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Investigation of welding residual stress distribution in a thick-plate joint with an emphasis on the features near weld end-start

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ABSTRACT

In this study, an advanced computational approach with considering moving heat source, temperature-dependent material properties, strain-hardening and annealing effect was developed to predict welding temperature field, residual stress distribution and deformation in multi-pass welded joints. The welding residual stress distributions in austenitic stainless steel thick-plate multi-pass joints performed by the different deposition patterns and different deposition directions were simulated through using the developed computational procedure. Based on the numerical results, the features of residual stress distribution near the weld end-start location were examined. Meanwhile, experiments were carried out to measure the welding residual stress distributions in two mock-ups. The numerical results are generally in a good agreement with the experimental measurements. Both experiment and numerical model show that the distribution of welding residual stress near the weld end-start location has an apparent discontinuous feature. The research results indicate that deposition pattern has a significant influence on welding residual stress, and it not only can change the distribution shape of residual stress but also can alter the peak value of residual stress. Under the condition of identical deposition pattern, the distribution of welding residual stress seems not sensitive to deposition direction.

1. Introduction

Welding-induced residual stress and distortion are the consequences of the inhomogeneous temperature field arising during welding process. The magnitudes of welding residual stress in a steel structure are often as large as or even larger than the yield stresses of base metal and weld metal. Tensile transient or residual stress is an important factor causing hot crack and cold crack in the course of welding process [1,2]. In addition, tensile residual stress due to welding is one of the major factors resulting in stress corrosion cracking, fatigue damage and brittle fracture during service [3]. Therefore, from the viewpoint of structural safety, it is very important and necessary to obtain welding residual stress distribution in a welded structure.

Generally, there are two methods that can be used to obtain welding residual stress. One is experimental method, and the other is numerical simulation technology. Recent research trends indicate that numerical models based on finite element method have received more and more attention [4,5].

Since the early 1970s, a number of numerical models based on thermo-elastic–plastic finite element method (FEM) have been developed to simulate welding temperature field, residual stress distribution, deformation and even microstructures in welded joints [1,3]. The early contributions to computational welding mechanics were made by Ueda and Yamakawa [6], Hibbit and Marcal [7]. In 1980s, significant achievements include the double-ellipsoid heat source model proposed by Goldak et al. [8] and the material models considering solid-state phase transformation [9,10]. Since the 1990s, three dimensional (3-D) finite element models with considering moving heat source and temperature-dependent material properties have been increasingly employed to predict welding residual stress and deformation [11–13] in typical joints. At the beginning of the 21st century, computational approaches with fast computing speed based on the iterative substructure method (ISM) and *i*-ISM thermo-elastic–plastic FEM [14–16] have been developed to estimate welding residual stress and distortion for large welded structures. Most recently, a number of attempts have been made to simulate welding residual stresses

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in various thick-plate multi-pass joints using full 3-D finite element models [17–20]. The above researches have greatly promoted the development of computational welding mechanics. Meanwhile, welding numerical simulation technology has been playing an important role in engineering applications.

Even though a number of numerical models have been proposed to simulate welding residual stress and deformation, most of them focus on the characteristics of residual stress distribution within the steady region of a weldment. Till present, only a few researches discussed the distribution of welding residual stress near a weld end-start location. Mochizuki and his co-workers [21] discussed the residual stress distribution near the start-finish point in a pipe joint using numerical model. Recently, Turski et al. [22] studied the effect of stop-end features on residual stress in multi-pass 304 stainless steel weld by means of neutron diffraction method and incremental deep hole drilling method. Deng and Kiyoshima [23–25] have investigated the features of welding residual stress distributions near the weld end-start locations in girth-welded austenitic stainless steel joints, thick-plate joints and *J*-groove joints by means of both experimental method and finite element analysis.

The above researches show that the distribution of welding residual stress near the weld end-start location is more complicated than that in the steady region. Therefore, it is necessary to further study the characteristics of welding residual stress distribution near the weld end-start location and to clarify how deposition pattern used in multi-layer and multi-pass joint affects the final residual stress distribution.

In this article, the features of welding residual stress distribution near the weld end-start location in a SUS316 thick-plate multi-layer and multi-pass joint were studied by means of both experimental and numerical methods. Especially, the influences of deposition pattern and deposition direction (welding direction) on final residual stress were examined experimentally and numerically. In addition, a concept named "thermal-end effect" was proposed to explain why the welding residual stress distribution has an irregular distribution around the weld end-start location.

2. Experimental procedure

To examine the features of welding residual stress distribution near the weld end-start in thick-plate welded joints, two experimental mock-ups (Mock-ups I and II) were fabricated in the current study. The material is SUS316 austenitic stainless steel, and the length, width and thickness of the mock-ups are 211 mm, 211 mm and 55 mm, respectively. The dimensions of the experimental mock-ups are shown in Fig. 1. To remove the initial residual stress induced by manufacturing process, these two mock-ups were annealed at 900 °C, and held for 2 h, then slowly cooled down to room temperature. The details of groove are shown in Fig. 2, and the deposition sequences of the two mock-ups are shown in Fig. 3. In Mock-up I, all weld runs started at the both ends (A-side or B-side) of plate and ended at the middle of plate. In Mock-up II, half of weld runs started at the left end (A-side) of plate and ended at the middle of plate, and half of weld runs started at the middle of plate and ended at the right end (B-side). In the both mock-ups, the total number of weld runs is 24, and the order of weld runs is shown in Fig. 1. As mentioned above, the difference between Mock-ups I and II only is the deposition direction.

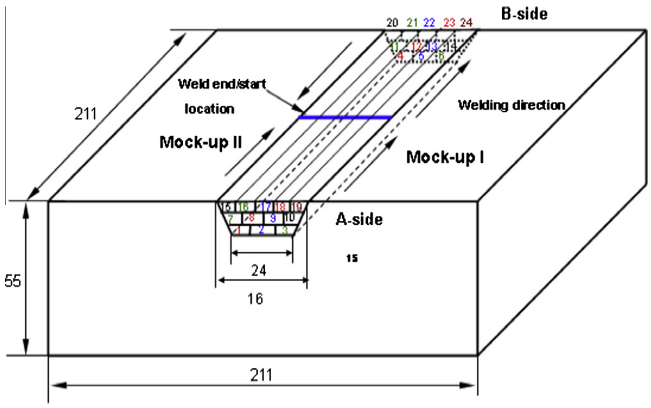

Fig. 1. Geometry of groove-welded plate along with the locations of individual weld beads as determined from a companion GTAW test weld.

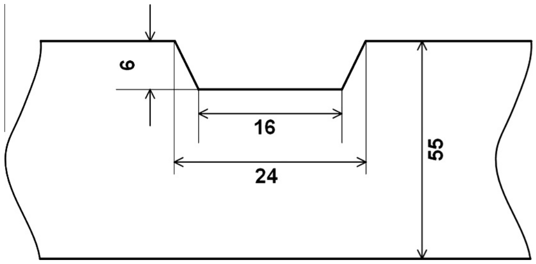

Fig. 2. Dimension and shape of groove.

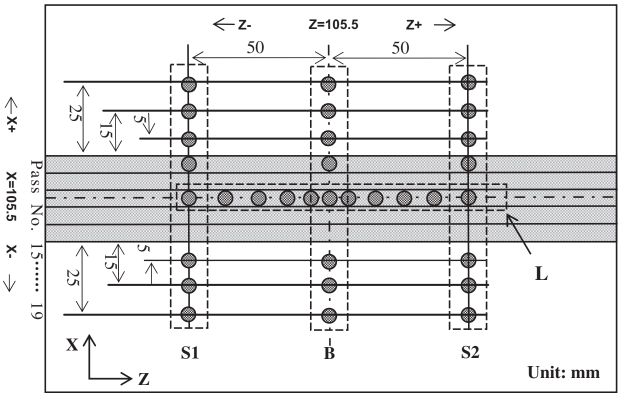

Fig. 3. Arrangements of strain gauges on the top surface of welded joint.

In the experiments, gas tungsten arc welding (GTAW) process was used to perform the welding. The filler metal is Y316, and its chemical components are similar to those of the base metal. The welding conditions are shown in Table 1. For all weld runs, the welding parameters are identical, and the inter-pass temperature was controlled to be lower than 100 °C.

In this study, it was assumed that the stress component on the weld bead surfaces in the thickness direction could be neglected. For the sake of convenience, only the longitudinal and transverse residual stresses were measured on the surface of weld metal through using electrical strain gauge with 1 mm length. The locations of strain gauges are shown in Fig. 3. To obtain the released strain components, wire-cut method was used to divide the mock-up into small pieces. After recording the released strain components, the longitudinal residual stress (σ_L) and the transverse residual stress (σ_T) were calculated by the following two equations.

$$\sigma_L = -\frac{E}{1-\nu^2}(\varepsilon_L + \nu\varepsilon_T) \tag{1}$$

$$\sigma_T = -\frac{E}{1-\nu^2}(\varepsilon_T + \nu\varepsilon_L) \tag{2}$$

where E is Young's modulus, ν is Possion's ratio, ε_L and ε_T are the released strains in longitudinal and transverse directions, respectively.