Identification Method of Residual Stress Distribution in Butt-Welded Plate by Boundary Element Analysis (Experimental Examination)

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ABSTRACT

Welding residual stresses cause buckling or brittle fractures in welded structures so that estimation of residual stress is required to protect the structures. In previous works, an identification method by thermo-elastic boundary element analysis was proposed to estimate the magnitude and the distribution of the residual stress in butt-welded plate from a few measured data. The method can also estimate the maximum stress value at the welding line, where the X-ray diffraction method is inapplicable. The validity of the method was examined using numerical simulations while experiments were not carried out. This paper investigates the effectiveness of the method using experimentally measured stresses in butt-welded plate. The estimated stresses were in good agreement with those measured in the experiments when the measurement points were at suitable locations. The maximum residual stresses were estimated using the stresses measured near the line by the X-ray diffraction method.

KEYWORDS

Inverse Problem; Residual Stress; Boundary Element Method; Weld Joint; Computational Mechanics; Nondestructive Inspection; Simplified Identification Method

INTRODUCTION

Large structures like ship, crane and LNG tank are categorized into welded structures because they are assembled using welds. The weld generates the residual stress that may cause buckling or brittle fractures of the welding structures [1][2]. Thus, the estimation of the welding residual stress is required to protect the welded structures from fracture.

The measurement of the welding residual stress is usually performed by either destructive or non-destructive methods [1][2]. Sectioning method is one of the destructive measurement methods. The method measures the released strain in the piece that is cut in the region where the residual stress develops. The residual stress is calculated from the released strain. On the other hand, the measurement by X-ray diffraction is a typical non-destructive method to measure the residual stress.

The welding residual stress is caused by the shrinkage of the weld metal [3]-[6]. The shrinkage is called inherent strain. The residual stress is examined using stress analysis if the distribution of the inherent strain is given. The inherent strain is replaced by thermal strain in the stress analysis.

A simplified identification method using thermo-elastic boundary element analysis [7]-[9] was proposed in the previous papers [10] [11] to estimate the distribution of the inherent strain due to butt-welds of a plate. The method can identify the inherent strain distribution from a few measurement data, which are measured at points away from the welding line of butt-welded plate by the X-ray diffraction method. The distribution and the highest value of the residual stress can be obtained using boundary element analysis if the inherent strain distribution is identified by the proposed identification method.

The previous papers examined the applicability and the effectiveness of the proposed method by some numerical examples with and without errors in measured values. However, the examination used assumed stresses at the measurement points to identify the inherent strain distribution in the calculations because experimental data of the residual stress of butt-welded plate was not available. It wasn't also clear whether the selected locations for the measured points were actually suitable.

This paper investigates the results in the previous papers using the experiment data of the residual stresses of the butt-welded plate. The measurement of the residual stress is conducted by sectioning method and X-ray diffraction stress measure method. The effectiveness of the proposed method is confirmed from the results of the comparison between the identified residual stresses and the measured ones.

EXPERIMENTAL PROCEDUERS

Figure 1 shows a specimen of butt-welded plate to measure welding residual stress. The material of specimen is type 316 austenitic stainless steel. The thickness of the plate that used for the specimen is 6mm. Welding grooves are made in two plates and four tab plates. Those plates are annealed at a high temperature to release the residual strain after the tab plates are connected with the two plates at the edges of the welding line by spot welding. The specimen that uses for measurement of the welding residual stress is made by butt-welds after those treatements. An automatic TIG welding device is used for the butt-welds of the plate. The tab plates of both end edges of the specimen plate are cut after welding. The edges (y=200mm) of both sides of the specimen are constrained by a number of jigs so that the specimen doesn't rotate from the welding line. The constraint is to prevent angular deformation of the specimen after welding. The measurements of the residual stress of the butt-welded specimen are conducted by two kinds of methods. One is sectioning method in destructive measurement method. This method measures the released strain of the piece when the welding part of the specimen is cut to small pieces by a cutter machine. The residual stresses are calculated from the released strain. The merit of sectioning method is that it is simple while the demerit is that it destructs the specimen. The other method used is the nondestructive measurement method by the X-ray diffraction. The X-ray diffraction is common for nondestructive measurement method. The method can measure the residual stress but it needs an expensive device and also special technical ability for the use of the device. Moreover, the method is difficult to measure the residual stress produced at a welding line where the residual stress reaches its highest value and therefore it is very important.

In this paper, the residual stresses are measured at the locations of butt-welded plate by sectioning and the X-ray diffraction methods. The measurement using the X-ray diffraction is conducted by $\sin^2\psi$ method. The device of Rigaku Ltd. is used for the stress measurement. The locations of the measurement points are polished by electrolysis grinder. The residual stresses in a butt-welded specimen are measured by the X-ray diffraction stress measurement device after the polishing on the surfaces of the specimen.

Next, the residual stresses are measured by sectioning method. Three-axial strain gages are installed at the locations of the measured points in the butt-welded specimen. The parts of the measured points are cut to small piece of dimension of 10mm×10mm×6mm. The specimen during cutting is cooled by water. The strain gage of 2mm length and the gage 1mm length at the welding line only are used for the specimen.

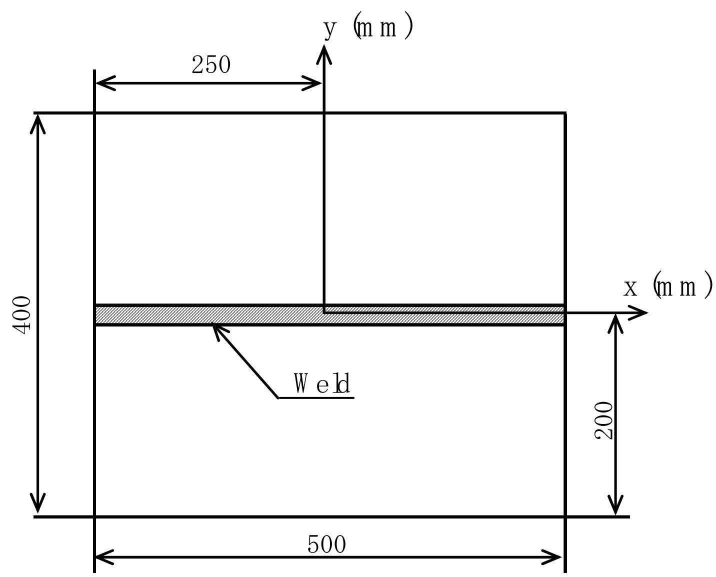


Figure 1 Specimen of butt-welded plate

Table 1 Location of measurement points

No.	x (mm)	y (mm)
1	75	80
2	125	80
3	165	80
4	200	80

NUMERICAL EXAMINATIONS

Numerical simulation of identification of inherent strain is made. Figure 2 shows the model used for the boundary element analysis to identify the inherent strain distribution from the data measured by the X-ray diffraction method. Two-dimensional plane stress condition is assumed in the analysis because the thickness of the specimen is small. 57 boundary elements of constant type are used in the analysis model in Fig.2. Also 42 cells of linear type are placed in the domain of specimen. The material of the specimen is type 316 austenitic stainless steel. Young' modulus of the material is 194.0MPa and Poisson's ratio is 0.266. For the sake of symmetry of the analysis model the displacement in the x-direction on y-axis and that in the y-direction on x-axis are constrained.

The proposed method is checked before the examination using experimental results. Figure 3 shows the flowchart of the calculation procedure to identify the the distribution of the inherent strain from the measured data. The asuumed inherent strains in the simulation are given in the domain cells of the analysis model in Fig.2. The stresses at the locations of measued points are calculated by thermo-elastic bounary element analysis. The stresses are used to identify the inherent strain in the domain cells of the analysis model from the stresses at measured points.

The proposed method in the previous papers can identify the distribution of the inherent strain from a few measured values of the residual stress away from the welding line. Thus, the magunitude and the distribution of the resudual stress in the butt-welded specimen was calculated to give the identified inherenet strain in the analysis model.

Table 2 shows the identified results. The assumed inherent strain is constant distribution and the magunitude is –0.004. The measurement point number is one in Table 1. The stresses σ_x and σ_y at the measured points are used for the calculation. The identified inherent strain coincided with the assumed one.

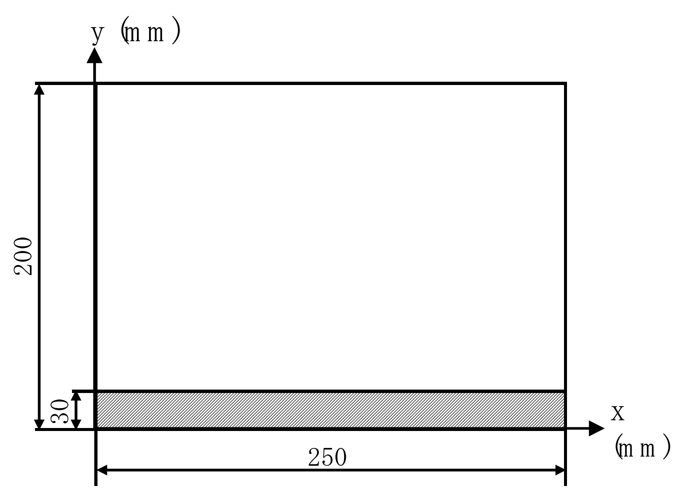


Figure 2 Analysis model by boundary element method

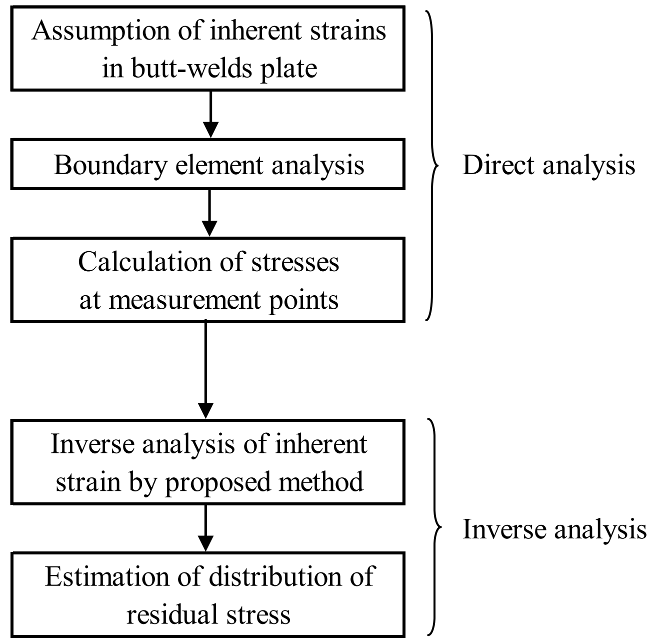


Figure 3 Flowchart of the calculation procudure in numerical simulation

Table 2 Inherent strain estimated by inverse analysis

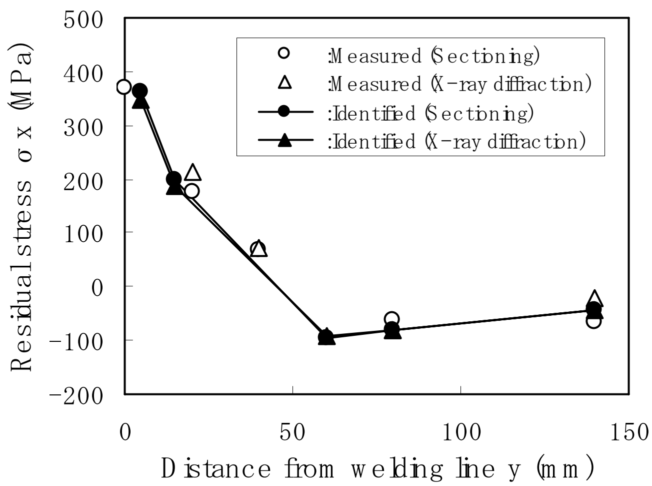
Actual inherent strain	Estimated inherent strain
-0.00400	-0.00400

The validification of the identification mehod is confirmed from the comparison between the asumed inherents and the identified one in the model in Fig.2.

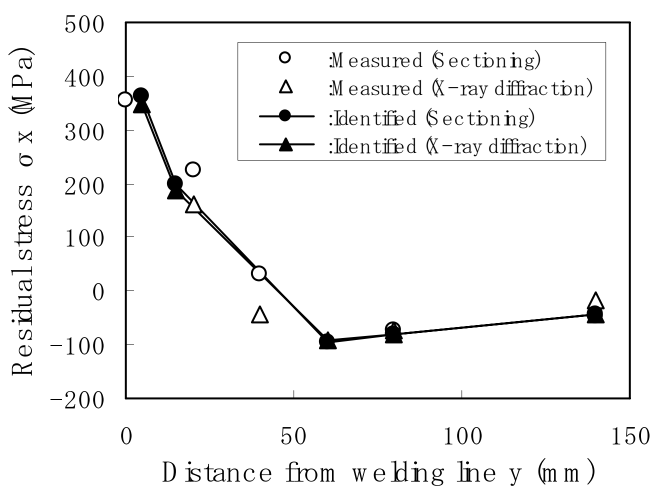
EXPERIMENTAL RESULTS

The estimation of residual stress distribution is made using experimentally obtained data. The stresses at the locations of measurement points were measured by sectioning and X-ray diffraction methods. An inverse analysis was conducted to identify the distribution of the inherent strain in butt-welds specimen in Fig.1. The distribution of the inherent strain was identified from the measured residual stresses at four points in Table 1 by using the proposed method. The residual stresses were calculated from the distribution of the inherent strain by boundary element analysis.

Figure 3 shows the residual stresses that are calculated from the identified inherent strains. The identified results in Fig.3 show the y-directional distribution of the residual stress σ_x on lines of x=75mm and x=125mm, respectively. The identified residual stresses were compared with the measured one by sectioning and X-ray diffraction methods. The result denotes that the identified residual stresses are in good agreement with the measured ones and the distribution of the inherent strain can be identified from a few measurement data, which are measured at point away from welding line by the X-ray diffraction method. It was also found that the residual stress produced at a welding line could be exactly identified and was about 350MPa.



(a) σ_x on line of x=75mm



(b) σ_x on line of x=125mm

Figure 3 Measured residual stresses and estimated distribution of residual stress σ_x on lines of x=75mm and x=125mm

CONCLUSIONS

In this paper, the welding residual stresses of butt-welded specimen of austenite stainless steel were measured. The measurement of the residual stress was conducted by both destructive and non-destructive methods. The distribution of the inherent strain of the specimen was identified from those measured values of a few numbers by using the method proposed in the previous papers. The residual stresses were calculated from the identified inherent strains by thermo-elastic boundary element analysis. The effectiveness of the proposed method in the previous paper was confirmed from experimental results. It was found that the proposed method could effectively predict the distribution of the residual stress and the maximum value at welding line from the measured results.

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