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Modeling of defects in friction stir welding using coupled Eulerian and Lagrangian method

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ABSTRACT

In the current research, a coupled Eulerian and Lagrangian method is used to model the friction stir welding process. Volume of fluid principle is used to predict the formation of defects during the process. Model is validated with experimentally observed spindle torque and axial force. Three different pin heights were simulated and pin height of 2.5 mm was found as the optimum value. Experimental defects are observed using the X-ray computer tomography method. The model has successfully predicted the presence of defect for different welding parameters. Defect free weld is produced at a tilt angle of 2°. Qualitative comparisons of effective plastic strain and welding efficiency were carried out and correlation among them is proposed.

1. Introduction

Friction stir welding (FSW) is a solid state joining technique developed in 1991 by The Welding Institute (TWI) at Cambridge, UK [1]. It is an efficient technique to weld different grades of aluminum alloys, which are difficult to weld with fusion welding. FSW is a remarkably simple process and is carried out in three stages viz. plunging, dwelling and welding. In plunging, a non-consumable rotating tool penetrates the abutting edges of the clamped workpieces to generate heat as shown in Fig. 1(a). Afterwards, during dwelling the tool is kept rotating in its position to further increase the temperature beneath it as shown in Fig. 1(b). Lastly, the tool is given a travel velocity along the joining line to form the joint by stirring the material as shown in Fig. 1(c). FSW holds several advantages over fusion welding techniques such as higher mechanical strength, finer grain size, low distortion etc. [2]. Defects in FSW occur due to selection of inappropriate parameters and a lot of experimental and post-weld analyses are required to optimize the process parameters. Kim et al. [3] have studied the influence of plunge force on three types of defect. They concluded that excessive and insufficient heat input led to flash formation and void/groove, respectively. Higher rotational and welding speeds lead to abnormal stirring of the material and cause groove formation. Li et al. [4] investigated defects using multiple non-destructive techniques (NDT) like X-ray detection, ultrasonic C-scan testing etc. Based on conservation of volume principle, they estimated the inner volume loss of the material due to the defects. Apart from destructive and non-destructive methods, researchers have used various techniques like image processing [5], wavelet analysis [6,7] for the defect identification.

Numerical simulation of FSW is an efficient way to identify the defects that can possibly originate during the process and help reduce initial trial experiments required for optimising the process parameters. Jain et al. [8] developed a three-dimensional model based on the Lagrangian method. They studied the influence of process parameters on force and torque and compared conical pin with cylindrical in terms of material velocity. The method effectively predicted the temperature and forces, but does not give any information about the formation/generation of defects in the process. Badour et al. [9] have used coupled Eulerian Lagrangian (CEL) method to simulate the FSW and predict defects. Adiabatic condition has been assumed over the workpiece. The model was used to successfully predict the formation of voids and compared with experimental observations. However, the model was not able to successfully predict defect-free condition in force control mode. Hossfeld [10] used CEL model to simulate FSW process. Researcher defined the workpiece as two separate sheets and predicted the material flow during the plunging of the tool. Cao et al. [11] used CEL model to simulate the friction stir spot welding of AA6061-T6 alloy. Johnson Cook material model was used to define the flow stress of the workpiece. They reported that hook defect is produced due to insufficient flow of the material. Grujicic et al. [12] studied the material flow during FSW by using CEL method. They used marker material technique to study the mechanism of the material flow phenomenon. They reported that majority of material flow is on a plane parallel to backing

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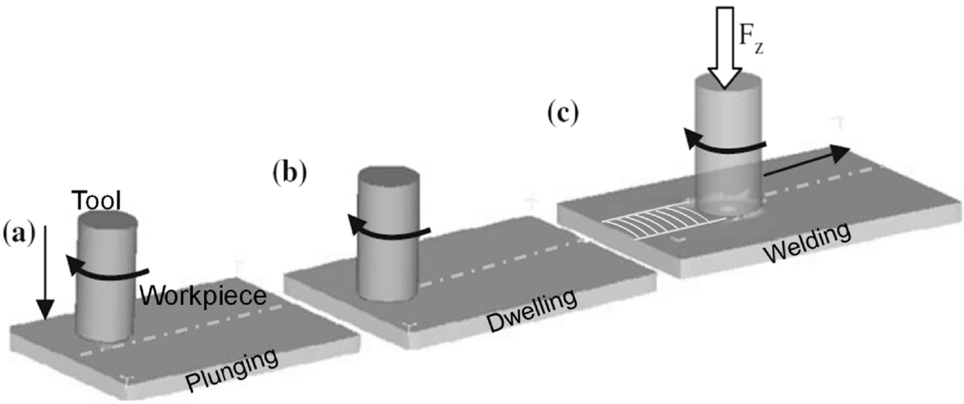

Fig. 1. Different stages of friction stir welding process (a) plunging (b) dwelling (c) Welding.

plate. Vertical material flow was also observed, but it was prominent on the advancing side as compared to the retreating side. Ducobu et al. [13] compared ALE and CEL method by modeling orthogonal turning process. They reported that stable time increment reduces with ALE method due to mesh distortion while it remains constant for the CEL method. This lead to higher computation time for ALE as compared with CEL method. They also found that CEL and ALE predicted results are close to each other but mesh distortion in ALE method can lead to pre-mature failure of the simulation which was absent in case of CEL method [14]. Hedayati et al. [15] compared Lagrangian, Eulerian and ALE method to model bird strike problem. They also reported that ALE method cannot handle excessive mesh distortion though this method is better than Lagrangian method.

Researchers have mainly focused on the modeling of temperature and material flow, while modeling of defects is still in nascent stage. Literature suggest that CEL method could be used to predict the defect formation [9]. Therefore in the current research, a three-dimensional thermo-mechanical model is proposed to simulate all the three phases of FSW based on the CEL method to predict defect formation during FSW. The workpiece is defined as an Eulerian body and defect is predicted based on volume of fluid (VOF) principle along with forces and spindle torque. The developed model was validated with the experimentally measured spindle torque during welding, and axial force during plunging phase. Current research focuses on the following three areas (i) to optimize the pin height such that minimum or negligible material erosion takes place from bottom face of the workpiece, (ii) to find the tilt angle that produces defect-free weld and compare it with the experimental observations, (iii) to qualitatively compare the model predicted effective plastic strain with the experimentally observed tensile strength of the weld.

2. Experiment details

A 20kN CNC controlled FSW machine was used to perform the FSW of two pieces of AA 6061-T6 in butt configuration. Chemical composition of AA6061-T6 is shown in Table 1. Each of the workpiece had a thickness of 3.1 mm, with a length and width of 110 mm and 57 mm, respectively. H13 tool steel was selected as the tool material. The tool had a flat shoulder with 16 mm shoulder diameter along with a cylindrical pin of 5 mm diameter and 2.5 mm height. The FSW machine has inbuilt strain gauge type load cell in vertical and welding directions. Load cell was connected to a computer through a data acquisition system, and the LabVIEW software is used to store the data in Excel files. Forces and torque data were acquired at intervals of 0.1 s. The load cell has a sensitivity of 1% of the rated capacity of the machine.

Table 1
Chemical composition of AA6061-T6 (in weight percentage).

Elements	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Al
Percentage	0.26	0.34	0.66	1.08	0.11	0.55	0.16	0.223	Balance

Experiments were performed at four different rotational speeds of 600, 900, 1200 and 1500 rpm, keeping other parameters like plunge depth and welding speed constant with a value of 0.2 mm and 60 mm/min, respectively. Tool plunging speed was kept at 15 mm/min. Tensile test specimen was cut from the welded sample by using CNC wire electro discharge machine (Elecktra, Maxicut 523) in the direction perpendicular to the welding. Sub size specimens with overall length of 100 mm based on ASTM E8 standard [16] were used for the tensile tests. Tensile test was performed on a 100 kN universal testing machine (Instron, 1344) at a constant crosshead speed of 1 mm/min.

2.1. Experimental defect analysis

A three-dimensional X-ray micro-computer tomography (CT) (General Electric, phoenix vtome x s) scanning system is used to analyze the defects, as shown in Fig. 2. The machine has a voltage and current capacity of 240 kV and 3 mA, respectively to produce X-rays. It is a non-destructive technique to visualize the defects and also provides information of the total welded region. The machine consists of an X-ray source, a detector to measure the X-ray attenuation along the multiple beam path and a rotational chuck on which the welded sample is mounted. The welded sample is placed on the rotating chuck in between the X-ray source and the detector such that it can make one complete rotation. Magnification of the scan is decided by the distance between the chuck and X-ray source; lower the distance, higher would be the magnification. For the present defect analysis, X-ray is generated by setting the voltage and current at 130 kV and 110 μA, respectively. The chuck rotates at a speed of 0.36° per second to capture a total of 2000 images or slices of the sample. Further, the images are imported to

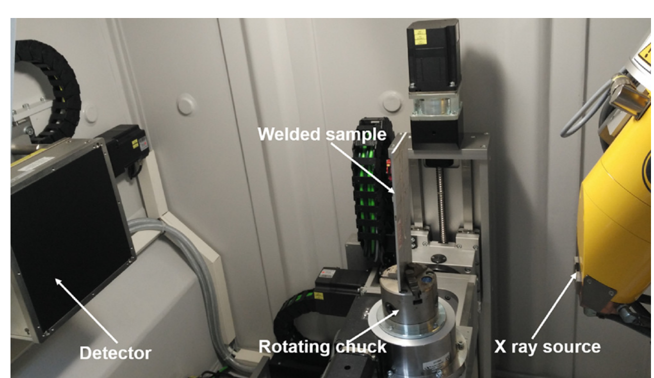

Fig. 2. X-ray CT scan setup for defect measurement.