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Finite element analysis of residual stress distribution in a thick plate joined using two-pole tandem electro-gas welding

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ABSTRACT

A computational approach considering moving heat sources was introduced to predict the residual stress distribution produced by electro-gas welding (EGW) joints. Considering the two-pole tandem of EGW, a finite element analysis (FEA) was suggested to evaluate the thermal behavior of EGW applied to a joint of ultra-thick plates. Based on a thermo-mechanical FEA, the profiles of the residual stresses are investigated for EH40 thermo-mechanical control process (TMCP) steel plates with a thickness of 80 mm. In order to simulate the weaving motion of two weldment poles, a quasi-steady heat flux model is introduced based on Goldak's double ellipsoidal heat source model. The X-ray diffraction methods were used to measure the residual stress field on the surface treated by chemical polishing. The residual stress profiles determined by the FEA and measurement showed quite good agreement, as regards the values both peaks and of the profile. Residual stresses relieved by post-weld treatments, particularly by ultrasonic peening and toe grinding, is also presented.

1. Introduction

Recently, the major shipyards have begun using thermos-mechanically controlled ultra-thick plates with thicknesses of more than 70 mm and yield strengths of approximately 460 MPa, in order to meet the strength requirements near the upper deck and hatch coaming area of very large container carriers. These ships transport containers from 10,000 to 18,000 twenty-foot equivalent units (TEU) (Park et al., 2007; Han et al., 2009). The shear strakes or deck plates of a large container carrier and FPSO vessels are fabricated by joining the ultra-thick plates. Traditionally, welding processes such as submerged arc welding (SAW) and flux-cored arc welding (FCAW) are preferred for welding these thick plates. FCAW is used more widely in many shipyards, particularly for butt welds during the erection procedure and for vertical butt welds during the joining process of the side shell. FCAW has some benefits over other processes in that it is relatively easy to automate and requires less heat input, both of which are key parameters for improving productivity during the fabrication process of large merchant ships. FCAW always entails a relatively large number of welding deposits, normally more than 15, for the thick-sectioned plates, eventually leading to low productivity. EGW is considered to be an alternative process that may replace the traditional FCAW process due to its higher welding speed and better efficiency.

Electro-gas welding (EGW) is a continuous vertical position arc welding process in which an arc is struck between a consumable electrode and the work piece. EGW entails higher heat input than other welding processes such as SAW or FCAW because it requires only one or two layers of thick weld bead. The high heat input can induce a larger tensile residual stress at the weld toe, leading to reduced fatigue strength. Therefore, the shipping classification society began to focus on the fatigue strength of a thick section weldment, (thickness of more than 65 mm), because of the undesirable consequences induced by the applied welding process (Bang et al., 2009). Some authors claim that deeper investigations need to be undertaken in terms of the residual stress and fatigue strength between thick-sectioned welded joints fabricated by the FCAW and EGW processes (Teng and Chang, 2004).

As a result of the advantages and disadvantages of both processes, a hybrid FCAW and EGW process, wherein, the two processes are combined, and the tandem EGW process, wherein the two electrodes are positioned in a row, have been proposed as shown in Fig. 1 (Sasaki et al., 2004). Welding-induced residual stress and its adverse effects on fatigue strength are still in question for these newly proposed welding processes. Therefore, a detailed investigation of the distribution of residual stress through

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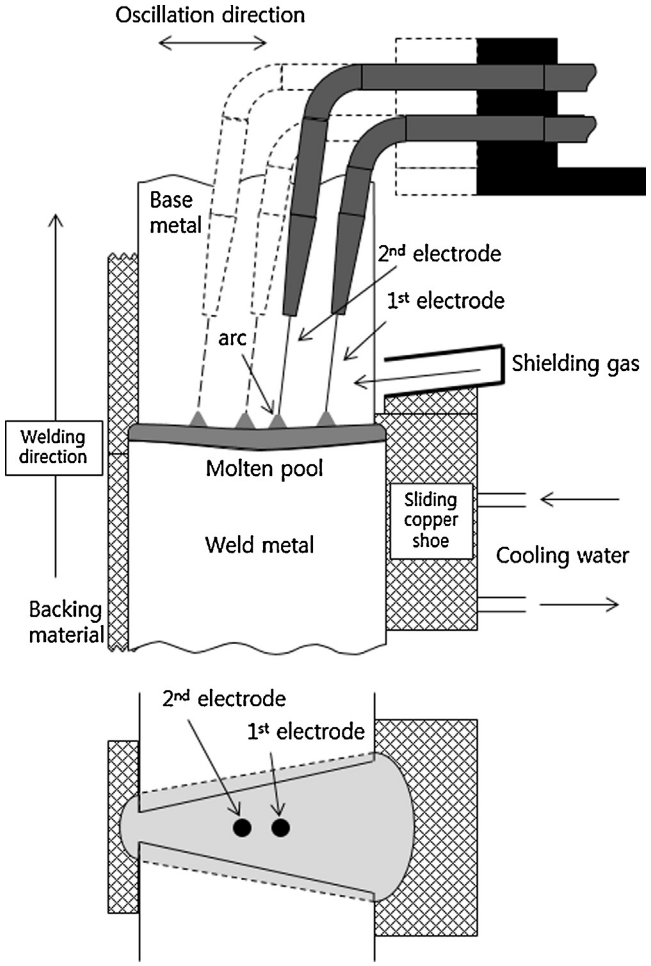

Fig. 1. Schematic diagram of two-electrode EGW (Sasaki et al., 2004).

advanced numerical analysis and a reliable measurement technique are required.

In this study, a numerical analysis procedure for a three-dimensional (3-D) nonlinear elasto-plastic finite element analysis that targets the prediction of the residual stress distribution of a butt-welded joint made by a tandem EGW process was developed. In addition, the actual residual stress induced by the local heat-up and cool-down processes was measured, and the results are compared with the results from numerical analysis.

What distinguishes a numerical simulation of the tandem EGW from other traditional methods such as gas metal arc welding (GMAW) and FCAW is the vertical motion and weaving of the welding electrodes of EGW, which is the main source of the larger volume molten pool formation. A numerical simulation of the traditional welding process typically only considers the transverse steady movement of the electrode, but some transient motion of the electrode in the tandem EGW process creates difficulties. Because the difficulties are linked to the large heat input of the weaving electrodes, previous numerical studies have been limited to the two-dimensional simulation (Bang et al., 2009). In the present study, X-Ray diffraction (XRD) was used to measure the distribution of weld residual stresses on the surface of a butt-welded joint joined by tandem EGW. For validation, the measured residual stress field was compared with the numerical analysis results, and the complicated motion of the welding electrode with high heat input was considered. The commercial finite element program MSC.Marc was used in the analysis.

Table 1
Chemical composition of EH40 (wt%).

C	Si	Mn	P	S	Ni
0.08	0.03	1.56	0.009	0.0013	0.01

Table 2
Mechanical properties of EH40.

Steel	Thickness (mm)	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)
EH40	80	470	582	25

Table 3
Welding conditions of tandem EGW.

Welding conditions	Electrode number	
	1	2
Current (A)	380	380
Voltage (V)	42	42
Speed (cm/min)	2.8	2.8
Heat input (kJ/mm)	34.47	34.47
Total heat input (kJ/mm)	68.95	

2. Material and welding conditions

The material used in this study is TMCP EH40 steel, which is less susceptible to thermal cycling during the welding process. Fig. 2 shows the weld condition and Fig. 3 shows the test specimens cut from welded plates. Table 1 and Table 2 summarize the chemical composition and mechanical properties of the material, respectively.

The specimen was fabricated according to a welding process currently practiced in shipyards. Fig. 2 shows the arrangement of the two plates prior to being joined together, along with the detailed groove shape. The tandem EGW process was applied to the vertically arranged plates, with two electrodes moving upward with a weaving motion to generate a molten pool with a larger volume. The shape of the molten pool normally depends on factors including the welding current, speed, weaving motion, and root gap of the groove. The size of the plates was 1250 × 2400 mm with a thickness of 80 mm, and the root gap of the V-groove was 10 mm with an angle of 20°.

Table 3 lists the welding conditions of the tandem EGW as applied to specimen fabrication. The same values of electric current, voltage, and speed were applied to both electrodes.

3. Residual stress measurement

Residual stresses remain after welding due to non-uniform thermal cycling during the welding process. The local heat-up tends to generate a stress field during the heat-up process, and the stress can easily reach the yield strength locally due to the lower yield strength at elevated temperatures. This process can leave a nonuniform permanent plastic strain field (Joshi et al., 2010). After cool-down, the induced permanent plastic strain field acts as an internal restraint and causes an elastic stress field, which is called the residual stress. The thermal cycle leaves not only a residual stress field but also a change in mechanical properties depending on the thermal cycle history at a given location. Several different types of residual stress measurement techniques can be used, such as the hole-drilling method, X-ray diffraction (XRD), neutron diffraction, ultrasonic methods, the Barkhausen noise method, and magnetic methods. XRD and the neutron diffraction method are non-destructive methods using radiation based on the volume difference between the normal and distorted alignment of lattices of the material (Price et al., 2008). XRD, which is one of the most