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A study on transient flow characteristic in friction stir welding with real-time interface tracking by direct surface calculation

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ABSTRACT

A numerical analysis model of friction stir welding was suggested by the direct interface area calculation method aided for axisymmetrically and non-axisymmetrically shaped tools. A general moving object was used to represent the tool movement based on the commercial CFD software. The plunging and welding processes were performed in the Eulerian description. Based on energy conservation laws, the torque induced power input, interface friction heat, and plastic deformation heat were modeled and evaluated. The measured temperature and torque were compared with the calculated results. The results of the combined error mode showed the conditionally acceptable results. The proposed model could be used for the torque and temperature prediction with a relatively short calculation time.

1. Introduction

Friction stir welding (FSW) is a solid-state joining process that uses a non-consumable tool to join two or more different workpieces. As one of the solid-state joining techniques, the FSW process does not involve melting of the material, which allows it to avoid many of the disadvantages of conventional fusion welding processes. However, as in the conventional fusion welding process, it is difficult to observe the characteristics of material flows in the FSW process with experimental methods. In light of the limitations of experimental investigation, numerical analyses of the FSW process have been carried out using various numerical methods (Dialami et al., 2017b).

The FSW process involves the generation of heat, which is produced by friction and pressure between the tool and weldment, which are pressed together. As a result of the generated heat, the weldment surfaces in contact soften, become plasticized and mix (Yilbas and Sahin, 2014). Modeling of the thermo-mechanical behavior is an essential part of the numerical analysis of the FSW process.

The trend in the development of the numerical analysis of the FSW process over the last five years can be summarized as follows. Ji et al. (2012) examined the effect of tool geometry on material flow with an assumed temperature and a tool-weldment boundary condition using the Finite Volume Method (FVM). Al-Badour et al. (2013) reproduced void formation, which was affected by the friction coefficient, in the Finite Element Method (FEM). An FVM based numerical analysis considering viscous heat dissipation as a heat source (Albakri et al., 2013) was suggested, which compared experimental peak temperatures. Buffa et al. (2013) calculated the FSW process in the Eulerian description (tool moving) considering a plunging and welding process with frictional heat at the tool and weldment interface, using FEM. Chen et al. (2013) suggested an FVM analysis method which considered a volumetric plastic deformation heat source. Veljić et al. (2013) calculated the thermo-mechanical behavior of the FSW process considering Interface Fraction Heat (IFH) and Plastic Deformation Heat (PDH) for the plunging process using FEM. Shi et al. (2015) reproduced an ultrasonic vibration enhanced FSW process considering IFH, PDH, and a sonotrode-workpiece contact heat source in FVM. The Material Point Method (MPM) based numerical model was suggested, which considered the tilted tool condition in the Eulerian description (Fagan et al., 2016). Jalili et al. (2016) suggested a simple analysis model without taking into account tool-weldment interaction, to calculate thin plate deformation and residual stress. Instead of heat generated by the tool-weldment interaction, heat generation by PDH was implied with a presumed maximum strain rate.

In 2017, studies on the numerical analysis of FSW process steps moved towards modeling actual process conditions. Dialami et al. (2017a) evaluated the effect of a tool pin shape with a non-axisymmetric shape considering tool-weldment interaction in the Arbitrary Eulerian-Lagrangian (ALE) analysis environment. Also, Tongne et al. (2017) successfully reproduced voids, considering the material flow of the FSW process with a trivex type pin shape using the Coupled Eulerian-Lagrangian (CEL) method. With the help of a multiple phase flow

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analysis environment, Liu et al. (2017) showed the mixing and material flow of dissimilar materials in the FSW process using Computational Fluid Dynamics (CFD) software. Shi and Wu (2017) reported transient analysis results including plunging, dwelling, welding, and cooling processes, considering an axisymmetric tool-weldment interaction, with validation using a measured torque history.

The ultimate goal of such numerical analyses is to predict rather than reproduce the phenomena. The development of numerical models for forecasting ultimately depends on how many undetermined assumptions are rationalized. To predict the FSW process is also necessary to reproduce actual process conditions as a model. In particular, the model must be able to predict thermal behavior and mechanical behavior in real time, as well as consider the complex shape of the tool-weldment interaction.

In this study, as a step towards this goal, a direct interface area calculation method is proposed, in the Fractional Area/Volume Obstacle Representation (FAVOR) environment, based on the commercial CFD software, FLOW3D (Hirt and Nichols, 1988). The method is then used for transient analysis including plunging, dwelling, and welding processes in the Eulerian description. Based on energy conservation laws, torque, IFH, and PDH were modeled and evaluated. For the process variables that were theoretically difficult to determine, the impacts were identified and confirmed through case studies. To validate the numerical model, the Friction Stir Spot welding (FSSW) process using an axisymmetric tool, and the FSW process using a non-axisymmetric tool were tested, and torque and surface temperature were measured.

2. Experiment

Table 1 gives the welding conditions used to produce a FSSW weldment with a cylindrical type (CYL) tool (Fig. 1(a)) and a FSW weldment with a tab type tool (Fig. 1(b)) (Daewha Alloytech - WC-Co 12%). A $100 \times 60 \times 4.8\,\mathrm{mm}^3$ sized AL5052-O plate was used for each experiment. For the stability of the numerical results, the tilt angle was set to zero. Then, some iterative experiments were carried out to determine appropriate experimental conditions. The indicated rotational speed and process time were maintained using the feedback control of the FSW machine (Hwacheon - F1300). However, the actual insertion depth was not measured due to the absence of a control system.

Fig. 1(c) and (d) illustrate the locations where thermal cycles were measured (+ marks). When the stage was moving, the positions where the temperature was measured were kept at a distance of 16 mm from the center of the tool using a fixed IR camera (FLIR - T620). The IR camera based temperature measuring system was calibrated with the thermocouple-based measuring system. The net torque was also measured, with a torque sensor (Artis MARPSOS - DDU4). The temperature and net torque data were recorded once every two seconds.

3. Numerical analysis

3.1. Calculation environment

3.1.1. Introduction to the FAVOR method and interface traction method

The FAVOR method is one of the straightforward extensions of the traditional Finite Difference Method (FDM), used to treat curved boundaries and obstacle in a discrete control volume calculation domain (Tsukiyama et al., 1993). A moving obstacle is defined by a rigid body. The motion is described by the centroid coordinate value. If the moving rigid obstacle, knows as the General Moving Object (GMO), is placed in a unit Control Volume (CV), the volume fraction of the GMO (or, the closed volume fraction, V_G) and the volume fraction of the fluid (or, the open volume fraction, V_F) have fractional conservation as follows.

$$V_G + V_F = 1 \tag{1}$$

However, because of the limitation of the discrete environment of the numerical domain, even if the actual shape of the GMO-fluid interface is not flat, the FAVOR method the interface in the CV is considered to be a flat interface, as shown in Fig. 2. Therefore, the area of the interface is not preserved. Instead, it is determined by the relative size of the CV to the GMO. In addition, with this representational technique, the ratio of the interface of the CV that is not covered by the GMO is provided as an open area fraction of the i-directional CV boundary (A_{+i}). While the three positive open area fractions were utilized to track the interface CV in a previous study (Kim et al., 2017) in 3-dimension, in this study the open volume fractions of a particular CV and its surrounding CVs were utilized to track the interface CV.

3.1.2. Governing equations

A set of governing equations were solved together with the process model to analyze the heat and mass transfer in a CFD simulation using commercial software. An incompressible laminar flow condition with strain-rate and a temperature dependent viscosity model were assumed. These assumptions led to simplified continuity, momentum, energy, and Volume of Fluid (VOF) equations, respectively. In the Cartesian coordinate system (x, y, and z), the continuity equation is calculated as

$$\rho\left[\frac{\partial}{\partial x}(uA_x) + \frac{\partial}{\partial y}(vA_y) + \frac{\partial}{\partial z}(wA_z)\right] = S_m \tag{2}$$

where the ρ is fluid density. The velocity components (u, v, and w) are in the coordinate directions (x, y, and z). A_i is the fractional area open to flow (open area fraction) in the i-direction. The last term on the right side of Eq. (2) is a density source. The x-directional momentum equation is considered as

$$\frac{\partial u}{\partial t} + \frac{1}{V_F}\left(uA_x\frac{\partial u}{\partial x} + vA_y\frac{\partial u}{\partial y} + wA_z\frac{\partial u}{\partial z}\right) = -\frac{1}{\rho}\frac{\partial p}{\partial x} + f_x - \frac{S_m}{\rho}(u - u_s) \tag{3}$$

where p is pressure. u_s is the velocity components of the density source. Please refer the detailed descriptions of viscous acceleration terms f_x in (Hirt and Nichols, 1988). The energy equation is considered as

$$\begin{aligned} &V_F\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(huA_x) + \frac{\partial}{\partial y}(hvA_y) + \frac{\partial}{\partial z}(hwA_z) \\ &= \frac{1}{\rho}\left[\frac{\partial}{\partial x}\left(kA_x\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(kA_y\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(kA_z\frac{\partial T}{\partial z}\right) + S_{IFH} + S_{PDH}\right] \end{aligned} \tag{4}$$

where h and k are the enthalpy and thermal conductivity of the fluid. The last two terms on the right side of Eq. (4) are interface friction heat (IFH) and plastic deformation heat (PDH) per volume, respectively. The

Table 1
Process conditions.

CASE	Tool type	Rotational speed [rpm]	Travel speed [mm/min]	Plunging time [s]	[a]Plunging depth [mm]	Dwelling time [s]	Welding time [s]
FSSW	CYL	1000	–	14.0	3.7	36	–
FSJ	TAB	600	50	13.6	3.9	–	36.4

[a] Indicated value.