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A study on residual stress of butt-welded plate joint using inherent strain analysis

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ABSTRACT : The welding residual stress of an 18.2 mm-thick eight-pass butt-welded plate joint is evaluated using inherent strain analysis. The residual stress distribution is obtained in detail along the thickness direction from the measurement using multiple strain gauges. The residual stresses agree well with the results of thermal elastic plastic analysis, and are also similar to values obtained by direct measurement on the specimen surface. Direct measurement is not used for the inherent strain analysis. These results indicate that both inherent strain analysis and thermal elastic plastic analysis are effective in evaluating through-thickness residual stress. Therefore, each analysis method should be selected after considering the object to be evaluated and the analysis characteristics.

1 INTRODUCTION

Residual stresses caused by welding affect the performance of a welded structure in various ways. It is important to know precisely the distribution and magnitude of the through-thickness welding residual stress when designing the strength of a welded structure and evaluating the crack propagation. Thermal elastic plastic analysis is generally used to determine welding residual stresses [1-5]. It is also possible to estimate residual stresses by elastic analysis using an inherent strain, which is a source for generating the residual stress [6]. The evaluating method by inherent strain analysis can be involved in other estimating methods using both the released strain measurement and the finite element method. Through-thickness residual stresses of various welded joints have been estimated using inherent strain analysis [7-11]. However, the applicability of inherent strain analysis to the evaluation of through-thickness residual stress has not been validated by another method.

In this paper, the through-thickness welding residual stress of an 18.2 mm-thick eight-pass butt-welded carbon steel plate joint is evaluated using inherent strain analysis. The through-thickness residual stress distribution and magnitude is obtained in detail from the released strain measurement using multiple strain gauges. By comparing the results of inherent strain analysis with those of thermal elastic plastic analysis, we show that both methods are equally effective in evaluating the through-thickness welding residual stresses.

2 THEORY OF INHERENT STRAIN ANALYSIS

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

$$\{ \varepsilon \} = [H^*] \{ \varepsilon^* \} \tag{1}$$

$$\begin{aligned} \{ \sigma \} &= [D] \{ \varepsilon \} \\ &= [D] [H^*] \{ \varepsilon^* \} \end{aligned} \tag{2}$$

where $[H^*]$ is elastic strain and inherent strain matrix, and $[D]$ is elastic stress and 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, and so on. Therefore, the inherent strain is estimated from the observed value of elastic strain even if the geometry of an object changes due to cutting as follows.

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

$$\{ {}_m\varepsilon \} - [H^*] \{ \hat{\varepsilon}^* \} = \{ V \} \tag{3}$$

where $\{ \hat{\varepsilon}^* \}$ is the most probable value for inherent strain, and $\{ V \}$ is the residual.

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

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

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

3 RESIDUAL STRESS EVALUATION OF BUTT-WELDED PLATE JOINT

3.1 *Evaluation method using inherent strain analysis*

The butt-welded plate used in this study is shown in Figure 1. The base plate material and welding rod is mild steel. A specimen 18.2 mm thick was welded in eight layers and 8 passes. The first welding pass used tungsten innert gas arc and all other passes used shielded metal arc welding. The evaluation was performed on a cross section at the middle of the specimen.

The inherent strain and residual stress are evaluated by cutting the specimen and by measuring residual strain on the cross section surface, and is based on the assumption that strains in the specimen change elastically due to cutting. The shear components of inherent strains can be ignored. None of the components of inherent strain change along the weld line (x-axis) and the components ε_x^*, ε_y^* and ε_z^* are functions of y and z coordinates.

As the cutting lines show in Figure 2, T_y and T_z-specimens and $L_1 \sim L_m$ specimens are taken out of the original welded joint. The same magnitude of inherent strain exists in these specimens because the inherent strains do not change without production of plastic strains by the slicing action.

The component ε_x^* can be calculated using the measured strains from $L_1 \sim L_m$ specimens, and ε_y^* and ε_z^* can be calculated from T_y and T_z-specimens respectively. The inherent strain and residual stress distributions are obtained in detail along the thickness direction from the measurement using multiple strain gauges. Three dimensional residual stress can be calculated from inherent strain distributions.

3.2 *Evaluation method using thermal elastic plastic analysis*

Heat conduction and thermal elastic plastic analyses were performed by means of the finite element method [5]. Temperature distributions during welding were obtained by heat conduction analysis, which were given as thermal loads. The residual stress was calculated by thermal elastic plastic analysis. It was assumed that a welding heat source is simultaneously and instantaneously applied to the each welding pass position.

A two-dimensional model was used for heat conduction and thermal elastic plastic analyses, assuming the cross section could be maintained during welding. The material properties used for the analyses are temperature dependent as shown in Figures 3 and 4.

4 RESULTS OF RESIDUAL STRESS ANALYSIS

4.1 *Comparison of residual stress distribution*

Figures 5 and 6 show the residual stress distributions on the specimen surface obtained by thermal elastic plastic analysis and the inherent strain elastic analysis. Direct measurement values are also shown. The direct measurement values on the specimen surface is not used for inherent strain analysis. It can be seen that these three distributions agree very well.

A comparison of the results of through-thickness residual stress for thermal elastic plastic analysis and inherent strain analysis are shown in Figures 7 to 10. The residual stress distributions along the thickness direction agree well each other.

4.2 *Effectiveness in evaluating through-thickness residual stress*

These results indicate that both inherent strain analysis and thermal elastic plastic analysis are effective in evaluating through-thickness residual stress. Therefore, each analysis method should be selected considering the object to be evaluated and the analysis characteristics.

5 SUMMARY

The welding residual stress of an 18.2 mm-thick eight-pass butt-welded plate joint is evaluated using the inherent strain analysis.

(1) The residual stress distribution is obtained in detail along the thickness direction from the measurement using multiple strain gauges.

(2) The residual stresses obtained by inherent strain analysis agree well with the results of thermal elastic plastic analysis. These stresses are also similar to values obtained by direct measurement on the specimen surface, which is not used for inherent strain analysis.

(3) Either inherent strain analysis or thermal elastic plastic analysis methods should be selected after considering the object to be evaluated and the characteristics to be analyzed.

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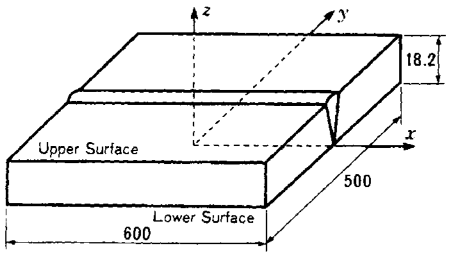

Fig. 1 Configuration of butt-joint

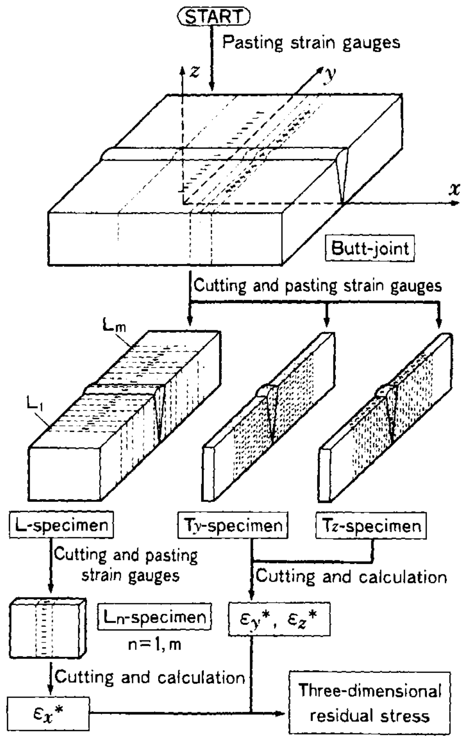

Fig. 2 Sequence of measuring inherent strain

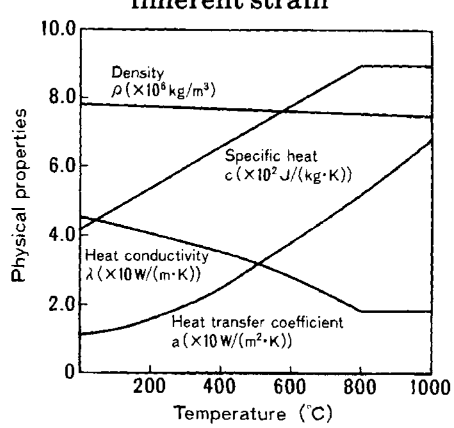

Fig. 3 Physical properties at heat conduction analysis

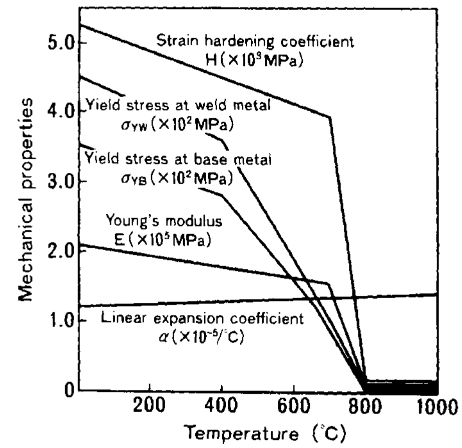

Fig. 4 Mechanical properties at thermal elastic plastic analysis

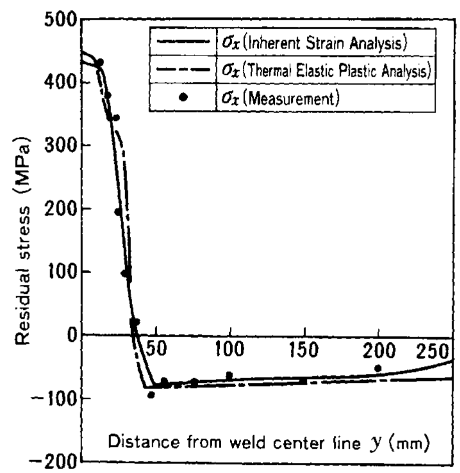

Fig. 5 Residual stress distribution on the upper surface

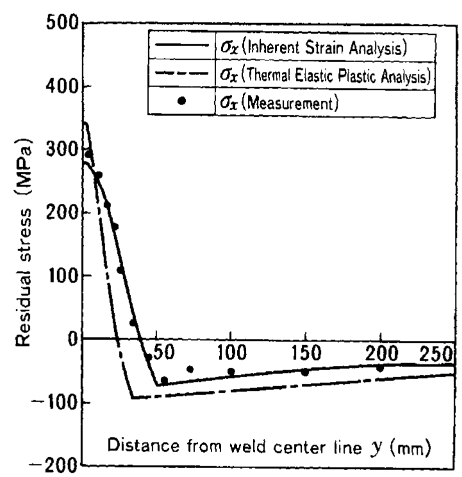

Fig. 6 Residual stress distribution on the lower surface

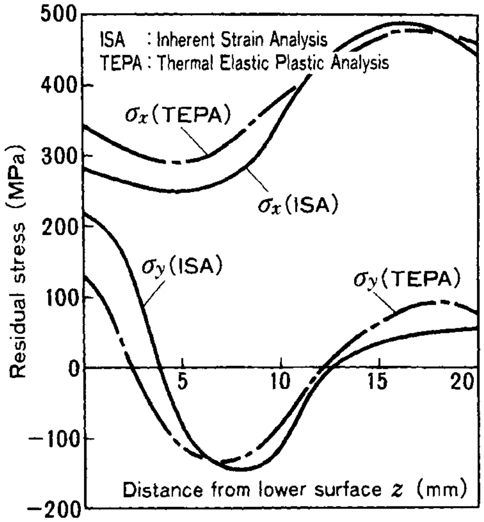

Fig. 7 Residual stress distribution through-thickness ($y=0$ mm)

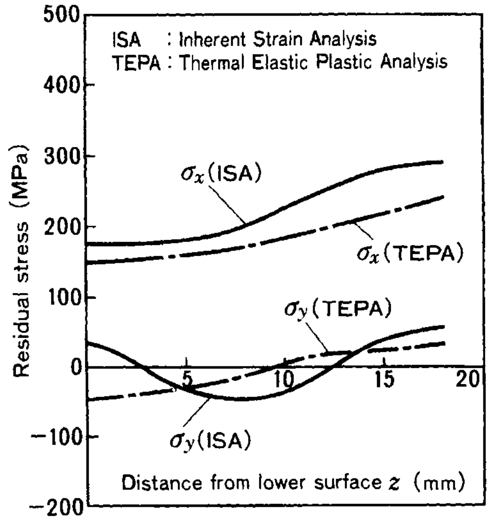

Fig. 9 Residual stress distribution through-thickness ($y=20$ mm)

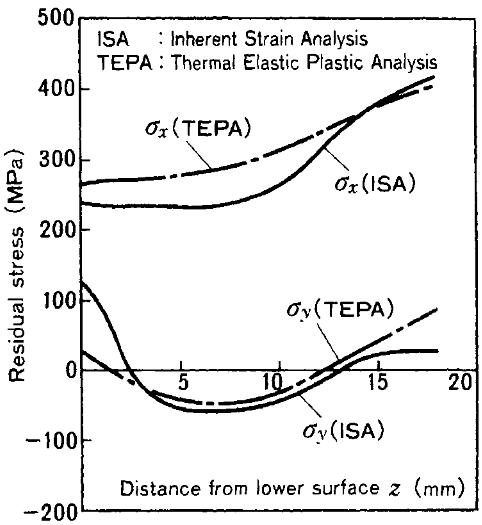

Fig. 8 Residual stress distribution through-thickness ($y=10$ mm)

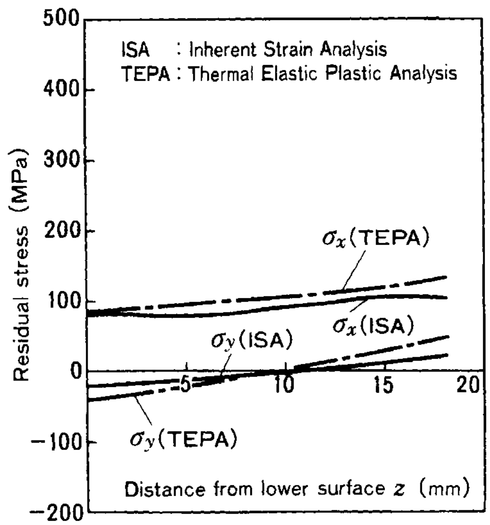

Fig. 10 Residual stress distribution through-thickness ($y=30$ mm)