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

— Determination of Standard Inherent Strain —

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Abstract

This paper proposes a method to determine the sizes of the standard model which is used in the proposed predicting method of welding residual stress, since the model is necessary for estimating the inherent strain (the source of the residual stress) produced in a joint. In this paper, the method is applied to a butt-welded joint.

Based on the distributions of inherent strain in a butt-welded joint that had been obtained before, it is also shown how to modity them in accordance to the changes of heat input and the kind of steel including the effect of phase transformation.

KEY WORDS: (Welding Residual Stress) (Inherent Strain) (Source of Residual Stress) (Butt-welded Joint) (Standard Model) (Transient Stress)

1. Introduction

In the previous report[1)], the new predicting method of welding residual stress was proposed and its validity was demonstrated by the numerical experiment using the finite element method.

For the application of the method, the inherent strain (the source of residual stress) should be obtained in advance. The distribution and magnitude of inherent strain change according to the size of a joint in strict sense, but they approach rapidly to the limiting ones as the sizes of plate become larger from a certain size to the infinite one. In actual welded joints, it is impossible to obtain the inherent strain produced in the infinite plate, but a certain size of plate may be equivalent to the infinite one. Here, this size of plate is called the standard model. In the following, the sizes of the standard model will be determined from the theoretical point of view.
It will be also studied how to modify them according to the changes of heat input and the kind of steel.

2. Determination of the Size of Standard Model

In this chapter, firstly, the necessary minimum width of the standard model, $2B_0$ is determined by considering the effect of the plate width $2B_0$ upon the width of plastic zone, 2b, (in the region of inherent strain). Secondly, the necessary minimum length of the standard model, $2L_0$ is chosen so that the influence of stress-free end is not extended to the middle part of the joint.

2.1 Width of standard model, $2B_0$

2.1.1 Distribution of temperature by instantaneous plane heat source

Although the actual welding heat source is moved along the weld line, it is assumed here that an instantaneous plane heat source is provided along the whole weld line of the butt welded joint. In this case, it becomes a problem of one-dementional heat conduction in the region where no influence from the ends of the joint is observed.

The temperature of the plate by the instantaneous plane heat source, T(y, t), is obtained by the following equation[2)].

$$T(y, t) = \frac{Q}{\sqrt{4\pi k t c \rho h}} \exp\left(-\frac{y^2}{4kt}\right) + T_0 \qquad (1)$$

Here,

Q: magnitude of heat input (J/mm)
T_0: room temperature (°C)
c: specific heat (J/g°C)
ρ: density (g/mm^3)
k: thermal diffusion rate (mm^2/sec.)
h: thickness of a plate (mm)

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At an arbitrary instant t, the maximum temperature T_{max} is observed at the distance from the center line, y_{hf}. y_{hf} and T_{max} are expressed as follows[2].

$$y_{hf} = \sqrt{2kt} \tag{2}$$

$$T_{max}(y_{hf}, t) = \frac{Q}{\sqrt{2\pi e}c\rho h y_{hf}} + T_0 \tag{3}$$

2.1.2 Transient stress under plane deformation state

When the length of the joint, 2L, is long enough comparing with the width 2B, the instantaneous plane heat source generates the same mechanical behavior in the middle portion of the joint, which is so called the plane deformation problem ($d\epsilon_x/dy = 0$).

In this case, the distribution of transient stress is obtained theoretically so as to satisfy the following three conditions: the condition of plane deformation, the equilibrium condition of forces and the yield condition of the material.

When the temperature dependent yield stress of the base plate and weld metal are assumed as in **Fig. 2** in which T_c, T_m, and $\bar{\sigma}_B$, $\bar{\sigma}_H$ are defined, the distribution of transient stress at time t, when the temperature of weld is cooled below T_c, is illustrated in **Fig. 3**. In this study, the rigidity recovering temperature T_m of the steel is considered to be equal to the A_1-phase transformation temperature.

At the distance y_H, the maximum experienced temperature T_{max} is equal to T_m. Here, the maximum experienced temperature is defined such as the maximum one in the entire temperature history of a point. The width $2y_H$ is assumed to be the same as that of heat-affected zone (HAZ), which can calculated by substituting T_m into the left side of Eq. (3).

$$y_H = Q/[\sqrt{2\pi e}c\rho h(T_m - T_0)] \tag{4}$$

y_{hf} is the location where the maximum temperature T_{max} is observed, and y_p is where transient compressive stress reaches the yield stress of the base material. Then, $2y_p$ is defined as the width of the plastic zone.

In the range where $0 \leq y \leq y_H$, the material is cooled from high temperature. The tensile stress σ_H is produced by the restraint against contraction at the cooling stage from T_m to the present time t, at which the rigidity of the material is recovered.

When the width of plastic zone, $2y_p$, becomes the largest at the cooling stage, the temperature at any points of the joint is below T_c. This is easy to confirm by substituting Eq.(7), mentioned later, into Eq.(1). At this time, σ_H becomes $\bar{\sigma}_H$.

In the range where $y_H < y \leq y_{hf}$, each point has been subjected to the individual maximum experienced temperature, T_{max}, and is at the cooling stage. The stress during this stage is in the elastic range, being unloaded from the yield stress which was produced by the compressive stress at the heating stage.

In the range where $y_{hf} < y \leq y_p$, the material is at the heating stage, since the maximum experienced temperature, T_{max}, has not been attained yet. Then, the compressive stress produced by the restraint of thermal expansion reaches the yield stress of base metal, $\bar{\sigma}_B$.

In the range where $y_p < y \leq B$, the material is in the elastic range, the sign and magnitude of stress are decided from the equilibrium condition at the cross-section.

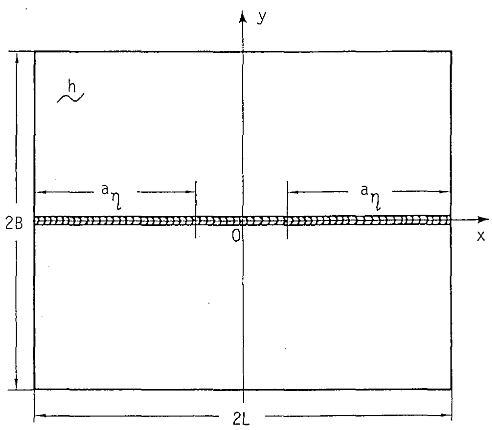

Fig. 1 Butt-welded joint.

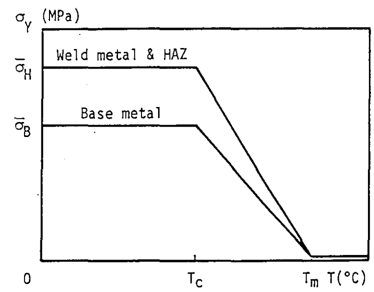

Fig. 2 Temperature dependency of yield stress.

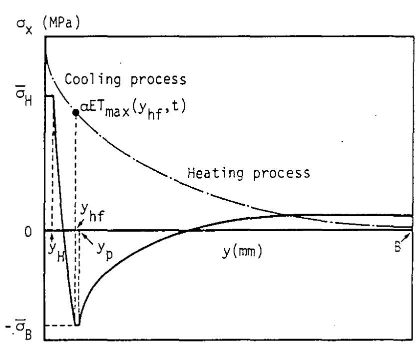

Fig. 3 Distribution of transient stress with the widest plastic region.

2.1.3 Maximum width of the plastic zone, $2y_p$

The width of the plastic zone, $2y_p$, mentioned above is obtained as follows.

When the stress distribution shown in Fig. 3 is approximated by a straight line in the range of $y_H < y < y_{hf}$, the following equation is obtained from the equilibrium condition.

$$\frac{1}{2}(\bar{\sigma}_H + \bar{\sigma}_B)(y_H + \sqrt{2kt}) + \frac{\alpha EQ}{c\rho h}\left[\frac{B - y_p}{\sqrt{4\pi kt}} \times \exp\left(-\frac{y_p^2}{4kt}\right) - \phi\left(\frac{B}{\sqrt{2kt}}\right) + \phi\left(\frac{y_p}{\sqrt{2kt}}\right)\right] = \bar{\sigma}_B B \quad (5)$$

Here,

$$\phi(u) = \sqrt{2\pi}\int_0^u \exp(-x^2/2)dx \quad \text{(Error function)}$$

With the elapse of time, the position, y_{hf}, where the maximum temperature has attained is apart from the weld line ($y = 0$), and the width of the compressive plastic zone, $2y_p$, become wider. At some instant, $t = t_b$, y_p becomes the maximum value b. (2b is called the width of the maximum plastic zone.)

This maximum value b is obtained from Eq.(5) by putting the derivative of y_p with respect to t to zero.

$$\left[1 - \frac{\sqrt{2\pi}c\rho hkt}{\alpha EQB}(\bar{\sigma}_H + \bar{\sigma}_B)\exp\left(\frac{b^2}{4kt}\right) - \exp\left(\frac{b^2 - B^2}{4kt}\right)\right] / \left(1 - \frac{b}{B}\right) = \frac{b^2}{2kt} \quad (6)$$

When the width of a plate is infinite, the left side of Eq. (6) is equal to 1. Therefore,

$$b = \sqrt{2kt} \quad (7)$$

When time t becomes t_b, the width of plastic zone y_p extends to the maximum value b. In the case of the infinite plate, t_b coincides to t_{hf} and also $y_p = b$ to y_{hf}, where the temperature attains the maximum experienced one.

This may be explained as follows: When the width of a plate is infinite, the thermal elastic-plastic behavior at the middle part of the plate is in the plane strain state ($\epsilon_x = 0$), and transient stress at each point is determined only by the temperature history at the respective point.

Therefore, when the temperature of each point becomes the maximum experienced temperature T_{max} in the respective thermal history, the transient stress of a point becomes the maximum value. If this transient stress is just equal to the yield stress at $y = y_b$, the width of the plastic zone becomes the greatest.

Making B infinite in Eq.(5), and substituting Eq.(7) into Eq.(5), parameter t can be eliminated and the width of the maximum plastic zone $2b'$ can be obtained for $B = \infty$.

$$b' = \alpha EQ/(\sqrt{2\pi e}\, c\rho h\bar{\sigma}_B) \quad (8)$$

In the case of finite plates, the left side of Eq.(6) is not equal to 1. However, the left side of Eq.(6) is very close to 1 for the standard model which has the equivalent effect on the production of the inherent strain as the infinite plate. Accordingly, b can be regarded as being y_{hf} approximately in this case, it is deduced that there is no serious effect on the equilibrium condition (Eq.(5)) even if b is considered to be equal to y_{hf}.

Consequently, substituting Eq.(7) into Eq.(5), the width of the maximum plastic zone, 2b, of a finite plate is calculated by the following equations.

$$b = [-A - \sqrt{A^2 - 2\alpha EQB(\bar{\sigma}_H + \bar{\sigma}_B)/(\sqrt{2\pi e}\, c\rho h)}] / (\bar{\sigma}_H + \bar{\sigma}_B) \quad (9)$$

Here,

$$A = \frac{Q}{\sqrt{2\pi e}\, c\rho h}\left[\frac{\bar{\sigma}_H + \bar{\sigma}_B}{2(T_m - T_0)} - 1.6557\alpha E\right] - \bar{\sigma}_B B$$

2.1.4 Width of the standard model, $2B_o$

The width of the standard model, $2B_o$, may be decided so that the ratio ξ to be defined by Eq.(10) is very close to 1.

$$\xi = b/b' \quad (10)$$

where b' and b are specified by Eqs.(8) and (9), respectively.

For $\xi = 1$, the necessary width of the standard model should be infinite, which is practically no use. Then, specifing the value of according to the required accuracy for the width of plastic zone, the width B can be calculated by Eq.(9), as such one which satisfies the condition, that is $b = \xi b'$. Firstly, Eq.(9) can be rewritten for B as,

$$B = \left[\frac{b}{2}(\bar{\sigma}_H + \bar{\sigma}_B) + \frac{Q}{\sqrt{2\pi e}\, c\rho h}\left(\frac{\bar{\sigma}_H + \bar{\sigma}_B}{2(T_m - T_0)} - 1.6557\alpha E\right)\right] / \left(\bar{\sigma}_B - \frac{\alpha EQ}{\sqrt{2\pi e}\, c\rho hb}\right) \quad (11)$$

Secondly, by substituting $b = \xi b'$ into Eq.(11), the width 2B is decided, which is taken as the width of the standard model, $2B_o$.

Table 1 Necessary widths of standard model for desired accuracy.

b' = 34.32 (mm)				
ξ (%)	99.2	98.4	97.2	95.6
2B (mm)	2000	1000	600	400

The accuracy of this decided width $2B_0$ is examined by the numerical calculation. The examples of the numerical experiment appeared in Reference 1 are analyzed here.

(Example 1)

Physical properties: ρ = 0.00782 (g/mm^3), c = 0.63 (J/g°C) mechanical properties α = 0.000012 (1/°C), E = 210(GPa) $\overline{\sigma}_H$ = 470(MPa), $\overline{\sigma}_B$ = 340(MPa), T_m = 700 (°C), T_c = 400(°C) heat input Q = 594 (J/mm), thickness of a plate h = 6(mm) room temperature T_0 = 15(°C).

The result obtained by this method is shown in Table 1.

When the width of standard model is assumed to be $2B_0$ = 1000(mm), it is shown by the result mentioned above that this width produces 98.4% of the width of plastic zone in the infinite plate. This agrees with that of the standard model selected from the result of the numerical experiment by the finite element method in the previous report.

The validity of this proposed method for determination of the width of standard model, $2B_0$ is demonstrated.

2.2 Length of the standard model, $2L_0$

In the case of long butt welded joints, the component of welding residual stress is only one in the welding direction, σ_x, except in the limited portion from the ends of the plate. This stress is generated mostly by the component of inherent strain in the welding direction, ϵ^*_x.

While, the component of inherent strain perpendicular to the weld line, ϵ^*_y, is produced by in-plane flexural deformation of the plate which is taken place at the heating stage during welding. This influences mainly the slope of linear distribution of compressive welding residual stress (Fig. 8). Therefore, if ϵ^*_y is neglected, the welding residual stress is generated by ϵ^*_x which is uniformly distributed along the weld line. This stress can be obtained by the sum of the stress distributions as shown in **Figs. 4 (a)** and **(b)**. The former one in Fig. 4(a) is produced by ϵ^*_x in the joint which is kept in the plane deformation state and is uniform in the longitudinal direction.

The latter in Fig. 4(b) exhibits the effect of stress-free boundaries at the ends. This is generated in the stress-free plate of the same size by imposing the same stress distribution as in Fig. 4(a) in the opposite direction at the ends.

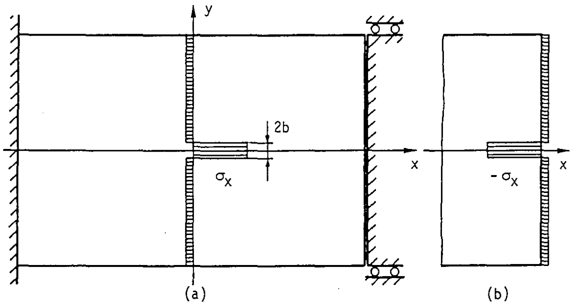

Fig. 4 Effect of free end.

This stress becomes smaller as being apart from the ends. According to Sainte Vennante's principle, if the length of the joint 2L is long enough, this stress vanishes in the middle part. Consequently, the distribution of welding residual stress is uniform in the middle part.

The minimum length $2a_\eta$, may be calculated by the following equation[3], so that the influence of stress-free boundaries may be reduced to 2.5%.

$$2a_\eta = 7.6\sqrt{b(B_0 - b)} \tag{12}$$

Here, 2b is the width of inherent strain, which is calculated by Eq.(9). Therefore, $2a_\eta$ can be taken as the length of standard model, $2L_0$.

This equation may be applied to the example 1 in Section 2.1. Specifying B_0 = 500(mm), and b = 33.77(mm), the minimum length is given as $2a_\eta$ = 954(mm). Therefore, it is proven to be rational that the length of the standard model in the example 1 is $2L_0$ = 1000(mm) $> 2a_\eta$.

3. Influence of Heat Input Upon Inherent Strain

Changes in the welding condition and the kind of steel may influence the distribution and magnitude of inherent strain. Therefore, in order to calculate welding residual stress, the new standard model has to be decided, corresponding to their changes and the inherent strain in the new model has to be calculated.

When the kind of steel is same and only the heat input changes from the specified magnitude, the new inherent strain is able to be simply estimated from the inherent strain which was known for the specified heat input. Here, this procedure will be described in the following.

In the case where the heat input provided to two welded joints of the same material is proportional to the sizes of the plates, their temperature histories should be the same at the same location in the non-dimensional coordinates, if the heat radiation from both faces of the plates is neglected.

Accordingly, the strain and stress histories at the similar points of the two joints, (x/L, y/B), should be the same[4] and this results in that the inherent strains are also the same.

If the deduction mentioned above is applied, the new inherent strain can be estimated for the new heat input using the inherent strain known for the specified heat input.

The magnitudes of inherent strain components, ϵ^*_x and ϵ^*_y, are the same in both plates because of the same kind of steel. The width of inherent strain distribution changes in proportion to the megnitude of heat input. This fact suggests that the sizes of the standard model become smaller or larger in proportion to the magnitude of heat input.

The method for modification of the inherent strain distribution is illustrated schematically in **Fig. 5**. The known inherent strain is indicated by suffix 1, while the inherent strain for the new heat input is by suffix 2. Two models with different magnitude of heat input are analysed to confirm the method mentioned above. The new heat input is twice as much as the specified one. The inherent strain of model 1 has been already estimated by the original method. While the inherent strain of model 2 is to be estimated by the method mentioned above, using the former inherent strain.

(Example 2)

The physical constants and mechanical properties of the materials are assumed to be the same as in example 1. The heat inputs and sizes of the two models are shown in Table 2.

By the two different methods, the distributions of

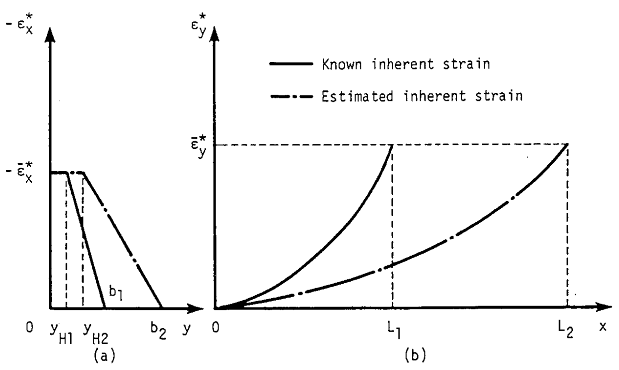

Fig. 5 Modification of inherent strain distributions in accordance to change of heat input.

Table 2 Heat input and sizes of models.

	Model 1	Model 2
Heat input Q(J/mm)	594	1188
Width B(mm)	500	1000
Length L(mm)	600	1200
Thickness h(mm)	6	6

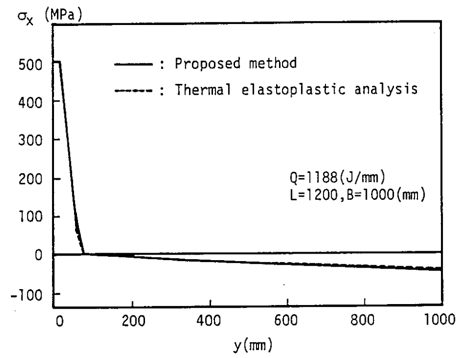

Fig. 6 Comparison of residual stresses calculated by thermal elasto-plastic analysis and the proposed method for change of heat input.

welding residual stresses at the central sections are obtained as illustrated in **Fig. 6**. They almost coincide with each other.

Consequently, when the kind of steel is same and only the magnitude of heat input changes, it is unnecessary to specify the size of standard model and calculate the inherent strain by the original method.

4. Effect of The Kind of Steel Upon Inherent Strain

When the kind of steel changes, the mechanical properties such as the yield stress, temperature of phase transformation and volume expansion coefficient may change. This results in change in the inherent strain.

In the case where the inherent strain of the standard model is known, this inherent strain can be modified in accordance with the different kind of steel.

4.1 Effect of change of yield stress

The effect of change of the yield stress upon the inherent strain distribution is examined.

In the following, suffix 1 and 2 are used for the model with known inherent strain and the model with a different magnitude of yield stress, respectively.

4.1.1 Component in the weld direction ϵ^*_x

The inherent strain produced at butt welded joint of a thin plate is composed of the component in the welding direction, ϵ^*_x and the component perpendicular to the weld line, ϵ^*_y, as mentioned before.

They exist in a narrow width parallel to the weld line, $y \leqslant b$. As an example shown in Fig. 5, ϵ^*_x becomes the largest in the absolute value, $-\bar{\epsilon}^*_x$ in $|y| \leqslant y_H$, which is obtained by the following expression.

$$\bar{\epsilon}^*_x = \eta\cdot(\bar{\sigma}_H/E) \qquad (1 < \eta < 1.1) \tag{13}$$

b changes according to the change of yield stress. It is recognized from Eq.(4) that y_H depends upon only the

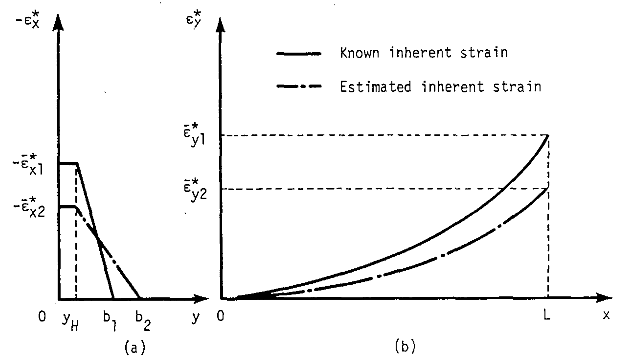

Fig. 7 Modification of inherent strain distributions in accordance to change of yield stress.

temperature history but the yield stress.

Therefore, for the different yield stress, ϵ^*_{x2} can be calculated by using known ϵ^*_{x1} as illustrated schematically in **Fig. 7 (a)**.

In $|y_2| \leqslant y_H$, the following equation for ϵ^*_{x2} is obtained from Eq. (13).

$$\epsilon^*_{x2} = -\bar{\epsilon}^*_{x2} = -(\bar{\sigma}_{H2}/\bar{\sigma}_{H1})\bar{\epsilon}^*_{x1}$$

In $y_H \leqslant |y_2| \leqslant b_2$, ϵ^*_{x2} at $y = y_2$ is obtained as,

$$\epsilon^*_{x2} = (\bar{\sigma}_{H2}/\bar{\sigma}_{H1})\,\epsilon^*_{x1}$$

However, ϵ^*_{x1} is the inherent strain at $y = y_1$, which is given by the following equation.

$$y_1 = [(b_1 - y_H)/(b_2 - y_H)]\,(y_2 - y_H) + y_H$$

4.1.2 Component perpendicular to the weld line, ϵ^*_y

The effect of change of the yield stress on the distribution of ϵ^*_y is considered in this section.

Considering the production mechanism of welding residual stress, two plates which have not been jointed yet exhibit independent in-plane flexural deformation by non-uniform temperature distribution until the temperature of the weld is cooled down to the rigidity recovering temperature T_m at the cooling stage after welding. Then, this deformation causes the linear distribution of compressive welding residual stress. Accordingly, ϵ^*_y is considered to be caused by the in-plane flexural deformation mentioned above.

In other words, if both plates are given such boundary condition at the ends of the plates that the plates can only make a parallel translation as being in the plane deformation state, in-plane flexural deformation is not produced by non-uniform temperature distribution in the cross-section even if the two plates are not joined at the cooling stage after welding. Then, ϵ^*_y is not producted. However, the same transient stress σ_x is produced at both ends of the plate as in the middle part of the plates.

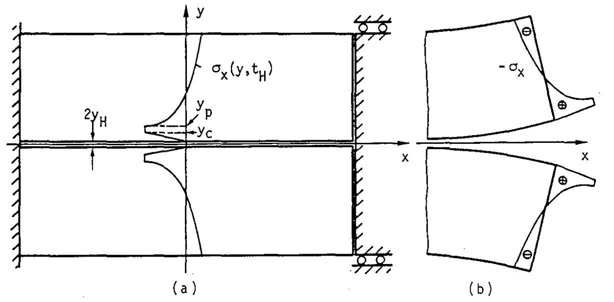

Fig. 8 In-plane flexural deformation of two plates during butt welding.

However, in the case of the practical butt weld joints, both ends of the plates are the stress-free boundaries where no normal stress is produced. Accordingly, the in-plane flexural deformation of the plates at the cooling stage is produced by the existence of free surfaces at both ends of the plates where the normal transient stress σ_x shown in **Fig. 8 (b)** disappears.

Concretely, this in-plane flexural deformation is produced by applying the same transient stress as in **Fig. 8 (a)** in the opposite direction on both ends.

Here, it is assumed that the magnitude of ϵ^*_y is in proportion to bending moment M produced by this transient stress σ_x. This bending moment is evaluated by the following equation.

$$M = \int_0^B -\sigma_x(y, t_H)\,(B/2 - y)\,dy \tag{14}$$

In the above equation, $\sigma_x(y, t_H)$ is the transient stress, shown in Fig. 8 (a), which can be theoretically calculated in the same way as in Section 2.1. Further, t_H is the time at which the weld metal recovers the stiffness and the temperature at $|y| = y_H$ reaches to the rigidity recovering temperature T_m.

$$t_H = y^2_H/2k \tag{15}$$

y_c in Fig. 8 (a) is the position whose temperature becomes to T_c and is obtained by the following equation.

$$y_c = y_H\sqrt{1 + 2\log[(T_m - T_0)/(T_c - T_0)]} \tag{16}$$

$2y_p$ is the width of the plastic zone produced at the time t_H of Eq. (15), and is calculated by the plane deformation condition, equilibrium condition and yield condition in the following.

Here, the standard model is dealt with, which is the finite plate with the same effect upon production of the inherent strain as the infinite plate. Then, as y_p should be almost same in both plates, it can be calculated as for the infinite plate (plane strain).

Here,

$$\sigma_x(y_p, t_H) = -\alpha E[T(y_p, t_H) - T_0] = -\overline{\sigma}_B$$

$$y_p = y_H\sqrt{1+2\log[\alpha E(T_m - T_0)/\overline{\sigma}_B]} \qquad (17)$$

Substituting $\sigma_x(y, t_H)$ into Eq.(14), the following equation is obtained.

$$M = \frac{\overline{\sigma}_B}{2}[(y^2_H + y^2_c + 5y_H y_c)/3 - (y_H + y_c)B/2] + \frac{\alpha EQB}{2c\rho h}[0.5 - \phi(\frac{y_p}{y_H})] - \frac{\alpha EQ}{\sqrt{8\pi}c\rho h} \times [(y_p - B)(\frac{y_p}{y_H}) + 2y_H]\exp(-0.5(\frac{y_p}{y_H})^2) \qquad (18)$$

Accordingly, using the known ϵ^*_{y1}, ϵ^*_{y2} for the different yield stress is estimated approximately by the following equation in the same way as in Section 4.1.1.

Here,

In $|y_2| \leqslant y_H$, it is expressed as follows.

$$\epsilon^*_{y2} = (M_2/M_1)\epsilon^*_{y1}$$

Here, M_1 and M_2 are the bending moments which are obtained substituting B_1 and B_2 into Eq.(18) respectively.

In $y_H < |y_2| \leqslant b_2$, ϵ^*_{y2} at $y = y_2$ is expressed as,

$$\epsilon^*_{y2} = (M_2/M_1)\epsilon^*_{y1}$$

However, ϵ^*_{y1} is the inherent strain of the original model at $y = y_1$ which is calculated by the following equation.

$$y_1 = [(b_1 - y_H)/(b_2 - y_H)](y_2 - y_H) + y_H$$

The validity of the approximate estimating method of inherent strain mentioned above is examined by the numerical experiment in the following.

Two models with different magnitudes of the yield stress are considered. The Inherent strain of model 1 is assumed to be known, and that of model 2 is calculated by the method mentioned above. Welding residual stress in model 2 is predicted by the method using the inherent strain of model 1. The result is compared with that analyzed by the thermal elastic-plastic analysis.

(Example 3)

The heat input, physical constants and mechanical properties of the materials except the yield stress are the same as in Example 1. The size of each model is the same such as B = 500(mm), L = 600(mm), h = 6 (mm). The yield stress of each model is shown in Table 3.

Table 3 Assumed yield stresses of base metal and HAZ.

	Model 1	Model 2
Base metal σ_B(MPa)	340	230
H A Z σ_H(MPa)	470	320

According to Eq.(18), M_2/M_1 is found to be 0.7. The distributions of welding residual stress at the central section calculated by the two different methods are illustrated in **Fig. 9**.

Comparing these distributions, it is obvious that they coincide with each other very well. Therefore, this method is considered very useful.

4.2 Influence of phase transformation

Here, the influence of phase transformation upon welding residual stress is studied by the numerical experiment as observed in the case of high tensile strength steel such as HT-80 and 9%Ni steel.

The distribution of welding residual stress produced at the joint of HT-80 is studied by the thermal elasto-plastic analysis for two cases where the phase transformation is included and excluded, as shown in **Fig. 10**.

The phase transformation is only taken place in the HAZ (including weld metal). Accordingly, the welding residual stress at the HAZ is lowered. The distributions of welding residual stresses in other part hardly change.

The stress history at the HAZ where the phase transformation occurs, is shown in **Fig. 11**. The stress analysis is performed on the uni-axial model, which is fixed at both ends and imposed the same temperature history as in the HAZ and the stress history is also illustrated in Fig. 11.

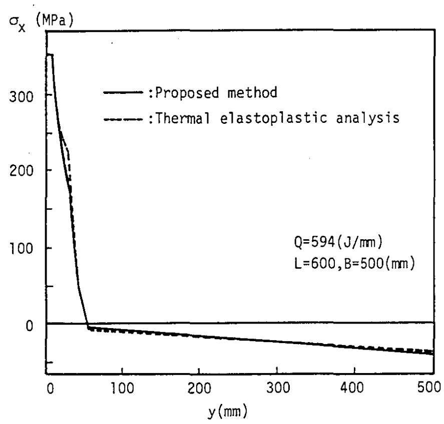

Fig. 9 Comparison of residual stresses calculated by thermal elasto-plastic analysis and the proposed method for change of yield stress.

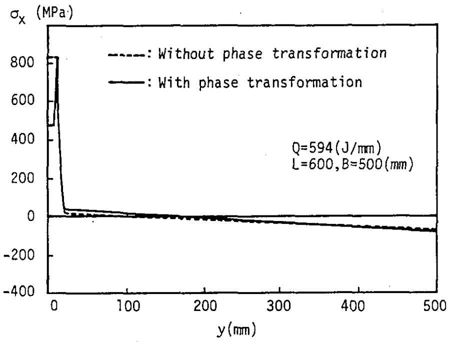

Fig. 10 Effect of phase transformation on the distribution of residual stress.

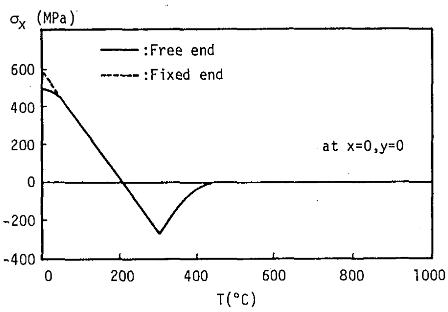

Fig. 11 Stress history of HAZ with effect of phase transformation.

The production history of welding residual stress at the HAZ is similar to that computed by the uni-axial elasto-plastic analysis and the magnitude of welding residual stress at room temperature is a little smaller than by the uni-axial one.

In summary, in the case of high tensile strength, two steps of modification on the known inherent strain are taken for different yield stress and phase transformation. At the first step, inherent strain can be modified for the change of the yield stress with a good accuracy by the method mentioned in Section 4.1, using the known inherent strain. At the second step, the magnitude of welding residual stress at the HAZ is adjusted by the value which is theoretically analysed or observed by the experiment on a uni-axial specimen fixed both ends under the same temperature history as in the HAZ.

The magnitude of thus modified welding residual stress at the HAZ should be higher than the actual one as in Fig. 11. The welding residual stress at the HAZ is decreased here as indicated above, so that the compressive welding residual stress in the remaining part should decrease to maintain the balance of the whole welding residual stress. However, when the width of the joint is large, this change should be negligible small.

5. Conclusions

In the previous report, a new predicting method of welding residual stress was proposed using the standard inherent strain. Here, the standard inherent strain is that produced in the standard model, which has the equivalent effect on production of welding residual stress to that in the infinite plate.

In this paper, the followings are the results of investigation;

(1) A theoretical method is proposed to determine the size of the standard model. The resulting standard inherent strain is proven to be very accurate.

(2) When the standard inherent strain has been already furnished for the specified welding condition and kind of steel, this can be easily modified in accordance to the change of heat-input by the proposed method.

(3) By using the known standard inherent strain, the new inherent strain can be calculated for the change of yield stress due to the change of the kind of steel and the influence of phase transformation. This modification method is demonstrated to be accurate enough by numerical experiments.

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