［溶接学会論文集　第 41 巻　第 2 号　p. 11s-15s（2023）　DOI: 10.2207/qjjws.41.11s］

Application of Simple Numerical Simulation of Welding Distortion Using Thermal Shrinkage Technique to Multi-layer Welded Joint*

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The thermal shrinkage technique with previously proposed input parameter values for single-pass welding was applied to a multi-layer butt-welded joint with four layers and six welding passes to validate whether these input parameters are applicable to multi-layer welded joints. The out-of-plate displacement distributions of the multi-layer welded joint obtained using the thermal shrinkage technique were in good agreement with those obtained in a thermal elastic-plastic analysis and an experiment. The angular distortion and transverse shrinkage at the center of the welding line obtained using the thermal shrinkage technique well agreed with the experimental and thermal elastic-plastic analysis results for each welding pass. Furthermore, the calculation time for the thermal shrinkage technique was 1/6 of that for the thermal elastic-plastic analysis. Our results demonstrate that the thermal shrinkage technique with the previously proposed input parameter values could be applicable to multi-layer welded joints.

Key Words: Thermal shrinkage technique, Welding distortion, Thermal elastic-plastic analysis, Multi-layer welding, Numerical simulation

1. Introduction

Welding distortion can decrease assembly efficiency, buckling strength, and fatigue strength. Its evaluating in advance is thus important for improving the efficiency of a manufacturing process. Thermal elastic-plastic analysis[1)], the inherent strain method[2)], and the thermal shrinkage technique[3)] have been developed for evaluating welding distortion. Although, some of these methods have been applied in practice, they are not widely used due to their long computation time or arbitrary input parameter values.

The thermal shrinkage technique has shown promise as a simple simulation method for predicting the welding distortion of large weld structures because it requires only two input parameters and it is relatively fast. In our previous studies, appropriate input parameter values that did not depend on the welding conditions in single-pass welding were determined and validated[4)]. In addition, the thermal shrinkage technique with these input parameter values was applied to a construction machine with 40 fillet welding passes (single-pass welding at 40 weld locations); it was found that the welding distortion was consistent with that obtained using a conventional method[5)].

In the present study, the thermal shrinkage technique with the previously proposed input parameter values for single-pass welding was applied to a multi-layer butt-welded joint with four layers and six passes to validate whether theses input parameter values are applicable to multi-pass welding.

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2. Numerical model for thermal shrinkage technique

2.1 Summary of thermal shrinkage technique

The dominant factor for welding distortion is the thermal strain generated during the welding thermal cycle that eventually becomes compressive plastic strain. The thermal shrinkage technique is a simplified method that models compressive plastic strain by considering only thermal shrinkage during the cooling process after welding (thermal expansion during welding is not considered). A schematic illustration of the thermal shrinkage technique is shown in Fig. 1. The input parameters are the shrinkage strain and the shrinkage zone. Weld distortion is calculated via elastic-plastic analysis by applying the shrinkage strain as the initial strain within the three-dimensional shrinkage zone.

The shrinkage strain ε is calculated using the following equation with thermal expansion coefficient α and temperature change ΔT.

$$\varepsilon = -\alpha \Delta T \quad (1)$$

The shrinkage strain ε is always negative, so the temperature change ΔT must be positive. The shrinkage strain is isotropic in all three dimensions ($\varepsilon_x = \varepsilon_y = \varepsilon_z$) and its value is constant within the

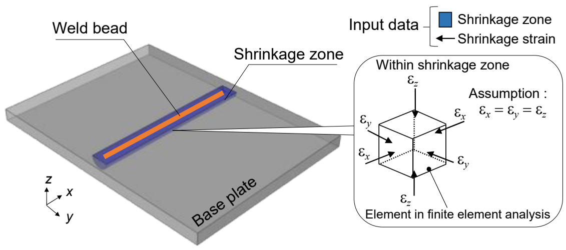

Fig. 1 Schematic illustration of thermal shrinkage technique[4)].

shrinkage zone for convenience. The shrinkage zone is defined as the area where the maximum temperature T_{max} reaches T_a or higher ($T_{max} \geq T_a$) because the range of the inherent strain, which dominates welding distortion, is determined according to the maximum temperature[6].

2.2 Input parameter values of thermal shrinkage technique

Since, the temperature change ΔT, which determines the shrinkage strain ε, and the maximum temperature T_a, which determines the shrinkage zone, are arbitrary parameters, our previous study showed that angular distortion can be accurately predicted for structural steel (thermal expansion coefficient $\alpha = 1.2\times10^{-5}$ (1/°C)) under various welding conditions by setting the temperature change ΔT = 1000°C and the maximum temperature T_a = 500°C. Angular distortion can be accurately reproduced by a convenient method that applies isotropic and uniform strain (shrinkage strain) in a defined region (shrinkage zone) because the input parameter values are determined such that the moment, which is the driving force for angular distortion, is equivalent to the actual moment. Angular distortion is caused by the difference in shrinkage between the top and bottom surfaces of a plate, as shown in Fig. 2. The angular distortion is determined by the moment determined by the product of the shrinkage S and the distance L from the center of the plate in the thickness direction. Previous studies have confirmed that the shrinkage S obtained using the thermal shrinkage technique agrees well with that obtained by thermal elastic-plastic analysis when the above-mentioned parameter values are used. In this study, welding distortion analysis using the thermal shrinkage technique was conducted using the above parameter values to confirm whether angular distortion can be reproduced for a multi-layer welded joint.

3. Experimental and numerical procedure

3.1 Experiment

The material used in this experiment was SM490 steel. The configuration of a specimen is shown in Fig. 3. A welded joint with a V-groove (root gap: 0 mm, root face: 3.0 mm) was fabricated using metal active gas welding. The dimensions of the specimen were 300 mm (length) × 300 mm (width) × 25 mm (thickness). Weld tabs (100 mm × 100 mm × 25 mm) were attached to both ends of the specimen and then multi-layer welding with six passes was carried out[7].

3.2 Thermal elastic-plastic analysis

Thermal elastic-plastic analysis was performed to validate the thermal shrinkage technique. In the thermal conduction analysis, a moving double-ellipsoidal heat source model[8] was utilized. The parameters of this heat source model were set to reproduce the measured shape of the heat-affected zone and temperature history. Following the heat conduction analysis, a thermal stress analysis was performed using the results of the heat conduction analysis as input data to calculate the welding distortion.

3.3 Thermal shrinkage technique

The material properties of SM490 are shown in Table 1. The input parameters were a shrinkage strain of $\varepsilon = -0.012$ ($\alpha = 1.2\times10^{-5}$ (1/°C), ΔT = 1000°C) and a shrinkage zone in which the maximum temperature reached 500°C or higher (T_a = 500°C). The shrinkage zone was determined based on the maximum temperature distribution obtained in the thermal conduction analysis. Figure 4 shows the maximum temperature distribution after each welding pass in a cross section at the center of the welding line. Shrinkage strain was applied in the shrinkage zone where the temperature was 500°C or higher (red + green in the figure) in each welding pass.

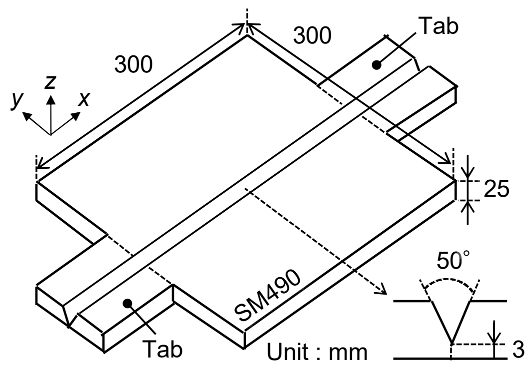

Fig. 3　Butt-welded specimen.

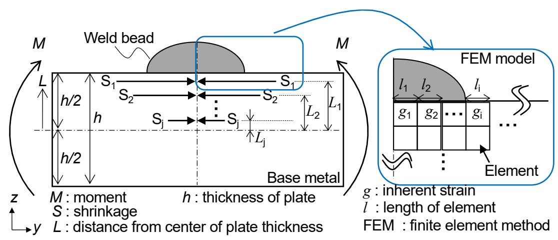

Fig. 2　Schematic illustration of moment[4].

Table 1　Material properties of SM490 used for thermal shrinkage technique.

Young's modulus, E (GPa)	228
Poisson's ratio, ν	0.3
Yield stress, σ_Y (MPa)	338(BM), 442 (WM)
Strain hardening coefficient, H (MPa)	228(BM), 228(WM)

*BM; Base metal, WM; Weld metal

4. Results and discussion

The out-of-plane displacement distribution (*z*-direction) after each welding pass is shown in Fig. 5. The displacements obtained using the thermal shrinkage technique and those obtained in the thermal elastic-plastic analysis were in good agreement for each welding pass. To further evaluate the weld distortion, the angular distortion and transverse shrinkage at the center of the welding line obtained using various methods are compared in Fig. 6 and Fig. 7, respectively.

Figure 6 shows that the angular distortion obtained using the thermal shrinkage technique after the second pass was slightly smaller than those obtained in experiment and thermal elastic-plastic analysis. The shrinkage zone in the second pass covered almost the entire thickness of the specimen, as shown in Fig. 4 (b). In other words, a uniform shrinkage strain was applied to the shrinkage zone, so transverse shrinkage was dominant rather than the moment, which is the driving force for angular distortion. Therefore, the angular distortion was smaller than those obtained in the experiment and thermal elastic-plastic analysis. Although, a slight difference was observed after the second pass, the angular

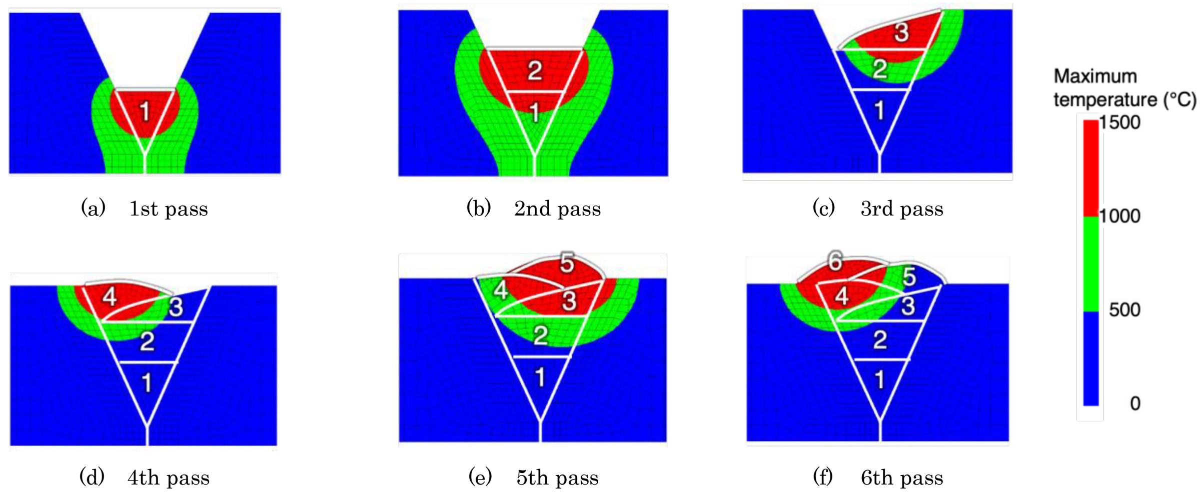

Fig. 4　Maximum temperature distributions obtained in thermal conduction analysis.

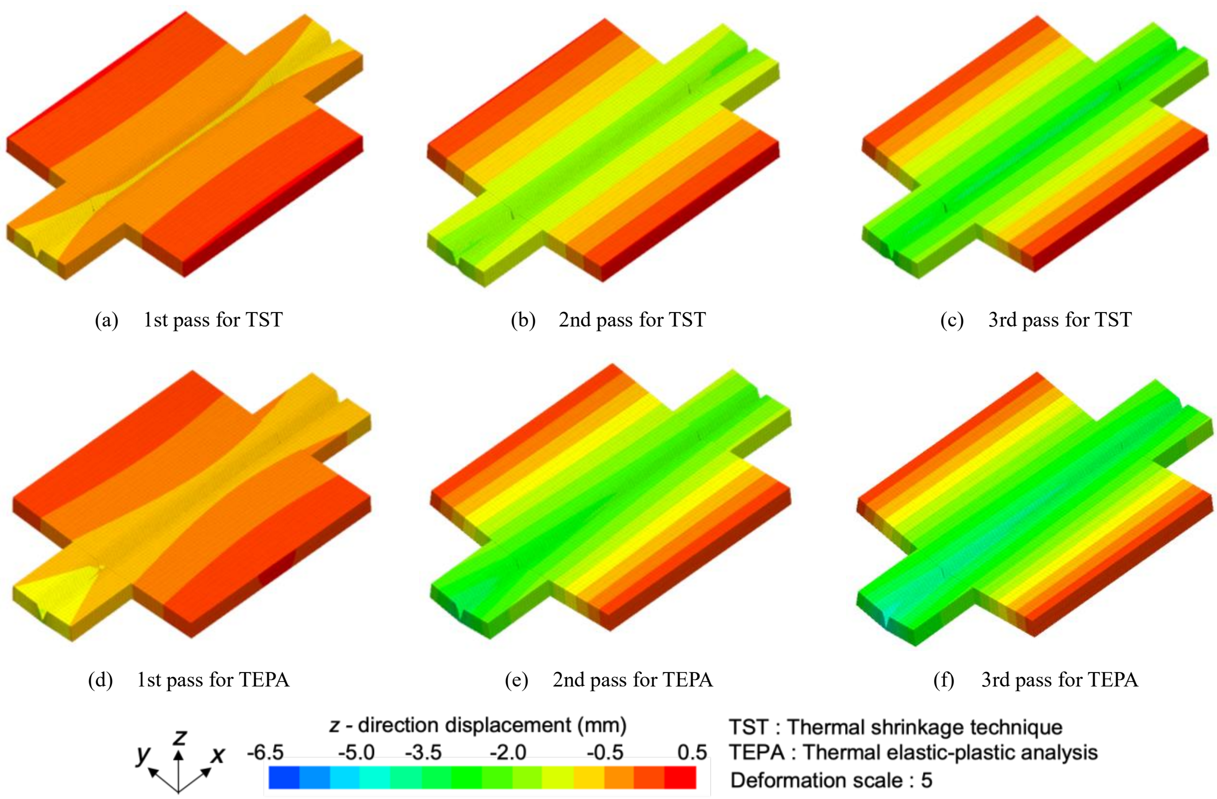

Fig. 5　Comparison of displacement distributions between thermal shrinkage technique and thermal elastic-plastic analysis.

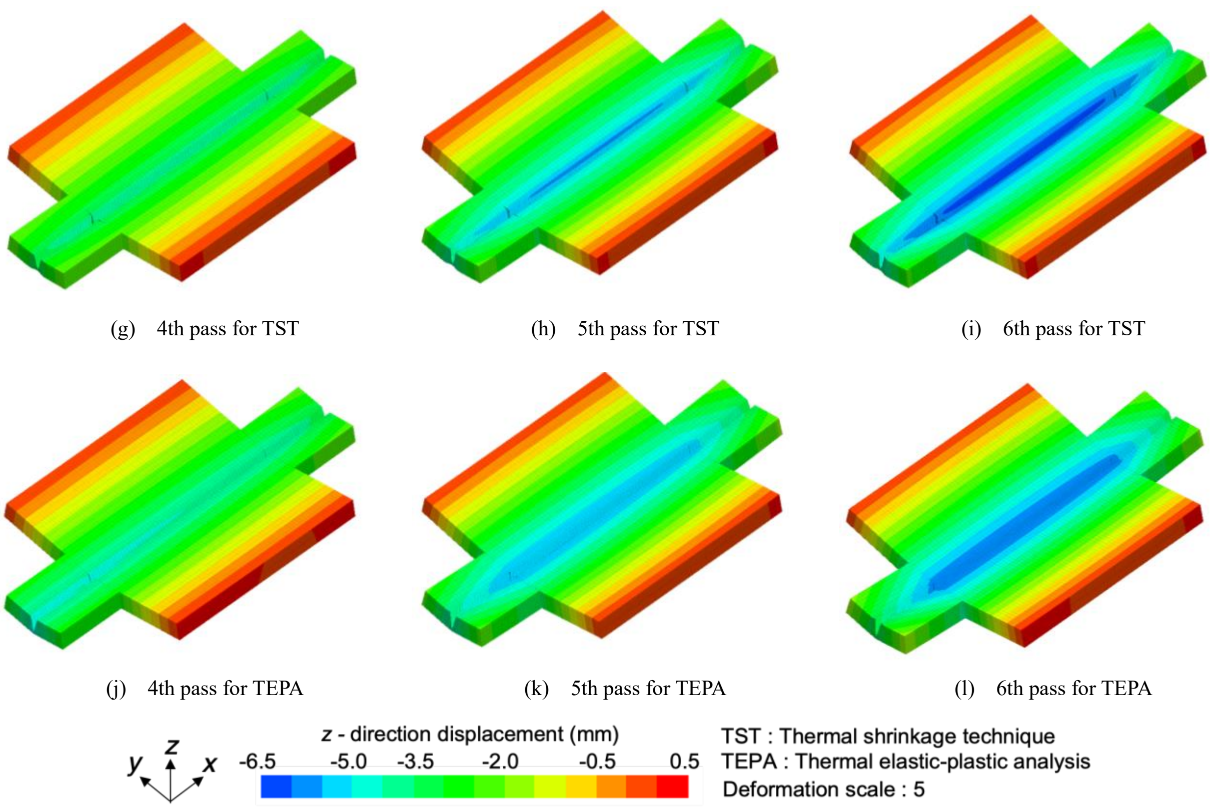

Fig. 5 Comparison of displacement distributions between thermal shrinkage technique and thermal elastic-plastic analysis (Continued).

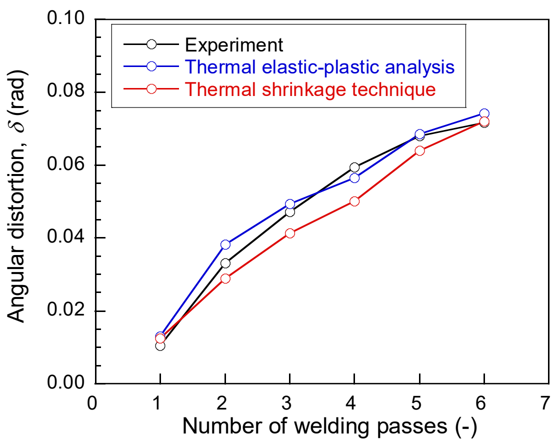

Fig. 6 Comparison of angular distortion among thermal shrinkage technique, thermal elastic-plastic analysis, and experiment.

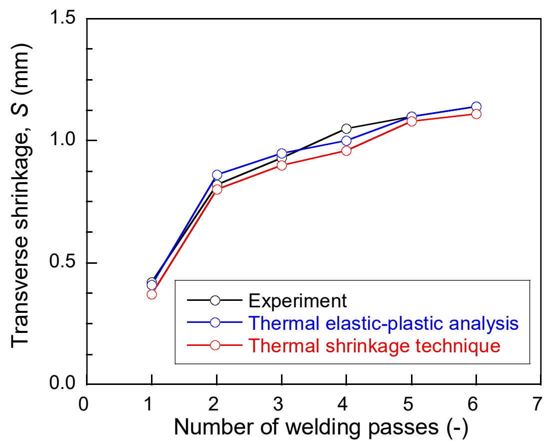

Fig. 7 Comparison of transverse shrinkage among thermal shrinkage technique, thermal elastic-plastic analysis, and experiment.

distortion after all other welding passes was in good agreement.

Figure 7 shows that the transverse shrinkage obtained with the thermal shrinkage technique was in good agreement with those obtained in the experiment and the thermal elastic-plastic analysis for all welding passes. This suggests that the concept of the thermal shrinkage technique, in which the input parameter values are determined such that the moment in the thermal shrinkage technique is equivalent to the actual moment, can be applied to multi-pass welding.

In addition, the longitudinal shrinkage was also evaluated as shown in Fig. 8. The longitudinal shrinkage obtained with the thermal shrinkage technique was smaller than that obtained with the thermal elastic-plastic analysis. The temperature range that dominates longitudinal shrinkage is considered to be $2T_p$[9] ($=2\varepsilon_Y/\alpha$ where ε_Y is the yield strain), and it was 247°C in this study. On the other hand, shrinkage zone where the maximum temperature reaches 500°C or higher was smaller than that temperature range for $2T_p$(=247°C), therefore smaller longitudinal shrinkage was obtained. The longitudinal bending distortion was also slightly smaller in the thermal shrinkage technique for the same reason.

Finally, calculation time for the thermal shrinkage technique and thermal elastic-plastic analysis were compared as shown in Fig. 9.

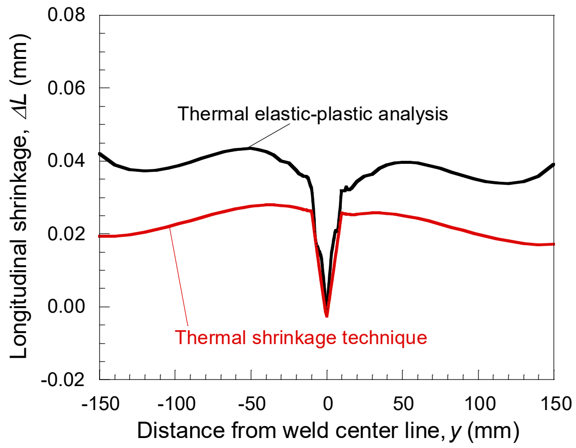

Fig. 8 Comparison of longitudinal shrinkage between thermal shrinkage technique and thermal elastic-plastic analysis.

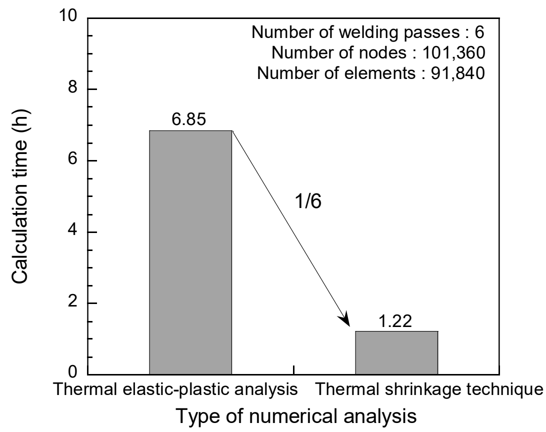

Fig. 9 Comparison of calculation time between thermal shrinkage technique and thermal elastic-plastic analysis.

The calculation time for the thermal shrinkage technique was 1/6 that for the thermal elastic-plastic analysis. The thermal shrinkage technique could be effective for simulating multi-pass welding without a high computational load. Our results demonstrate that the thermal shrinkage technique with the proposed input parameter values could be applicable to multi-layer welded joints.

5. Conclusions

In this study, the thermal shrinkage technique with previously proposed input parameter values for single-pass welding was applied to a multi-layer butt-welded joint with four layers and six passes to validate whether these input parameter values are applicable to multi-pass welding. The results obtained in this study are summarized as follows:

(1) The out-of-plate displacement distributions for a multi-layer welded joint, angular distortion, and transverse shrinkage at the center of the welding line obtained using the thermal shrinkage technique were in good agreement with those obtained by a thermal elastic-plastic analysis and an experiment.

(2) The calculation time for the thermal shrinkage technique was 1/6 that for the thermal elastic-plastic analysis.

(3) Based on the results, the thermal shrinkage technique with the proposed input parameter values could be applicable to multi-layer welded joints.

Acknowledgements

The authors would like to express our gratitude to all parties at the Technical Commission on Welded Structure of the Japan Welding Society for providing of experimental data.

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