Residual stresses caused by welding affect the performances of a structure in various ways. It is important to precisely know the distribution and magnitude of the welding residual stress when designing the strength of a structure. The thermal elasto-plastic analysis is generally used to determine the welding residual stresses [1-3]. However, it is also possible to estimate the welding residual stress by elastic analysis using an inherent strain, which is a source for generating the residual stress [4]. A predicting method of residual stresses by elastic analysis using the inherent strain is proposed for butt-joints of metal plate [5, 6], T-joints and I-joints [7], and its validity and applicability are proven by numerical calculation using thermal elasto-plastic analysis. However, the applicability of the predicting method to actual weldments has not yet been verified experimentally.

This paper studies the residual stress distributions in T-joints based on the inherent strains measured experimentally, which were the objects of numerical calculations in the previous report [7]. By comparing the experimental results with the numerical results calculated by thermal elasto-plastic analysis and with the predicted values obtained from the simplified estimating formulae proposed in Ref. 7), this paper experimentally verifies that it is possible to accurately predict the residual stresses in T-joints by using the proposed predicting method.

2. Experimental Measuring Method

2.1 Theory of measurement for inherent strain

The following elastic response equations are generally derived as the relationships between the inherent strain $\{\varepsilon^*\}$, elastic strain $\{\varepsilon\}$, and stress $\{\sigma\}$ which occur at any location in an elastic body owing to the inherent strain,

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

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

where [H*] : elastic response matrix, and [D] : stress-strain matrix.

The distribution zone and the magnitude of inherent strain do not change (invariance of inherent strain) so long as no new inherent strains are added by plastic deformation resulting from cutting, external loads, etc. Therefore, the inherent strain is estimated from the observed value of elastic strain even the geometry of an object changes due to cutting as follows [8, 9].

First, concerning measurement of the elastic strain induced in a structural member, as many change of strain $\{{}_m\varepsilon\}$ as possible are observed by cutting or the like. The following measurement equation is obtained from the above elastic response Eq. (1), since various kinds of errors in measurement may be included in the observed strains,

$$\{{}_m\varepsilon\} - [H^*]\{\bar{\varepsilon}^*\} = \{V\} \quad (3)$$

where $\{\bar{\varepsilon}^*\}$: most probable value for inherent strain, and { V } : residual.

The most probable value $\{\bar{\varepsilon}^*\}$ for the inherent strain can be determined from the condition that minimizes the sum of squares of the residual, as in the following equation.

$$\{\bar{\varepsilon}^*\} = ([H^*]^T[H^*])^{-1}[H^*]^T\{{}_m\varepsilon\} \quad (4)$$

For numerical experiments, elastic strain $\{\varepsilon\}$ determined by thermal elasto-plastic analysis may be used as the measured strain $\{{}_m\varepsilon\}$ in the above equation.

The most probable value $\{\bar{\sigma}\}$ for the welding residual stress can be determined by substituting the most probable value $\{\bar{\varepsilon}^*\}$ obtained for the inherent strain into $\{\varepsilon^*\}$ in Eq. (2).

2.2 Measuring object

The T-joint used in this study is shown in **Fig. 1**. The material of base plate and welding rod is mild steel as shown in **Table 1**. Welding was symmetrically and simultaneously performed with respect to the center axis of the web, by means of gas-shielded arc welding with a total heat input of 2,400 (J/mm). No peripheral restraints were given during welding.

In this study, it is necessary to pay attention to the residual stress σ_x in the welding direction, which greatly affects the buckling strength of the structural member. The weld length is 600 mm that is considered to be sufficient if the measurement of elastic strains is performed at the midlength where is not affected by the

Table 1 Chemical compositions and mechanical properties of materials.

Materials	Chemical compositions (%)					Mechanical properties			
	C	Si	Mn	P	S	σ_y (MPa)	E (GPa)	ν	α ($\times 10^{-5}$)
SM400B	0.12	0.23	0.89	0.020	0.006	330	210	0.30	1.20
SM400B (WM)	0.08	0.30	1.24	0.021	0.008	480	210	0.30	1.20

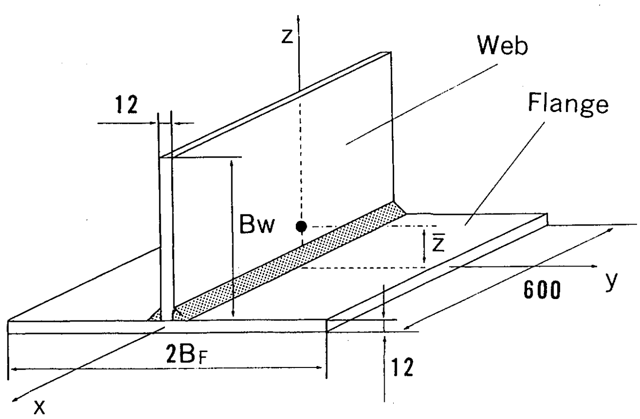


Fig. 1 A fillet welded T-joint.

Table 2 Geometrical parameters of T-joints for measurement.

	Type A	Type B	Type C
Width of Web B_W (mm)	150	250	300
Width of Flange $2B_F$ (mm)	300	200	150
Aspect Ratio $B_W / 2B_F$	0.5	1.25	2.0
Cross-sectional Area A (mm2)	5400	5400	5400

free-ends judging from the Saint-Venant principle.

Three types of test pieces A, B and C, as shown in **Table 2**, were each designed with the same cross-sectional area of 5,400 mm^2 to ensure a constant average temperature rise T_{av} during welding, and a geometrical ratio $B_W / 2B_F$ (the web depth B_W to the flange width $2B_F$) as a parameter. T_{av} is considered to have the greatest effect on the distribution of welding residual stress [10]. The flange thickness h_F and the web thickness h_W were 12 mm. This thickness is considered to allow the temperature distribution to be constant in the thickness direction so that the residual stress distribution is the same through the thickness.

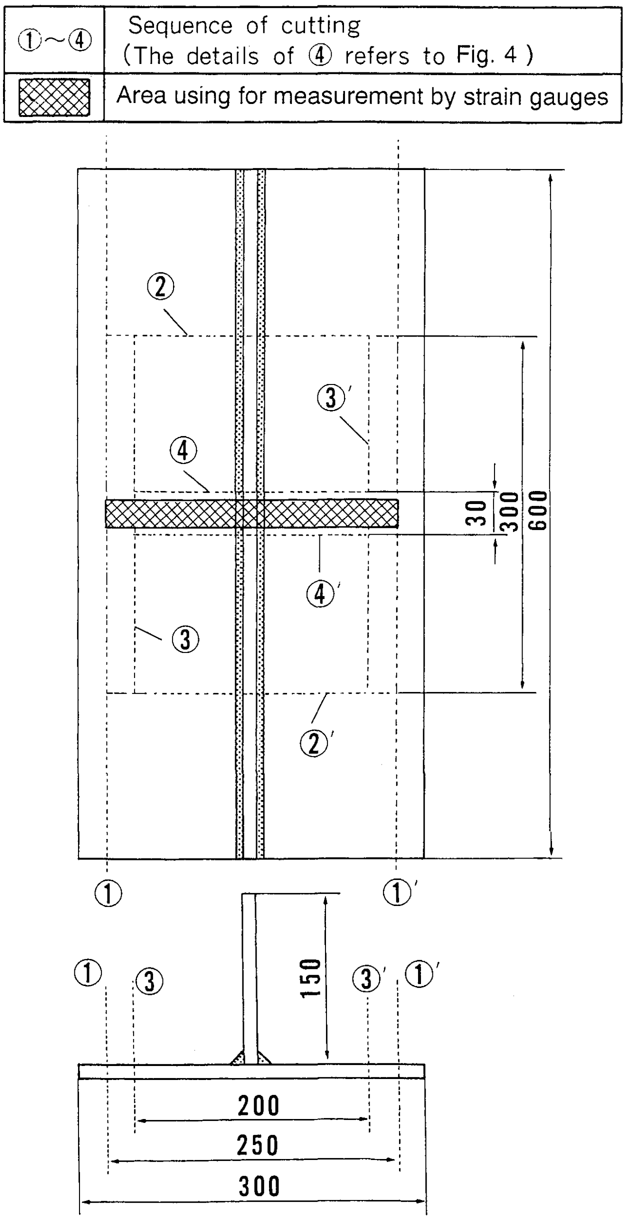


Fig. 2 Sequence of cutting T-joint (Test Piece A)

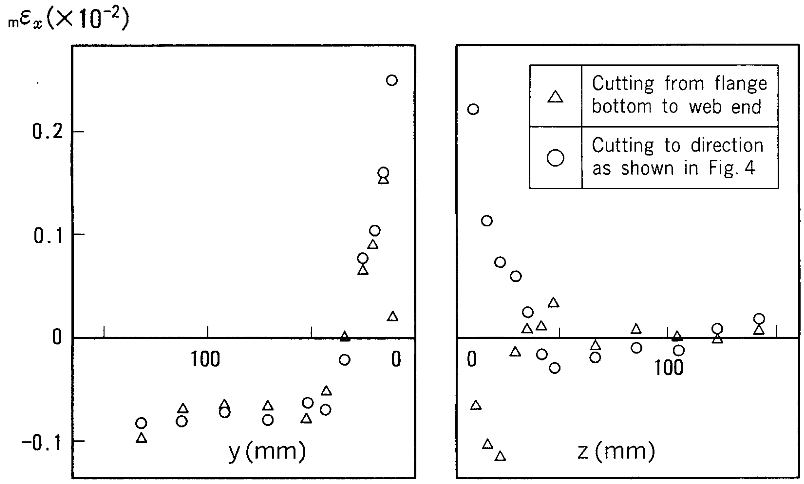
2.3 Measuring procedure for inherent strain in the T-joint

After the specimen was fabricated by welding, strain gauges are mounted on the test piece along the central portion ($x = 0$), as shown in **Fig. 2**, where is considered not to be affected by the free ends. The strain gauges are one-shaft ones with gauge length of 1 mm, and were cut by a motorized saw. The minimum interval between the gauge centers was set to 7 mm in consideration of the cutting allowance by the motorized saw. The measured gauges for each test piece were sixty-five.

The sequence of cutting off the T-joint for test piece A is shown in Fig. 2. The test piece with the mounted strain gauges was cut from a position far away from the measuring portion so as to gradually relax the stress, and then was alternately cut a little at a time from both ends of the cutting line to maintain the test piece symmetry. Finally, the sliced pieces with the each strain gauge were cut into smaller pieces to relax the stress at the measuring portion as much as possible. The cutting was carefully performed so as not to increase the temperature in the test piece, in order to prevent plastic deformation due to thermal strain which may be caused by the cutting friction.

The order and direction of cutting the test piece are important when measuring the inherent strain. That is because that as the cutting of the test piece proceeds, the stress is gradually released, and therefore, the distribution of the stress varies at each step of cutting, but the equilibrium of the stress in the test piece should be maintained in the course of the cutting. However, the redistributed stress may exceed the yield point depending on the order and direction of the cutting, thereby adding a new inherent strain. The sum of inherent strains due to welding and inherent strains due to cutting is included in the final measured results, and as a result, it is considered to have a distribution which is different from the inherent strain only due to welding.

Figure 3 shows the measured strains for test piece A, which were obtained by cutting straight from the bottom of the flange to the free end of the web, using a triangle mark. The distribution of the measured strains in the flange is regarded as common and reasonable, but that in the web is not, because inherent strains due to cutting might be added. Therefore, the order and direction of cutting should be determined so that a new inherent strain is not added the test piece during cutting. The cutting may be performed in such a way that a well-balanced stress is maintained along the cutting line. The order of cutting in a cross-section is shown in **Fig. 4**. To maintain a well-balanced stress along the cutting line, both the flange and the web were cut so that the plate thickness becomes



(a) Flange (b) Web

Fig. 3 Comparison of measured residual strain by different cutting sequences (Test piece A).

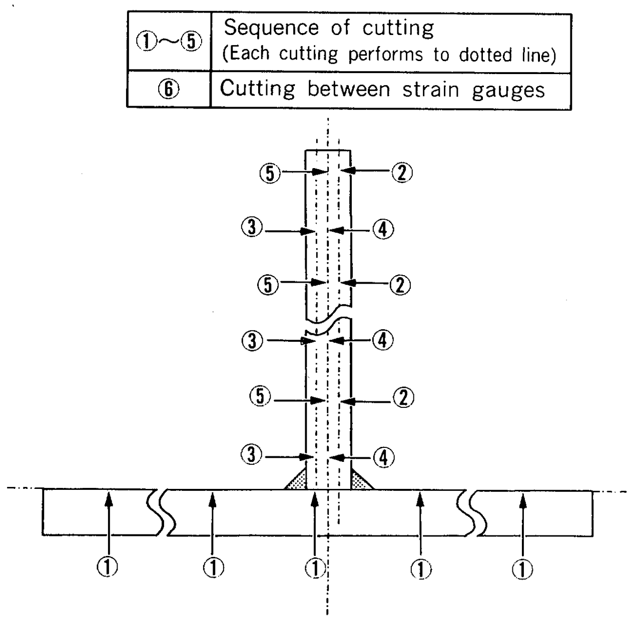


Fig. 4 Sequence of cutting off T-joint in section.

uniformly thinner in the width direction.

Firstly, the flange was cut uniformly in thickness, step by step, from the lower surface toward the upper one as circular mark 1 shown in Fig. 4, and then, the web was cut a little at a time alternately from both sides as circular marks 2, 3, 4, 5 shown in Fig. 4. The measured strains by this cutting order are also shown by a circular mark in Fig. 3. The distributions of measured strains are considered as reasonable in both the flange and the web by maintaining the stress equilibrium along the cutting line. Thus, the difference in the elastic strains before and after the cutting was measured to estimate the most probable for the inherent strain by each test piece.

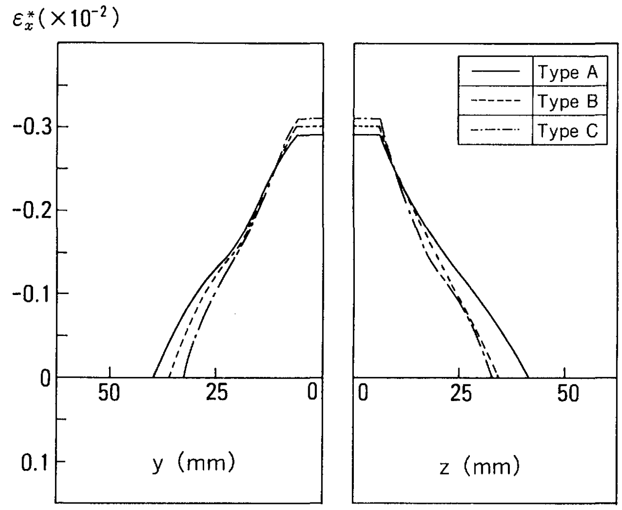
To meet the size limitation of the motorized saw, some portion of the flange of test piece A were cut before mounting the strain gauges. Then, the above-mentioned cutting procedure was taken, and the relaxation strain was measured as shown in Fig. 2. In this case, the redistributed residual stress can be determined after cutting off some portion of the flange, but it is not possible to determine a residual stress distribution existing in the original shape directly from the measured strains as the conventional stress relaxation method is applied. Even in this case, the inherent strain distribution does not change by cutting. Therefore, the correct residual stress distribution in the original shape can be obtained. This is also one of the merits of this measuring method which uses inherent strain as a parameter

3. Comparison between Numerical Analysis and Experimental Results

Heat conduction and thermal elasto-plastic analyses were performed by means of the finite element method. Temperature distributions during welding were obtained by heat conduction analysis, which were given as thermal loads, and the residual stress was calculated by the thermal elasto-plastic analysis. It was assumed that a welding heat source is simultaneously and instantaneously applied to the both fillet weld positions. A two-dimensional model was used for analysis, assuming that the plane deformation condition in the cross-section could be maintained during welding [7]. The material properties used for the analyses are temperature-dependent and the same as in Ref. 11).

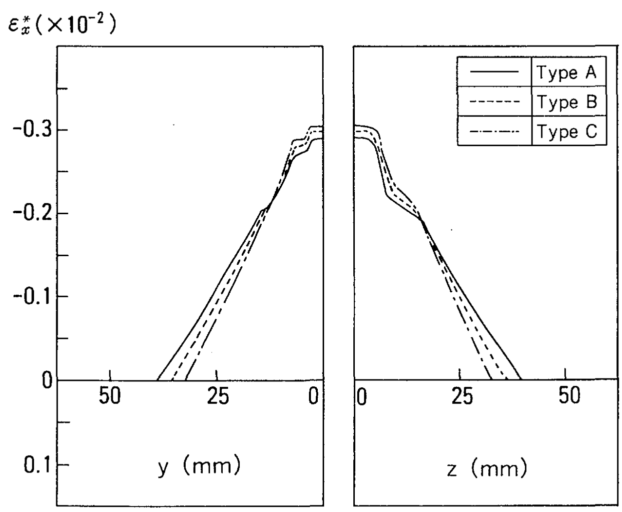
3.1 Inherent strain distribution

Figure 5 shows experimental inherent strain distributions in the T-joints that were estimated from the measured strains, and **Fig. 6** shows the inherent strain distributions estimated from the residual stresses calculated by thermal elasto-plastic analysis. Since the strain at the weld center ($y = 0$ and $z = 0$) could hardly be measured a value of yield stress, $\sigma_{YW} = 480$ (MPa) was adopted instead of the measured strain at the weld center. It can be seen from Figs. 5 and 6 that the analytical and experimental values agree fairly well with each other in both the magnitude and the width of distribution zone of the inherent strain for the three test pieces used in this study.



(a) Flange (b) Web

Fig. 5 Inherent strain distribution obtained by measurement.



(a) Flange (b) Web

Fig. 6 Inherent strain distribution obtained by thermal elasto-plastic analysis.

The more the geometrical ratio $B_W / 2B_F$ increases, the longer the distance between the weld center and the neutral axis of the transverse cross-section is, since the three test pieces used have the same sectional area. Accordingly, the bending moment resulting from a sudden temperature gradient caused by heat input becomes greater, and the rotational deformation of the cross-section easily takes place. The internal restraints which dominates transient strain and stress are then reduced. Therefore, it is considered that the width of distribution zone of inherent strain becomes smaller.

On the other hand, the inherent strains at the weld part are formed in cooling process when the temperature falls down to and below the mechanical melting temperature T_m. Since the temperature gradient is far smaller in cooling process than in heating process, the bending moment in cooling process hardly varies. As a result, it is considered that the magnitude of the distribution zone of inherent strain in the weld part is hardly affected to geometrical ratio $B_W / 2B_F$.

In view of the different distributions in these three test pieces, it can be said that both the analytical and the experimental inherent strains show theoretically reasonable distributions.

3.2 Residual stress distribution

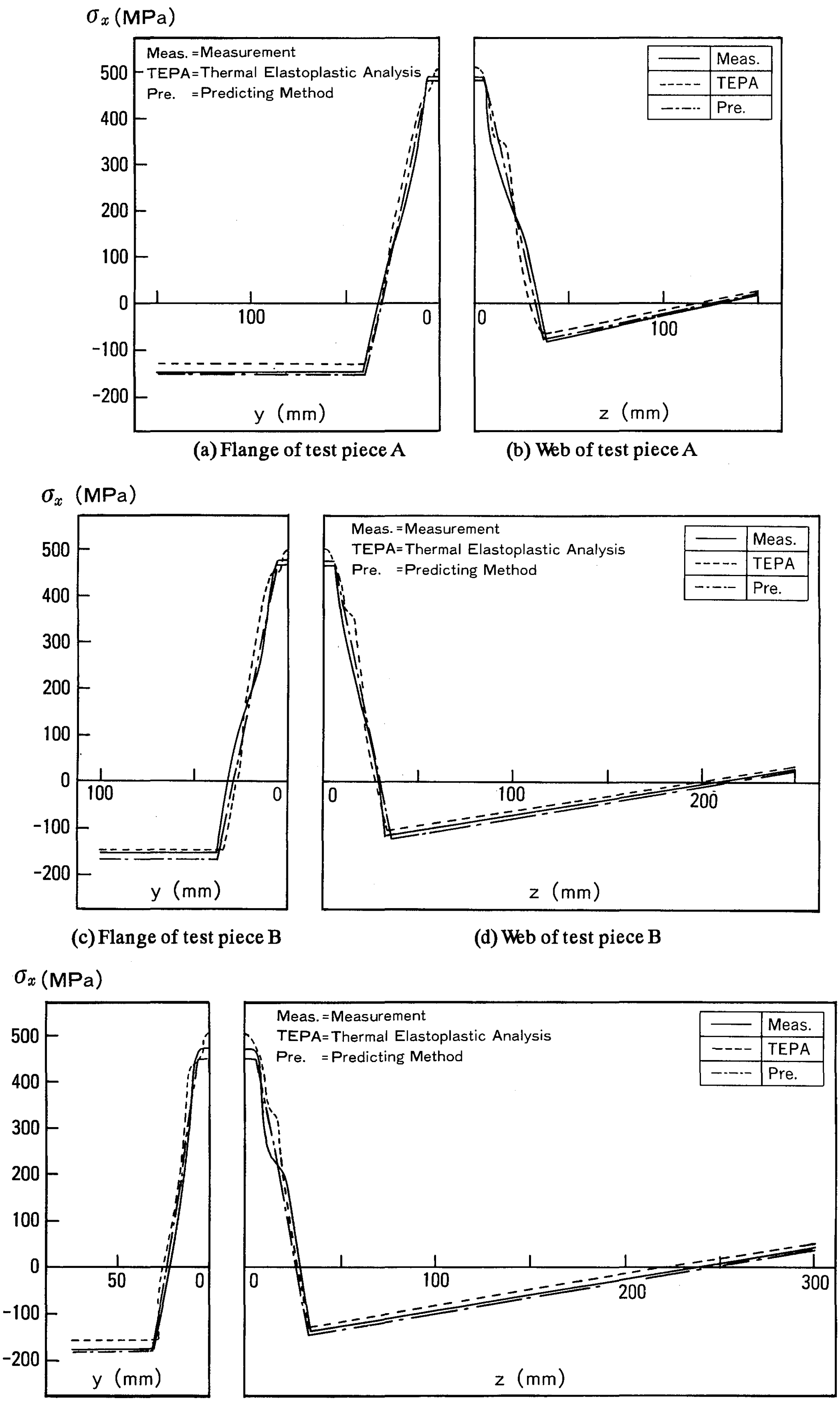
Figure 7 shows the residual stress distributions obtained by the thermal elasto-plastic analysis (TEPA) and the elastic analysis using the experimental inherent strains (Meas.) for the three test pieces. It can be seen that these two agree very well in each test piece.

It was also verified from the results that the inherent strain and the residual stress distributions can be accurately determined even if strain measurement is performed on a different shape of the test piece cut from the original one like test piece A.

4. Experimental Verification of the Proposed Predicting Method

4.1 Adequacy of estimating formulae of inherent strain

The shape of inherent strain distribution in a T-joint indicates that a maximum value is prevailed uniformly in the weld part, and it drops steeply, and finally becomes zero at a certain position when removed from the weld part. This can be approximated as a trapezoidal distribution, as shown in **Fig. 8**. The width b and the magnitude $\hat{\varepsilon}^*_x$ of the distribution zone of inherent strain are expressed by dimensionless parameters ξ and ζ as



(a) Flange of test piece A

(b) Web of test piece A

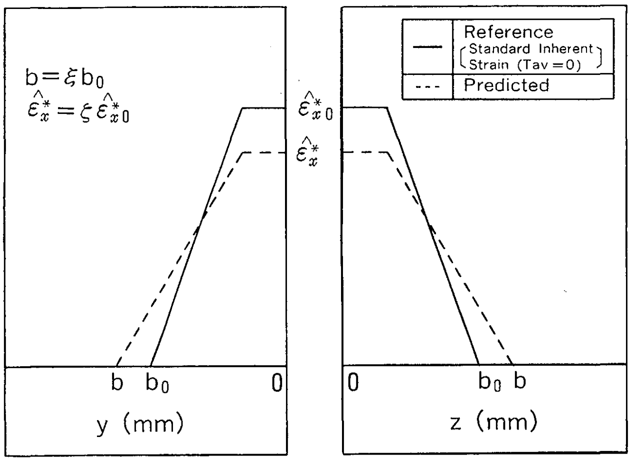
(c) Flange of test piece B

(d) Web of test piece B

(e) Flange of test piece C

(f) Web of test piece C

Fig. 7 Comparison of residual stress distributions obtained by measurement, thermal elasto-plastic analysis and predicting method.



(a) Flange (b) Web

Fig. 8 Prediction of inherent strain distribution

the ratios against the width b_0 and the magnitude $\hat{\varepsilon}^*_{x0}$ of the inherent strain, respectively, which corresponds to a test piece with B_W and B_F of infinite width. An average temperature rise Tav of the test piece with infinite width should be zero. The dimensionless parameters ξ and ζ can be approximately expressed by the following formulae (5) and (6) for the range of Tav = 0 to 250 (℃)[7]. The average temperature rise Tav and the welding eccentricity β are calculated using the mechanical properties of the mild steel adopted in the experiments as follows : the coefficient of linear expansion α = 0.000012 (1 / ℃), Young's modulus E = 210 (GPa), yield stress at the weld metal σ_{YW} = 480 (MPa), yield stress of the base plate σ_{YB} = 330 (MPa) and mechanical melting temperature Tm = 700 (℃).

$$\xi = 1 - 0.27\,\alpha\, E\, Tav\,(1+\beta)/\sigma_{YB} \qquad (5)$$

$$\zeta = -1 - 0.27\,\alpha\, E\, Tav/\sigma_{YB} \qquad (6)$$

where Tav are expressed by $Tav = Q/(\rho\, cA)$ denoting the heat input, specific heat, density and cross-sectional area by Q, c, ρ and A, respectively, and β are expressed by $\beta = -\bar{z}^2 A/I$, denoting the inertia moment of the transverse cross-section and the distance between the weld center and the neutral axis of the cross-section by I and $\bar{z}$, respectively. The welding eccentricity β represents the tendency of rotational deformation of the cross-section which is induced by the existence of distance between the weld part and the neutral axis of the cross-section.

The width b_0 of the distribution zone of inherent strain for a fictitious T-joint with infinite width is expressed by the following formula denoting the thickness of flange and web by h_F and h_W,, respectively.

$$b_0 = (0.484\,\alpha\, E)/\{c\,\rho\,(2h_F + h_W)\,\sigma_{YB}\} \qquad (7)$$

The magnitude $\hat{\varepsilon}^*_{x0}$ of inherent strain at the weld metal corresponding to b_0 is expressed by the following formula without taking the influence of bending moment into account.

$$\hat{\varepsilon}^*_{x0} = \sigma_{YW}/E \qquad (8)$$

For the determination of $\hat{\varepsilon}^*_{x0}$, it is necessary to use such a value of σ_{YW} that the effect of the plastic work-hardening upon σ_{YW} are taken into account which becomes large as the cross-sectional area becomes large. Thus, referring to the values of σ_{YW} in the T-joints dealt with in this study, σ_{YW} = 520 (MPa) at the weld part in a T-joint with the infinite width was used as a value when Tav = 0, instead of the yield stress σ_{YW} = 480 (MPa) as it is.

The width b and the magnitude $\hat{\varepsilon}^*_x$ of inherent strain at the weld metal for a T-joint are then expressed using formulae (5), (6), (7) and (8) as,

$$b = \xi\, b_0 \qquad (9)$$

$$\hat{\varepsilon}^*_x = \zeta\,\hat{\varepsilon}^*_{x0} \qquad (10)$$

The width of the distribution zone and the magnitude of inherent strain in the three test pieces obtained from the estimating formulae are shown in **Table 3**. It is seen

Table 3 Magnitude and width of inherent strain in T-joints.

	Tav	β	by measurement				by F.E.M.		by Eqs. (9), (10)	
			Web		Flange					
			b	$\hat{\varepsilon}_x^*$	b	$\hat{\varepsilon}_x^*$	b	$\hat{\varepsilon}_x^*$	b	$\hat{\varepsilon}_x^*$
Type A	90	0.21	41	0.0029	40	0.0029	39.7	0.00285	39.0	0.00295
Type B	90	0.63	34	0.0030	36	0.0030	34.6	0.00297	35.3	0.00295
Type C	90	0.92	33	0.0031	32	0.0031	31.8	0.00304	32.6	0.00295

that the estimating values agree well with the experimental results. Table 3 also shows the results obtained by the thermal elasto-plastic analysis performed in the previous section. The width and the magnitude of the distribution zone of inherent strain agree well with each other.

4.2 Comparison between the predicted and experimental residual stresses

Figure 7 shows the predicted value (Pre.) of residual stresses by elastic analysis using the inherent strain distribution estimated by the above simplified estimating formulae, and the experimental measured value (Meas.) for each test piece. They agree very well, as can be seen. And the effect of the longitudinal bending deformation in the T-joints is also confirmed. It was experimentally verified that the welding residual stress in a T-joint can be accurately predicted by using the simplified estimating formulae of inherent strain.

5. Conclusions

The adequacy and applicability of the method to predict the welding residual stress in a T-joint using the inherent strain were experimentally verified, and the following conclusions were achieved.

(1) The welding residual stress in a T-joint was measured using strain gauges. It was found that the measured results are affected by the order and direction of cutting the test piece. As a countermeasure against this effect, the cutting may be performed while a well-balanced stress is maintained along the cutting line.

(2) The inherent strain and the residual stress distributions which were experimentally obtained from the measured strains agreed well with the results of numerical analysis using a thermal elasto-plastic analysis for the same welding conditions.

(3) It was verified that the welding residual stress in a T-joint can be accurately predicted by using the proposed estimating formulae of inherent strain.

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