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Application of FEM to Theoretical analysis, Measurement and Prediction of Welding Residual Stresses†

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Abstract

For prediction of welding residual stress, the authors have developed the following three methods using the finite element method: (1)Thermal elasto-plastic analysis, (2)Experimental methoed for measurement of three dimensional residual stress using inherent strain (the source of residual stress) as parameter,and(3)Prediction method by elastic analysis using inherent strain which is stored in a data-base. These methods are outlined. Additionally, being paid attention to weld related cracking, a simple model is also presented for prediction of local welding residual stress induced by the last few layers of multi-pass welds. This model is effective for both theoretical analysis and experiments.

Welding residual stresses analysed and measured are shown, which are produced in various types of welded joints of thick plates and pipes. These are very useful to estimate welding residual stresses considering the relation to the degree of restraining condition.

KEY WORDS: (Welding Residual Stress) (Theoretical Analysis) (Source of Residual Stress) (Inherent Strain) (Measurement) (Prediction) (Thick Plate) (Pipe)

Introduction

Welding residual stress distribution through the thickness is regarded as uniform in thin plates and also thick plates with one pass-weld, and complex in thick plates especially when multi-pass welds are applied. In discussing the distributions, it should be classified into the above two categories. In the case of thin plates, its longitudinal component is most important in relation to buckling and many types of fracture. In contrast with this, welding residual stress in thick plates, the transverse component is also important in respect to various weld related cracking and fractures such as cold and hot ones, stress corrosion, fatigue and brittle fractures.

Here, attention will be paid to thick welded plates which are used in most offshore structures.

Prediction methods of welding residual stress may be classified into the following three: (1) Measurement on similar welded joints, (2) simple formulae derived based on accumulated experimental data, and (3) theoretical analysis.

Concerning (1), several methods have been proposed for measurement of three dimensional residual stress. The Sacks method [1] is accurate in very limited conditions, and the Rosenthal method [2] is based on an irrational approximation which reduces the accuracy of the result. The authors have developed the general theory of measurement of three-dimensional residual stresses and the basic procedures using the source of residual stress (inherent strain) as parameter based on the finite element method.[3–5]

As for (2) there are many formulae for prediction of welding residual stress, most of which are for uniform distributions through thickness. The distributions in thick plates seems complicated to be predicted by simple methods and it had been difficult even to measure three dimensional residual stress. So far prediction is mostly dependent upon information obtained from thermal elasto-plastic analyses and experiments. For residual stress in the last few layers of multi-pass welds where various types of cracks at the toe and under bead due to welding and post-weld heat treatment may occur, a very effective model [6] for thermal elasto-plastic analysis and experiments was proposed. For residual stress distributions uniform through thickness, the authors have recently developed a prediction method [7–9] using inherent strain as parameter. This is very accurate and versatile to take account of the construction sequence of build-up plate

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structures.

Concerning theoretical analysis, thermal elasto-plastic analysis by the finite element method [10-12] is the most powerful. This is a numerical simulation on which requires rational modeling of the phenomena. Although good modeling has been made for multi-pass welds [13-15], moving heat source [10] etc., more rational and accurate modeling on metal behavior under various thermal and strain histories should be developed. For large size problems, enormous computation time is also a problem to be solved.

The authors intend to present the results of their research on welding residual stress. Firstly, the basic theories and procedures of the thermal elasto-plastic analysis, measurement and prediction of welding residual stress will be outlined. Secondly, the characteristics of welding residual stress distributions due to multi-pass welds will be represented through several examples which were analysed and measured.

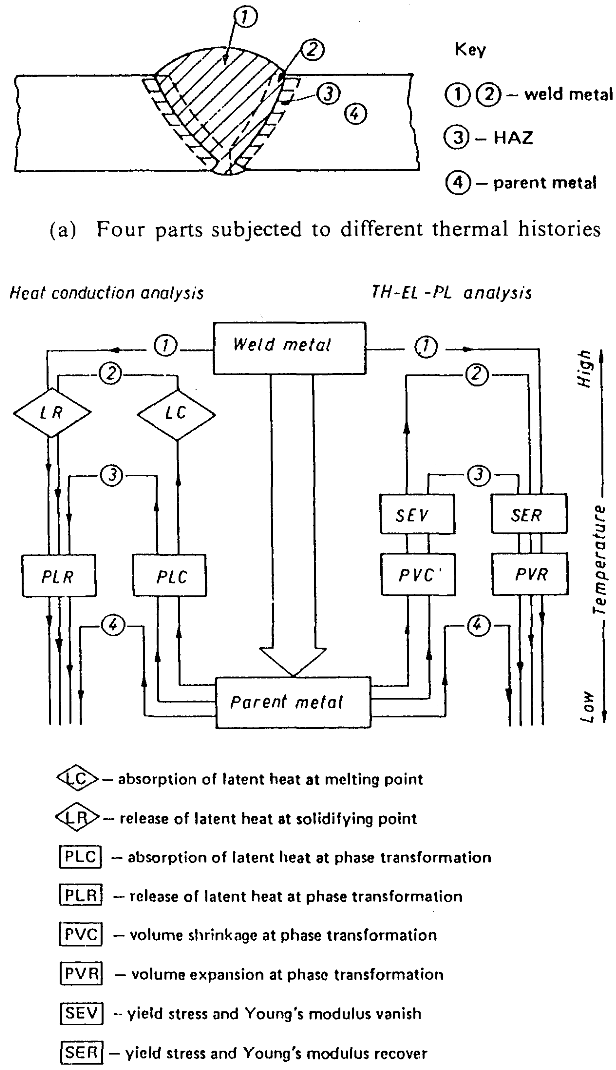
finally, an effective model [6] to estimate welding residual stress in the last few passes of multi-pass welds and a prediction method [7–9] for welded built-up plate structures will be presented.

Mechanical Behavior of Welding and Characteristics of the Source of Residual Stress (Inherent Strain)

The phenomenon of welding starts at the instant of providing a concentrated heat source which, in most welds, can be regarded as the weld metal. Heat transfer in the welded joint produces a changing temperature distribution which induces thermal stresses. An important point in the mechanical behavior is that there can be marked changes in the instantaneous mechanical properties as well as the physical properties. During this stage, the coupling of temperature and stress fields shoud occur, but its effect on residual stress is minor. If the coupling is disregarded, the temperature field is indifferent to the stress field.

In a one-pass weld, the welded joint can be divided into four parts: weld metal (deposit), weld metal (base), heat-affected zone, and parent metal, as indicated in **Fig. 1(a)**. Each part is subjected to an individual thermal history and the related changes of the physical properties and the mechanical properties of the materials **(Fig. 1(b))** [16].

In multi-pass welds the new weld metal fuses a small region surrounding it and relieves the residual stresses which were already produced. After redistribution of the residual stresses the characteristics of the succeeding phenomena are considered the same as in a one-pass weld, although some part of the joint may be subjected to loading and unloading in the plastic range. As the magnitude of strain reversal is usually not large, the Bauschinger effect



(a) Four parts subjected to different thermal histories

(b) Thermal histories and related changes of physical and mechanical properties

Fig. 1 Characteristics of welded joint

is very small.

During welding, the thermal stress may produce plastic strain. After the welded joint is cooled down, the thermal stress results in residual stress. Main components of the source of residual stress are plastic strain and shrinkage strain of the material including the weld metal and base metal, which is produced after the weld metal starts to exhibit resistance against deformation at the cooling stage. The sum of these strains is the source of residual stress which is called here as inherent strain [3–5]. Therefore, residual stress in a welded joint should be predicted if the associate inherent strain is known [7–9].

The distribution of inherent strain does not change unless new plastic strain and/or thermal strain are imposed. Therefore, under the above mentioned conditions, the distribution would not change even the welded joint is cut into small pieces [3–5].

Basic Theory of Thermal Elasto-Plastic Analysis and Measurement and Prediction Using Inherent Strain as Parameter

If the coupling between temperature and stress fields of a welded plate is desregarded, analyses on temperature and stress fields are independent. Welding thermal stress analysis is composed of these two analyses. In both analyses the basic equations are derived in the incremental forms on the assumption that any changes during a small increment of time are linear. Then the accumulation of the solution to the basic equations for each step furnishes the entire histories of temperature, stress, and strain. As details of the derivation of the basic equations are in the original papers listed, [10–12] the main effort here will be devoted to a description of the idealization and treatment of the problems and fundamental assumptions and important equations of the theories.

Heat conduction analysis

Two types of approach (the finite element method and finite difference method) are powerful in the analysis of unstationary and nonlinear heat conduction in an object of arbitrary geometrical configuration. It is required to solve a set of simultaneous equations in the finite element method, but a successive manner in the finite difference method. The condition of stability of the solution is formulated in the latter, but not in the former. The finite difference method is therefore advantageous in its application.

As the analysis is perfomed by the incremental method the temperature-dependency of the physical properties can easily be taken into account. Attention has to be paid to the treatment of the latent heat at phase transformation. There are two methods to deal with the latent heat: one is to regard it as an internal heat source (positive or negative) and the other is a sudden change in the heat capacity. In most situations, however, the effect of the latent heat is very small on the final residual stresses.

Thermal elastic-plastic analysis [10,11]

The basic assumptions for the derivation of the basic equation are:

1 The material used is orthotropic (including isotropic)
2 Yielding of the material is determined by Mises' Yield condition
3 The behavior in the plastic range is described according to the incremental strain theory of plasticity
4 Temperature-dependent mechanical properties, stresses and strains change linearly during a small time increment

In dealing with nonlinearity of material it is most important to define the stress and strain relationship for the derivation of the fundamental equations.

For a small increment of time, dt, the relationship between stress increment $\{d\sigma\}$ and strain increment $\{d\varepsilon\}$ is represented in the following general form, taking account of the effects of temperature upon the elastic and plastic behavior

$$\{d\sigma\} = [D]\{d\varepsilon\} - \{d\tau_0\} \tag{1}$$

The explicit forms of the terms $[D]$ and $\{d\tau_0\}$ in the above differ according to the condition of stress, that is, in the elastic or plastic range.

Denoting the stiffness matrix of an element by $[K]^e$, the relationship between the increment of the nodal force $\{dF\}^e$ and that of the nodal displacement $\{dW\}^e$ is written as

$$\{dF\}^e = [K]^e\{dW\}^e - \{dL\}^e \tag{2}$$

Where $[K]^e$ is the integral of the term including $[D]$ in eqn(1) and the equivalent nodal force $\{dL\}^e$ is that including $\{d\tau_0\}^e$ of the same eauation. In usual welding the external forces are not applied and the equilibrium equation on the whole object is expressed by

$$\Sigma\{dL\}^e = \Sigma[K]^e\{dW\}^e \tag{3}$$

This is the fundamental equation.

Methods of measurement of residual stresses [3–5]

As stated before, welding residual stress is produced by the source of residual stress, that is (effective) inherent strain. With the aid of the finite element method the relationship between the inherent strain $\{\varepsilon^*_j\}$ and the resulting elastic strain $\{\varepsilon_i\}$ at an arbitrary point in the object can be easily formulated as follows

$$\{\varepsilon_i\} = [H^*_{ij}]\{\varepsilon^*_j\} \quad (i=1\cdot\cdot n,\ j=1\cdot\cdot q) \tag{4}$$

where n is the total number of components of the elastic strains
q is the total number of components of the inherent strains
H^*_{ij} is the ith component of the elastic response strains subject to the jth component of the inherent strains being unit

If m number of measured strains $\{_m\varepsilon_i\}$ are obtained, eqn(4) becomes

$$\{_m\varepsilon_i\} = [H^*_{ij}]\{\varepsilon^*_j\} \quad (i=1\cdot\cdot m,\ j=1\cdot\cdot q) \tag{5}$$

When $m=q$ the inherent strain $\{\varepsilon^*_j\}$ is determined as the solution of the simultaneous eqn(5) and with these strains the stresses induced by them, that is the residual stresses, are evaluated from eqn(4).

As stated in the preceding chapter, the distribution of inherent strains does not change eve if the welded joint is cut into small pieces. Once the inherent strains in each small piece are determined from the change of elastic strain (residual stress), the sum of these provides the entire distribution of inherent strain. This characteristic enables us to measure three dimensional residual stresses. The theory was extended to take account of measuring error with the aid of the theory of statistics.

Prediction of welding residual stress [7–9]

In the case of butt welded joints of the same thickness which are furnished under the same welding condition, the resulting longitudinal residual stress distributions are different due to changes of the width and length, but it was found that the (effective) longitudinal inherent strain distributions are almost same each other and their patterns are as simple as trapezoidal. Being left detail description about the distribution to the latter chapter, welding residual stress distribution can be predicted by an elastic analysis imposing this simple distribution of effective inherent strain to a stress-free plate of any size. The basic equation is the same as eqn(4) and the welding residual stress at any point in the plate can be obtained. It should be reminded that inherent strain distribution can be determined by the theory which has been described in the preceding section.

Analysed and Measured Welding Residual Stresses in Joints of Thick Plates

Longitudinal and circumferential multi-pass butt welded joints in a penstock (Material: HT80. Plate thickness: 50mm) [17]

Using a large size penstock model, three-dimensional residual stresses produced in a tubular shell plate by (1) cold bending, (2) welding of a longitudinal joint, and (3) welding of a circumferential joint were measured respectively. The penstock model and the location of each specimen for measurement are shown in **Fig. 2**. Submerged arc welding was applied first to the inner side and then to the outer side of the X-grooves.

Distributions of three-dimensional residual stresses produced in the shell plate by cold bending are shown in **Fig. 3**. It is considered that they have the typical characteristics of residual stress distributions by this type of cold bending.

Distributions of welding residual stresses in a circumferential joint are shown in **Fig. 4**. Comparing them with the distributions induced under restraining conditions A and B of the standard specimen to be described in next chapter, it is estimated that angular distortion occurs to some extent and longitudinal bending deformation little.

Multi-pass butt welded joint of thin and thick pipes (Material: SUS304, Plate thickness: 5.5, 8.6, and 30.9 mm) [18–20]

Residual stresses produced in SUS304 steel pipes by circumferential multi-pass butt welding (V-groove) were theoretically analysed. The sizes of the supplied pipes are 2B pipe (5.5 mm thickness), 4B pipe (8.6 mm), and 24B pipe (30.9 mm), and the sequence of welding is shown in **Fig. 5**. From the third layer, the heat-sink welding by which the inner surface of the weld zone is cooled by strong water-spraying during welding was applied, in addition to the conventional welding by which a joint is naturally cooled. This heat-sink welding aims to produce compressive residual stresses on the inner surface of the weld zone to prevent stress corrosion cracking.

Analysed residual stress distributions are shown in **Fig. 6**. for 4B pipes (heat-input is increased to Q-14, Q-23, Q-45). If the heat-sink welding is used, the inner surface is

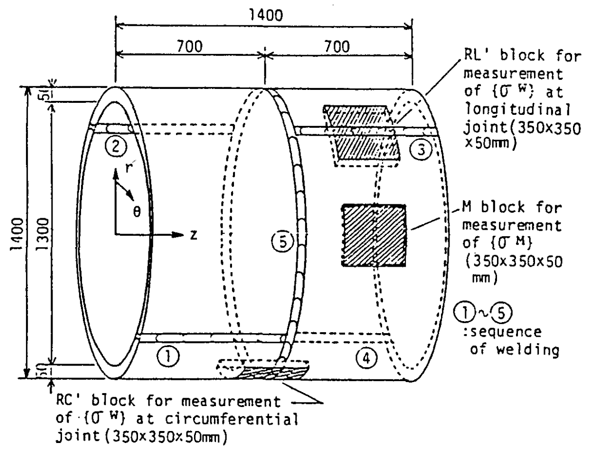


Fig. 2 Model of penstock and locations of specimens for measurement of residual stresses

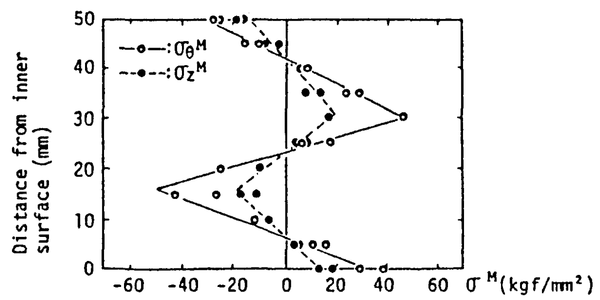
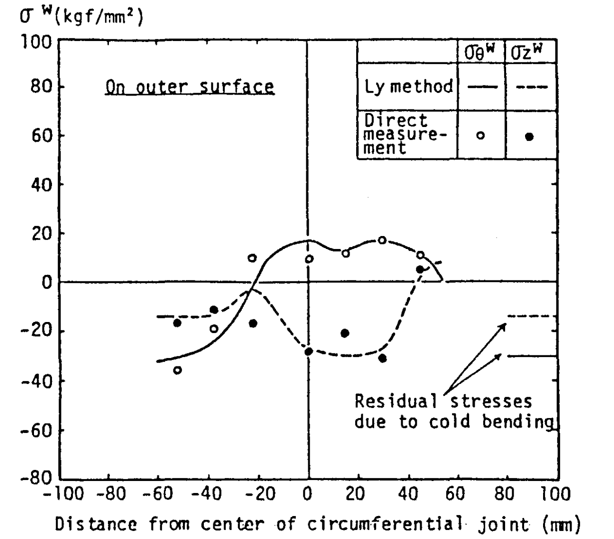
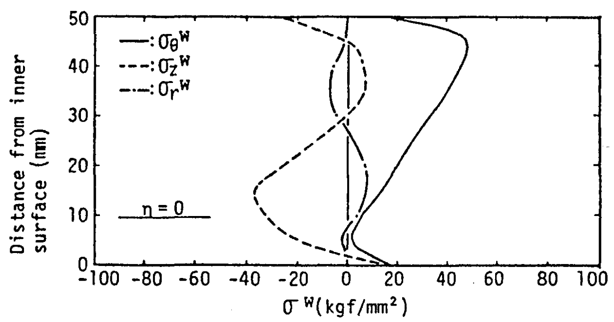


Fig. 3 Measured residual stresses due to cold bending in shell plate



(a) On outer surface



(b) At cross section

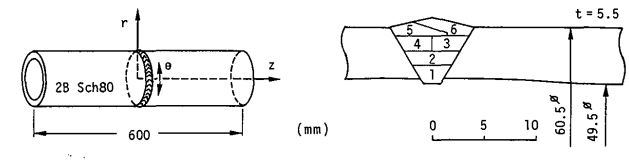
Fig. 4 Measured welding residual stresses of circumferential joint

compulsorily cooled, so that a great temperature difference occurs in the plate thickness direction like the case of thick plates. Therefore, even in the case of thin plates such as 2B pipe and 4B pipe, residual stresses distribute similarly to those in the standard specimen (butt-joint of thick plates) under restraining condition B in the next chapter, and compressive stresses remain on the inner suface of the weld zone.

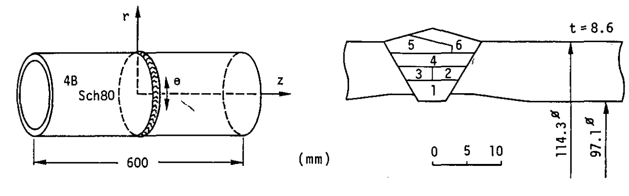
Multi-pass corner welded joint of thick plane plates (Material: SM50, Plate thickness: 40 mm) [21–23]

In order to investigate and prevent lamellar tearing and root cracking of a multi-pass corner joint from a dynamical view point, welding residual stresses produced in such a joint have been analysed under various conditions. CJC(*C*orner *J*oint Weld *C*racking) test model [21] shown in **Fig. 7** was used for the analysis of a corner joint.

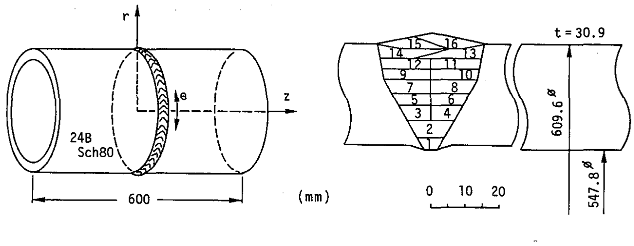
Changing the external restraint, theoretical analyses were performed for the cases when bending restraint intensity is



(a) 2-inch pipe



(b) 4-inch pipe



(c) 24-inch pipe

Fig. 5 Dimensions and built-up sequences of pipes used in analysis

large ($K_B = 10^6$ Kgf mm/mm rad) and the least ($K_B = 0$). Furthermore, with the purpose to prevent initiation of lamellar tearing by decreasing tensile stresses on the top surface of the vertical plate even when bending restraint is large, residual stresses were analysed on four types of groove (**Fig. 8**). Residual stress distributions near the top surface of the vertical plate are shown in **Fig. 9**. Tensile residual stresses of types P and C are smaller than those of type M.

Circumferential multi-pass fillet weld tubular joints to thick plates (Material: 2 1/4 Cr-1Mo, Plate thickness; 15 mm for pipe, 50 mm for base plate) [24]

In order to reproduce welding residual stresses at the joint of a nozzle to the heavy shell of a pressure vessel, a simple model was used for theoretical analysis as represented in **Fig 10**. The nozzle is a set-in type and connected by 5 layers/8 passes welded. Thermal elasto-plastic analysis was perfomed to obtain information on welding residual stress at the toe to clarify the relation to cracking due to weld and post-weld heat treatment. Welding residual stress distributions through thickness at the toe of the finishing pass are represented in **Fig. 11**. The circumferential and radial components are very large at the toe. After post-weld heat treatment (the holding temperature and time are 600°C

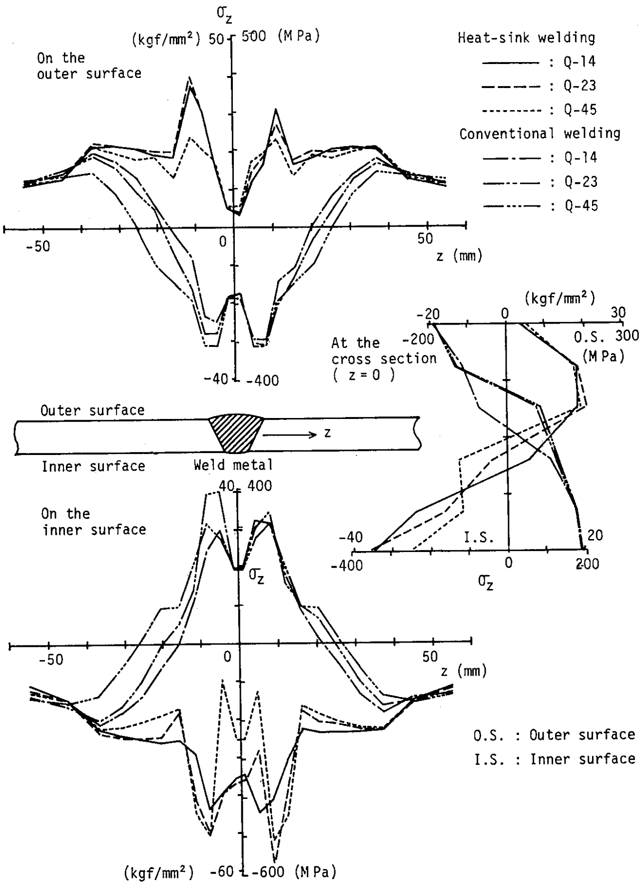


Fig. 6 Calculated axial welding residual stress of 4-inch pipes at the middle cross-section

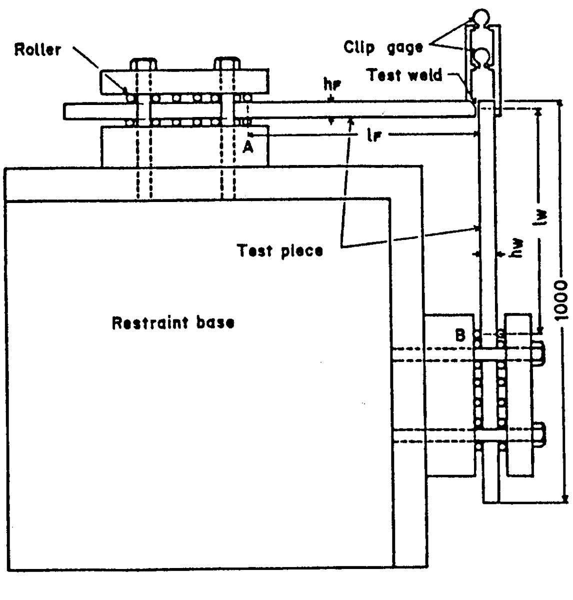


Fig. 7 Corner joint weld cracking test (CJC-test) apparatus

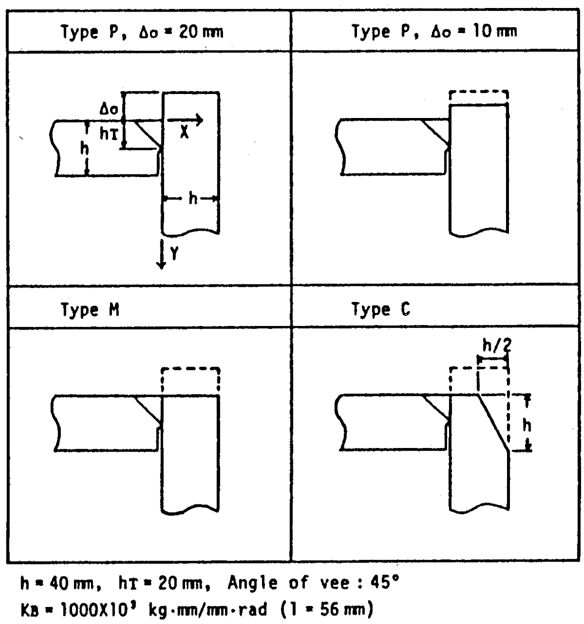


Fig. 8 Shapes of grooves of corner joints

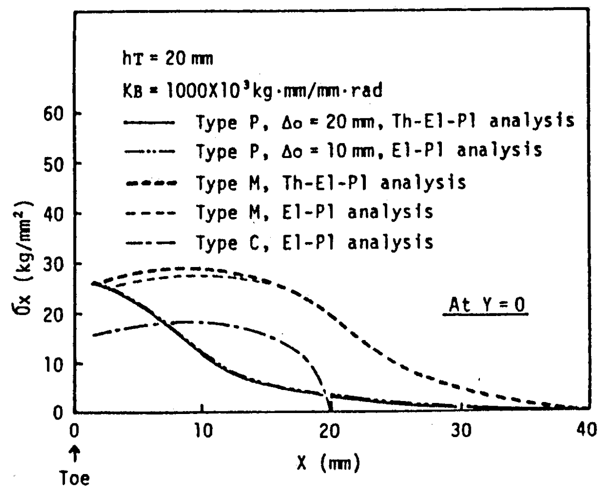


Fig. 9 Calculated transverse welding residual stresses of corner joints of four different types (on top surface)

and 9 hours), every component of the welding residual stress is reduced greatly and a great amount of creep strain is also produced.

A Simple Model for Multi-Pass Butt Welded Joints of Thick Plates [6]

It is a well-known fact that cold cracks in multi-pass butt welds of thick plates are produced mainly at the weld metal and HAZ of the last few beads where large tensile residual stresses including the maximum are induced. A simple model for estimation of the above mentioned residual stress was developed in order to save the time and labor [6]. This

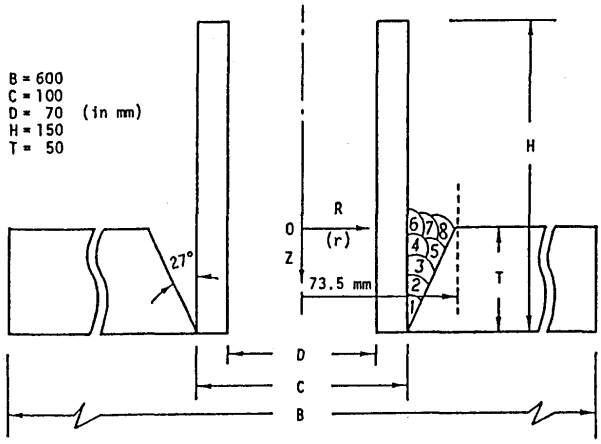


Fig. 10 Analysis model of welded joint of a nozzle to thick plate

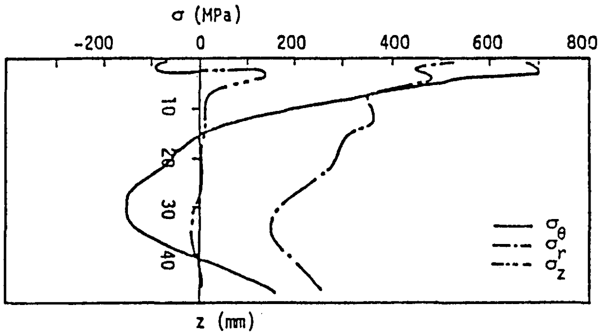
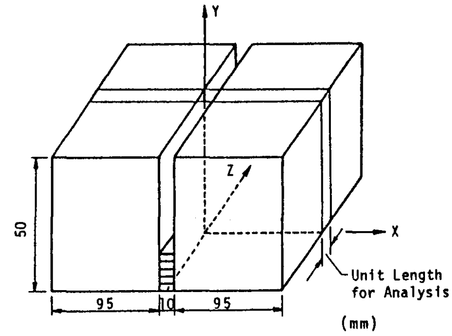
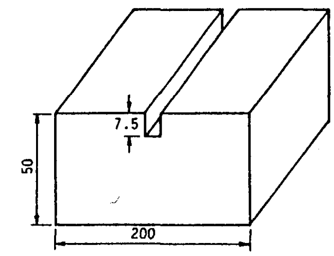


Fig. 11 Welding residual stress distributions through thickness (at the toe, r = 73.5 mm)



(a) Standard specimen



(b) Simple model

Fig. 12 Specimen and model for analysis

model can be used for both theoretical analysis and experiments.

From the previous studies [13, 14] on residual stresses due to multi-pass butt welding, it was found that the residual stresses near the finishing bead are induced mainly by the last few welding passes. Using the proposed model as shown in **Fig. 12(b)**, the finite element analysis was performed to find that almost same stress distributions as in the original joint were obtained in the weld metal and HAZ of the last few beads. In the following, effectiveness of the model will be demonstrated with the aid of numerical ananlysis and the result will also display the characteristic of residual stress distribution of multi-pass welds.

Standard specimen and its simple model

Two long plates (SM50 steel) of 50 mm thickness are joined by multi-pass (20-pass and 20-layer) welding for 10 mm gap using narrow gap arc welding. This welded joint is called "standard specimen" and shown in **Fig. 12(a)**. The "simple model" has the same dimensions as the standard specimen but the groove is processed only near the top surface where 3 passes of weld metal is laied as shown in Fig. 12 (b).

As the restraining condition of the specimen (model), two extreme conditions A and B are adopted. In restraining condition A, no external restraint is imposed on the specimen. In restraining condition B, longitudinal bending deformation and angular distortion are completely restricted.

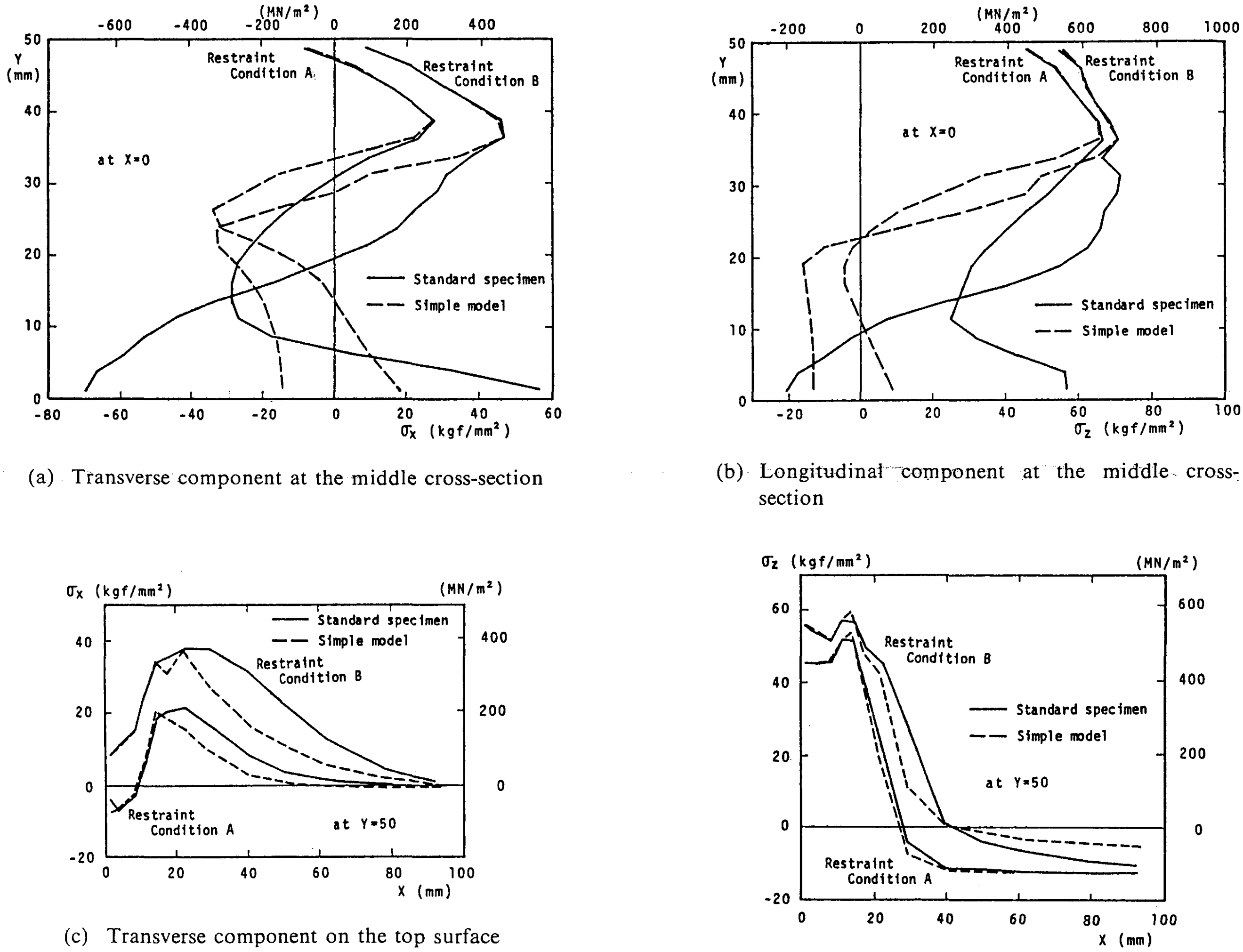
Results of thermal elasto-plastic analysis

Figure 13 shows residual stresses produced in the standard specimen and the simple model. In the standard specimen, the residual stresses near the bottom surface are very different, depending on the restraining condition. For both restraining conditions, welding residual stresses near the last few beads in the simple model show the almost same distributions as the standard specimen, especially, the magnitudes and locations of the maximum tensile stresses of σ_X and σ_Z.

This fact confirms that the welding residual stresses near the last few beads of multi-pass welds can be reproduced only by the last few welding passes not only in the analysis but also in experiments. The simple model enables us to save CPU time in the analysis and labor both in the analysis and the experiment to a great extent.

Prediction of Welding Residual Stresses Distributing Uniformly Through Thickness [7–9]

As described in the second chapter, residual stress is



(a) Transverse component at the middle cross-section

(b) Longitudinal component at the middle cross-section

(c) Transverse component on the top surface

(d) Longitudinal component on the top surface

Fig. 13 Welding residual stress distributions in standard specimen and simple model under restraining conditions A and B

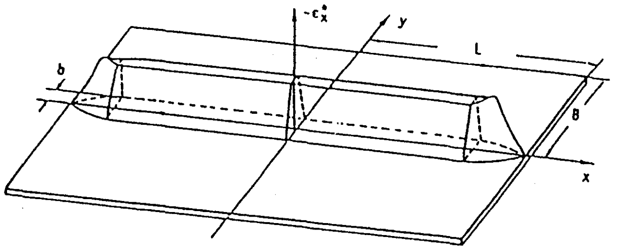
created by so-called inherent strain which exists in a narrow width along the weld line. It is obviously easy to obtain the residual stress through the elastic analysis using inherent strain as an equivalent load if it is known to the specified material and welding conditions. According to the recent research [7–9], it is found that inherent strain can be predicted easily for several types of joints prepared under the given conditions, and so the residual stress can be predicted easily only by the elastic calculation.

Characteristics of inherent strain distributions

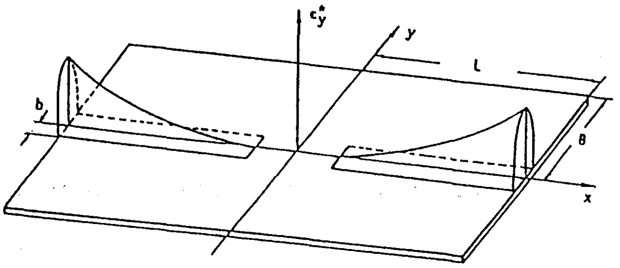
The method will be illustrated through numerical simulation applied to single butt-welded plates with the aid of FEM. The welding is assumed to be carried out on 6 (mm) thick plates by a moving heat-input of 1200 (J/mm) with a speed of 3 (mm/sec). The heat-input efficiency is supposed to be 75% and the effective heat-input is then 900 (J/mm) which is to be used in theoretical calculation later.

A distribution of inherent strain is shown in **Fig. 14** which was calculated from the distribution of residual stress (elastic strain) obtained by the thermal elasto-plastic analysis instead of measured one. The component in the weld direction, that is ε_x^*, is a result of compressive plastic defomation in the heating process and has a tendency to make the plate shrink. While the component perpendicular to the weld line, that is ε_y^* which exists only in the portion near the two ends of the plate, is a result of free edges of the plate and has a tendency to make the plate bend.

The influence of width and length of plates on inherent strain distribution is shown in **Fig. 15**. It is found that ε_x^* has a simple distribution in transverse cross-sections regardless the width of plates. As the width of plate becomes wider, the magnitude of ε_x^* becomes larger and the width of ε_x^* - distribution becomes smaller. If the width

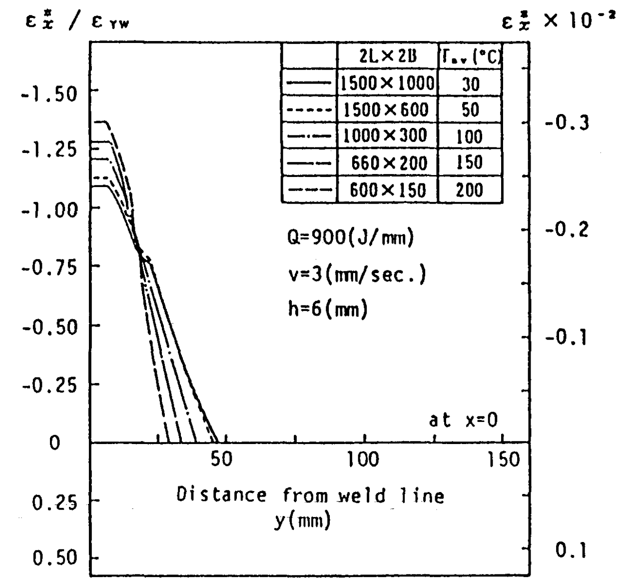


(a) Longitudinal inherent strain ε_x^*

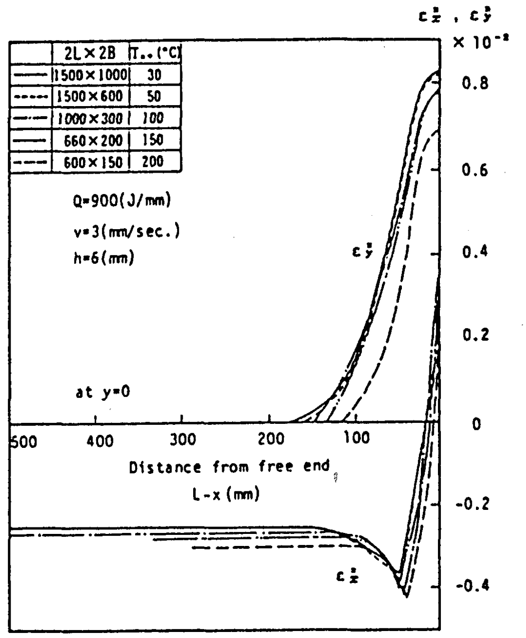


(b) Transverse inherent strain ε_y^*

Fig. 14 Schematic representation of inherent strain



(a) Longitudinal component at the middle cross-section



(b) Transverse and longitudinal components near the end of plate

Fig. 15 Inherent strain distributions for different sizes of plates

of plate is sufficiently wide, however, to the specified heat-input, that is $T_{av} < 50$(°C) where $T_{av} = Q/(2c\rho\, hB)$, the distribution of inherent strain is almost unchanged. While ε_y^* is nearly the same even in plates of different width unless it is too small.

Prediction method: Elastic analysis of residual stress

With the above discussion, it is not difficult to anticipate that if the relation between the magnitude and width of the inherent strain distribution as shown in Fig. 15 (a) and the welding conditions, type of joint and material properties are specified, it is possible to predict the entire distribution of inherent strain of the plate from some standard inherent strain distribution which has been known from experiments or literatures, by adjusting it be the specified condition.

Assuming that heat-input is supplied instantaneously along the entire weld line of the joint which is long enough so that the influence of stress-free bounaries appears only near the two ends of the weld line, it is found that the magnitude and width of distribution of inherent strain ε_x^* can be represented by the following equations.

$$b = \xi b_o \tag{6}$$

$$\xi = 1/\left\{ 1 + \frac{aET_{av}}{2.0664\sigma_{YB}} \left(\ln \frac{\sigma_{YB}}{\xi aE(T_m - T_o)} - 4.1327\phi\left(\frac{\sigma_{YB}}{\xi aE(T_m - T_o)}\right) - \frac{\sigma_{YW} + \sigma_{YB}}{aE(T_m - T_o)} + 3.0664 \right) \right\} \tag{7}$$

$$b_o = 0.242 \frac{aEQ}{c\rho h\sigma_{YB}} \tag{8}$$

and

$$\hat{\varepsilon}_x^* = -\varsigma\, \hat{\varepsilon}_{xo}^* \tag{9}$$

$$\varsigma = 1/\left\{ 1 - \frac{aET_{av}}{4.1327\sigma_{YB}} \left(\xi + \frac{\sigma_{YB}}{aE(T_m - T_o)} \right) \right\} \tag{10}$$

$$\hat{\varepsilon}^*_{xo} = \sigma_{YW}/E \qquad (11)$$

Here, b = width of inherent strain distribution
$\hat{\varepsilon}^*_x$ = Magnitude of inherent strain
C = Specific heat
ρ = density
α = Linear expansion coeff.
E = Young's modulus
T_m = Mechanical melting temperature
T_0 = Room Temperature
σ_{YW} = Yield stress of weld metal
σ_{YB} = Yield stress of base metal

When the width of butt-welded plate is extremely large to a specified heat-input, that is $T_{av} \fallingdotseq 0$, the width and magnitude can be described by eqns (8) and (11) respectively.

Then, residual stress in a butt-welded plate can be estimated as follows. As a standard inherent strain, the inherent strain shown in Fig. 15 by short dashed line (T_{av}=50(°C)) is considered here.

Step 1: Calculate normalized width and magnitude of the inherent strain distribution, ξ and ζ, for the object by eqns (7) and (10);

Step 2: Adjust the standard inherent strain distribution so that the widths of ε^*_x and ε^*_y become ξ times while the magnitude of ε^*_x becomes ζ times;

Step 3: Perform an elastic analysis using redistributed standard inherent strain to obtain residual stresses.

Residual stresses in different butt-welded plates estimated by this method are represented in **Fig. 16** using several marks. By thermal elasto-plastic analysis, residual stresses in the respective plates are calculated and are also shown in Fig. 16 using different types of lines. It is observed that the residual stresses can be pridicted accurately by the proposed elastic analysis method for different sizes of plates. This method is successfully applied also to joints of T and I types [9].

Concluding Remarks

In this paper, the authors presented three different types of prediction methods; thermal elasto-plastic analysis, measuring method and estimating method for welding residual stresses, based on their research. The last two method is to utilize inherent strain (the source of residual stress) as parameter. This idea is quite new and enables us possible to measure three dimensional residual stress and estimate it at any point in welded plate elements by only elastic analysis, respectively. In order to apply them to individual types of welded joints, further effort is needed.

As for thermal elasto-plastic analysis, modeling of complex metal behavior shoud be developed especially at phase transformation and higher temperature, even the basic theory has been developed well based on the classical theories of elasticity and plasticity.

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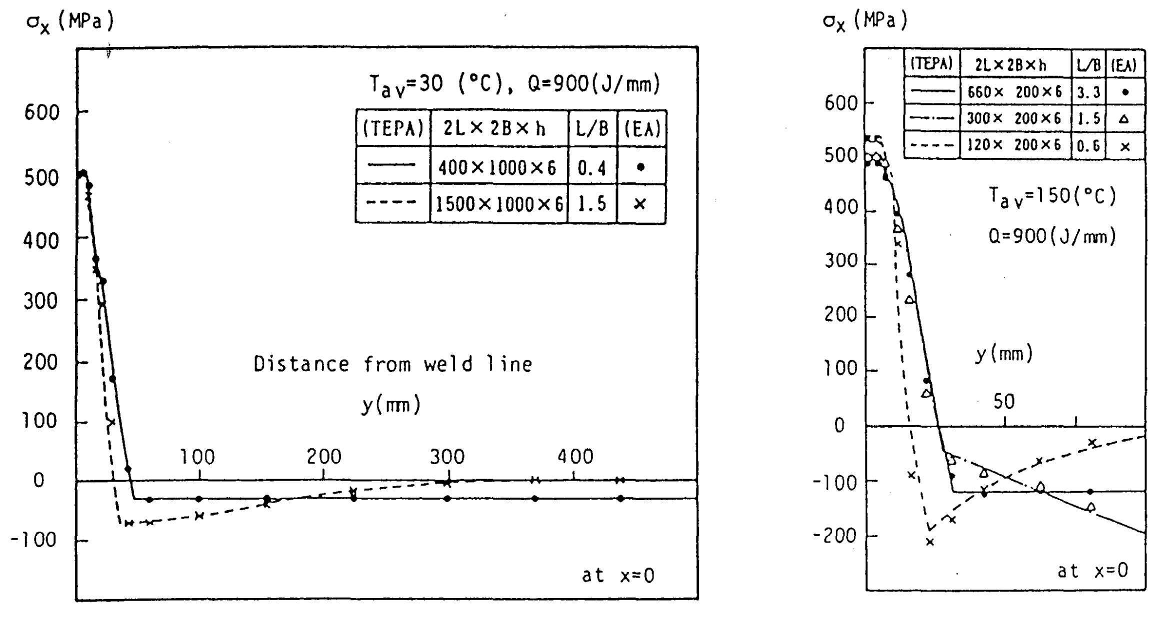

Fig. 16 Comparison of residual stresses obtained by thermal elasto-plastic analysis (TEPA) with that by elastic analysis (EA) using inherent strain

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