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Thermal metallurgical analysis of GMA welded AH36 steel using CFD–FEM framework

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ABSTRACT

A temporal combination of CFD mass and heat transfer, and FEM conductive heat transfer analysis was conducted using a proper temperature history implantation scheme. The phase distribution in an AH36 steel weldment was predicted and compared with experimental results. The numerical phase fraction estimation was performed using the critical austenite temperature model in the heating process as a function of heating rate. The CCT information based transformation starting and finishing temperature, and the maximum phase fraction models were utilized with instant cooling rate in the cooling process. The thermal analysis result agreed well with the FZ shape and measured temperature history. The calculated hardness slightly overestimated the measured hardness. The steep reduction of hardness in the HAZ and the tempered zone was much more affected by the change in austenite critical temperature than the cooling rate. Based on the potential results of this work, predicting weldment deformation by considering phase transformation will be extended.

1. Introduction

Welding procedures, especially the gas metal arc welding (GMAW) process, have frequently been investigated by numerical approach due to the difficulties of experimental observation. As a numerical thermal analysis method, the finite element method (FEM) has been used from the early days of computational simulation. The surface model, the volumetric model, and their combination are employed as the heat source, with analytically assumed dimensions for each heat source model. Artificial thermal properties are used to account for heat transfer due to fluid flow in the weld pool, by a limitation of the conductive heat transfer analysis. Additionally, the bead shape of the weldment is predefined by experimental results. Nevertheless, FEM is still used to model the welding process due to its relatively short computational time and good agreement with experimental results. Moreover, its accessibility to stress analysis is an advantage.

Meanwhile, the finite difference method (FDM) [1–10] and computational fluid dynamics (CFD) [11–15] have also been employed for numerical thermal analysis. The advantages of FDM and CFD are that they can account for heat and mass flows, including filler metal behavior, arc pressure, electromagnetic force (EMF) and measured heat source model. In these approaches, the fluid flow inside of the molten pool is revealed, and accuracy is more trustworthy. In spite of those advantages, FDM and CFD need more computational power and time to get the same amount of results obtained by FEM analysis.

Numerical predictions of phase transformation in the cooling process begin with the heat treatment process [16] with time–temperature-transformation (TTT) diagram, and continuous cooling transformation (CCT) diagram data. These data are built from the constant temperature condition or constant cooling rate condition. The welding process does not occur at a constant temperature and or constant cooling rate, but previous researchers [17–20] have made prediction of phase transformations with additional assumptions and hypothesis. The main target has been the prediction of weldment deformation, but the phase fraction of the weldment has not been validated yet. However, recent FEM based welding deformation studies are extended to the various types of weld joints [21–26], materials [27], and process conditions [28–29]. Also metallurgical investigations [30–32] are carried out for welding procedure. The validated numerical prediction scheme of phase transformations with the legacy of recent welding deformation studies might lead to more reasonable result of the numerical prediction process.

In order to compare a numerical thermal analysis with a weldment deformation prediction, in this study, the phase distribution in an AH36 steel weldment was predicted and compared with experimental results. The validated temperature history was incorporated using the results of two thermal analysis methods' for better accuracy and shorter computational time. The mass and heat flow analysis results from CFD were adopted from welding start to solidification, and the conductive thermal analysis results in FEM were employed for the cooling process. A new assumption of austenite critical temperature, with more complicated CCT diagram's fit by cooling rate and simplified fraction calculation model with constant thermal properties, was employed for predicting phase distribution.

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Table 1
Welding conditions.

Feed rate m/min	Current A	Voltage V	CTWD mm	Welding speed mm/s	Electrode diameter mm	Shielding gas L/min
7.5	237.7	26.9	28	10	1.2	Ar20%CO/20

2. Methodology

2.1. Experiment and measurement

Table 1 gives the welding conditions used to produce a bead on plate (BOP) welding AH36 steel plate of 160 × 89 × 6 mm (thickness) using the GMAW process. Table 2 outlines the chemical composition of the base plate and the electrode wire. Fig. 1 explains the thermal cycles and the locations used for measuring micro hardness. Four K-type thermocouples were spot welded on the weldment bottom surface. The temperature data was recorded at a sampling rate of 2 Hz. The instantaneous welding current and voltage data were measured with open loop Hall Effect transducer and subsequently recorded at a sampling rate of 1 kHz. The welding arc images and droplet transfer were captured using a high-speed camera.

The weldment cross-sections were cut along the AA′, BB′ and CC′ lines, as shown in Fig. 1b. Next, these cross-sections were etched with 2% Nital solution to see the fusion zone (FZ) and the heat affected zone (HAZ). Further, the hardness distribution was measured using Vickers hardness tester (Akashi HM-124) by applying a force of 1 kgf for 15 s dwell time. A distance of 3.0 mm was maintained between the indentations [33]. The measured thermal cycles and the hardness distribution were utilized to validate the temperature distribution and the phase fractions calculated from the numerical model, respectively. The arc images information was utilized to measure the effective arc root dimension [34], and the droplet diameter and speed.

2.2. Thermal analysis

2.2.1. CFD–FEM framework

The temperature history was incorporated from the results of two thermal analysis methods' for the better accuracy and shortened computational time (Fig. 2). CFD mass and heat flow analysis results were adopted from welding start to solidification (period 1) and FEM conductive thermal analysis results were employed for the cooling process (period 2). As the initial condition for period 2, the temperature distribution of the end step of the period 1 CFD result was applied to the whole solution domain. The same thermal properties were used for continuity of temperature history.

2.2.2. The heat and mass transfer analysis in CFD simulation

A set of governing equations were solved together with the process models to analyze the heat and mass transfer in the CFD simulation. The same operation was performed using CFD commercial software, Flow3D [35]. The governing equations included the continuity, momentum, energy, and the volume of fluid (VOF) equations as explained by Eqs. (1)–(4), respectively. The VOF equation was utilized to track the fluid free surface.

$$\nabla \cdot \boldsymbol{V} = \frac{\dot{m}_s}{\rho} \tag{1}$$

$$\frac{\partial \boldsymbol{V}}{\partial \boldsymbol{t}} + \boldsymbol{V} \cdot \nabla \boldsymbol{V} = -\frac{1}{\rho}\nabla p + \frac{\mu}{\rho}\nabla^2 \boldsymbol{V} - K\boldsymbol{V} + \frac{\dot{m}_s}{\rho}(\boldsymbol{V_s}) + G \tag{2}$$

$$\frac{\partial h}{\partial t} + \boldsymbol{V} \cdot \nabla h = \frac{1}{\rho}\nabla \cdot (k\nabla T) + h_s \tag{3}$$

$$\frac{\partial \mathrm{F}}{\partial t} + \nabla \cdot (\boldsymbol{V} F) = \dot{F}_s \tag{4}$$

A set of GMAW process model were applied as the boundary conditions. These included the arc heat source, droplet heat source, arc pressure, electromagnetic force, drag force, and the heat loss model, as explained by Eqs. (5)–(10), respectively. The effective radius of the arc, droplet size, and impingement droplet speed were taken from the process image analysis. The detailed procedure and the model description have already been explained elsewhere [13–15].

$$q_{arc} = \frac{\eta VI}{2\pi\sigma_x\sigma_y} \exp\left\{-\left(\frac{x^2}{2\sigma_x^2}\right) - \left(\frac{y^2}{2\sigma_y^2}\right)\right\} \tag{5}$$

$$q_{droplet} = \frac{4}{3}\pi {r_d}^3 \rho \{C_s(T_s - T_{amb}) + C_l(T_{droplet} - T_l) + h_{sl}\} f_d \tag{6}$$

$$p_{arc} = \frac{\mu_0 I^2}{8\pi}\left(2\ \ln\frac{r_{arcroot}}{r_{arctip}} + 1\right)\frac{1}{2\pi\sigma_x\sigma_y}\exp\left\{-\left(\frac{x^2}{2\sigma_x^2}\right) - \left(\frac{y^2}{2\sigma_y^2}\right)\right\} \tag{7}$$

$$F_x = -J_{ze} \times B_{\theta e}\frac{x}{r_e} \tag{8-1}$$

$$F_y = -J_{ze} \times B_{\theta e}\frac{y}{r_e} \tag{8-2}$$

$$F_z = -J_{re} \times B_{\theta e} \tag{8-3}$$

$$J_{ze} = \frac{I}{2\pi}\int_0^\infty \lambda J_0(\lambda r_e)\exp\left(-\frac{\lambda^2\sigma_x}{2}\right)\frac{\sinh\{\lambda(c-z)\}}{\sinh(\lambda c)}d\lambda \tag{8-4}$$

$$J_{re} = \frac{I}{2\pi}\int_0^\infty \lambda J_1(\lambda r_e)\exp\left(-\frac{\lambda^2\sigma_x}{2}\right)\frac{\cosh\{\lambda(c-z)\}}{\sinh(\lambda c)}d\lambda \tag{8-5}$$

$$B_{\theta e} = \frac{\mu_m I}{2\pi}\int_0^\infty J_1(\lambda r_e)\exp\left(-\frac{\lambda^2\sigma_x}{2}\right)\frac{\sinh\{\lambda(c-z)\}}{\sinh(\lambda c)}d\lambda \tag{8-6}$$

$$\tau = G2\left(\frac{r}{H}\right)\frac{\rho U_0^2}{Re_0^{1/2}\left(\frac{H}{D}\right)^2} \tag{9}$$

$$q_{loss} = h_{conv}(T_{surf} - T_{amb}) + \sigma_{SB}\varepsilon\left(T_{surf}^4 - T_{amb}^4\right) \tag{10}$$

Table 2
Chemical composition of AH36 and SM70.

Chemical composition wt.%	C	Si	Mn	P	S	Cr	Ni	Cu	Mo	Nb	Ti	V	Al
AH36	0.157	0.392	1.501	0.014	0.003	0.030	0.010	0.015	–	0.002	0.003	0.003	0.042
SM70	0.07	0.83	1.48	0.017	0.020	–	–	–	–	–	–	–	–