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Arc interaction and molten pool behavior in the three wire submerged arc welding process

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ABSTRACT

A three-dimensional numerical heat transfer and fluid flow model is developed to understand the temperature distribution and molten pool behavior in a three wire submerged arc welding process. The model solves the equations of the conservation of mass, momentum, and energy along with the volume of fluid method. The volume of fluid method is used to track the shape of the free surface. Further, a physical model is developed to estimate the arc center displacement. For a given welding condition, connecting the leading electrode with direct current electrode positive polarity, the middle and trailing electrodes with trapezoidal alternating current waveform displayed deeper weld pools when compared to the sine waveforms. Within the range of welding conditions considered in the present work, weld width is significantly influenced by the leading arc whereas the penetration by the middle and trailing arcs. The computed weld width and penetration are in fair agreement with the corresponding experimental results.

1. Introduction

In any welding process, the temperature distribution and fluid flow decides the final weld bead dimensions, microstructure and the mechanical properties. The presence of multiple arcs and the associated arc interaction and molten metal deposition, increase the complexity in understanding the heat transfer and fluid flow in a three wire submerged arc welding process. Furthermore, analyzing the weld pool temperature distribution and velocity fields is very difficult experimentally. Instead, numerical process models help in understanding the same in a more efficient and economical way.

Although significant efforts have been put forth to understand the weld pool heat transfer and fluid flow in the deposition welding process like gas metal arc welding (GMAW), there has been little corresponding research on the submerged arc welding (SAW) process and its multi-wire variants. Pathak and Datta [1] proposed a finite element based conduction heat transfer model to analyze the single wire SAW process. A Gaussian distributed surface heat source was used to simulate the heat transfer from the welding arc. The filler metal deposition was not modeled adequately. Mahapatra et al. [2] reported a similar model using an element deactivation and activation approach to account for the addition of filler material. Goldak et al. [3] introduced a double-ellipsoidal volumetric heat source model to account numerically the heat transport inside the weld pool in a conduction based heat transfer analysis. Kiran et al. [4] performed a three-dimensional heat transfer analysis of the two wire tandem SAW (SAW-T) process. A novel application of two independent double ellipsoidal volumetric heat sources was used to account for the heat transfer from the leading and trailing arcs. However, the dimensions of the heat sources were decided from the weld bead dimensions. Kiran et al. [5] proposed a methodology to estimate the double ellipsoidal volumetric heat source dimensions based on the original joint geometry and welding conditions in SAW-T process. Nevertheless, the above described conduction heat transfer based weld pool simulations often fail to account for the convective transport of heat inside the pool, which can be significant, in particular, for a large weld pool generated in SAW process.

Cho et al. [6] developed a three-dimensional heat transfer and fluid flow model for the single wire SAW process. The influence of torch angle on the fluid flow and convective heat transfer was analyzed. It was reported that different torch angles and effective radii of the arc plasma could induce different weld bead shapes based on flow patterns. The volume of fluid (VOF) technique was used to calculate the accurate shape and motion of the free fluid surfaces. Kiran et al. [7] studied the arc behavior in SAW-T process and developed an arc interaction physical model to estimate the

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leading and trailing arc center displacements. Furthermore, few regression models were presented to estimate the effective radii of the leading and trailing arcs as a function of the welding current, voltage and arc center displacement. This information was further utilized in the heat transfer and fluid flow analysis of SAW-T process [8].

In summary, although numerical studies are available to understand the heat transfer and fluid flow in the single wire and two wire tandem SAW processes, no attempts have been made until now to address the same issues in a three wire SAW process. Here, the authors perform a three-dimensional transient heat transfer and fluid flow analysis of the three wire SAW process using the commercial CFD software. Three independent Gaussian distributed surface heat sources are used to account for the heat transfer from the three welding arcs. A physical model is developed and used to implement the arc interaction and droplet transfer direction in the numerical modeling of the three wire SAW process. The computed weld pool dimensions are validated with corresponding experimental results.

2. Experimental investigation

Fig. 1 depicts the double V-groove joint design and the orientation of electrodes used in the present work. The dimensions of the HSLA steel plate confirm to 1000 mm × 300 mm × 25.4 mm (thickness) with groove angle and depth of (50^0,*** 8.4 mm) and (50^0, 10.0 mm), respectively on the top and bottom of the plate. The leading, middle and trailing electrode diameters, and inclination angles confirm to (3.15, 3.15, 4.0 mm) and (-15^0, 5^0, 18^0),*** respectively. Table 1 gives the welding conditions used to perform bead-on-groove experiments using the three wire SAW process. The terms (I_L, V_L), (I_M, V_M), (I_T, V_T) and v in Table 1 refer to the leading arc current and voltage, the middle arc current and voltage, the trailing arc current and voltage, and the welding speed, respectively. The leading electrode is connected to the direct current electrode positive polarity (DCEP), and the middle and trailing electrodes are connected to the AC power sources. A phase shift of 90^0 is maintained between the middle and trailing arcs. The flux and the electrode combination confirm to AWS A5.23 specification. The instantaneous current waveforms corresponding to the leading and middle arcs current are monitored in real time with LEM current sensors by placing them in the welding circuit. The leading and middle arcs instantaneous voltage waveforms are monitored using two voltage pick-up points – one at the corresponding power source terminal and the other at the torch terminal of the welding machine. The sampling rate to record the current and voltage transients is set to 2.0 kHz. Note that the trailing arc instantaneous current is not measured due to the unavailability of the third current sensor. The arc images are recorded using CCD camera at a sampling rate of 1.0 kHz. The procedure to capture the arc images in a multi-wire SAW process is available in our previous work [7].

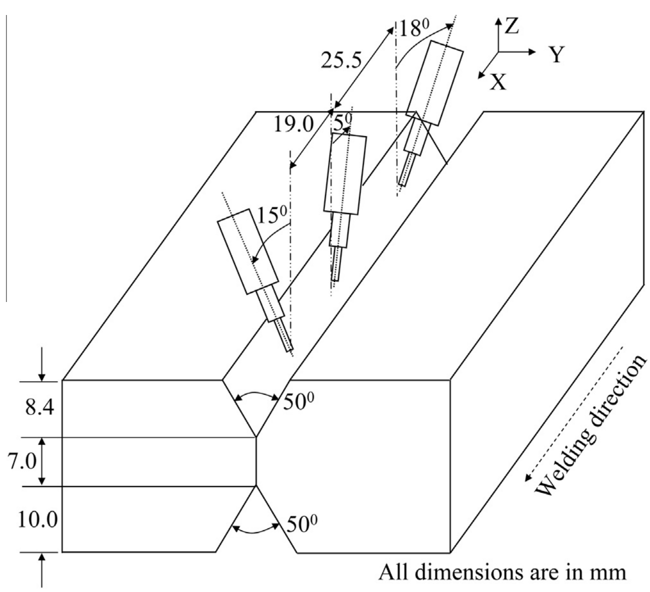

Fig. 1. Schematic representation of the joint design and electrode orientation.

3. Physical model of arc interaction in the three wire SAW process

The physical model of arc interaction in the two wire tandem SAW process, developed in our previous work [7] is extended to three wire SAW process here. Hence, the detailed procedure of the physical model derivation is not repeated. Figs. 2 and 3 schematically depict the procedure followed to derive the arc interaction physical model to calculate the leading arc center displacement only. The procedure to derive the middle and trailing arcs centre displacements are similar to that of the leading arc. Hence the same is not explained in the present manuscript. Initially, the leading, middle and trailing arcs are assumed as three independent arcs without any arc interaction. The corresponding arc orientation is shown in Fig. 2(a). The axes RR^1 and RT are the leading electrode and arc axes, respectively. Similarly, the axes (OO^1, OQ) and (YY^1, YF) are the middle and trailing electrode and arc axes, respectively.

Based on the literature [7,9] significant arc inclination is not observed for the electrode axis angles and the welding conditions considered in the present work. Hence, all the arcs are assumed to be perpendicular to the base plate (as shown in Fig. 2(b) and (c)). Fig. 2(b) and (c) also depict the orientation of the electro-magnetic field applied by the middle and the trailing arcs, respectively, on the leading arc centre. The detailed explanation of such kind of orientations was already explained elsewhere [7] and hence not repeating here.

When the leading, middle and trailing arcs having arc lengths of l_L, l_M and l_T, respectively, are brought closer to a distance of d_{LM} and d_{LT}, termed the inter-electrode distance, Lorentz force is generated on these arcs due to the magnetic field produced by each of them.

Table 1
Design table for three wire tandem submerged arc welding experiments.

Case	Waveform	Top groove					Bottom groove				
		I_L (A)	I_M (A)	I_T (A)	v (mm/s)	HI (kJ/mm)	I_L (A)	I_M (A)	I_T (A)	v (mm/s)	HI (kJ/mm)
1	Trapezoidal	1000	900	800	30.0	3.08	1000	900	800	25.7	3.59
2	Sine	1200	900	800	36.4	2.71	1200	900	800	29.4	3.36
3	Trapezoidal	1200	900	800	36.4	2.71	1200	900	800	29.4	3.36

* V_L, V_M and V_T are constant at 32, 35 and 36 V, respectively, for all the sets.
** Experiment is not done for case 3. Only numerical simulation is performed.