Journal of Manufacturing Processes 31 (2018) 46–55

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Research Paper

Thermomechanical modeling of friction stir welding in a Cu-DSS dissimilar joint

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ARTICLE INFO

Article history:
Received 21 July 2017
Received in revised form 29 October 2017
Accepted 3 November 2017

Keywords:
Thermo-mechanical simulation
Friction stir welding
Coupled eulerian-lagrangian

ABSTRACT

Thermomechanical simulation is used to predict material flow and residual stresses in joining duplex stainless steel (DSS) to a Cu-alloy by friction stir welding (FSW). The coupled Eulerian-Lagrangian (CEL) method was applied for modeling large deformation. Welding experiments are used to verify simulation results. Results indicate that DSS initially flows towards the Cu-alloy side on the top surface of the retreating side. Simulations indicate that the rotating flow zone (RFZ) is dependent on the welding parameters and has a maximum value when the rotation speed and tool offset are maximum and the travel speed is minimum. After surface flow, DSS chunks are separated and move towards the pin tip by rotation. In all the studied samples, DSS represents higher temperatures and residual stresses compared to the Cu-alloy. Longitudinal residual stress is decreased by increasing rotation speed and increased by increasing travel speed. Both speed parameters have a negligible effect on transversal residual stress. At one of the welding conditions, residual stresses are close to symmetry across the weld line. This test condition also represents optimum heat distribution and highest mechanical strength in previous findings.

1. Introduction

Friction stir welding (FSW) is a thermomechanical process which involves severe plastic deformation and flow of material around the tool. By application of finite element modeling (FEM), the effect of different process parameters on temperature distribution and flow behavior are studied [1]. Researchers apply different FEM methods for prediction of material behavior in FSW. These methods are categorized as thermal [2–4], and thermomechanical methods, with [5–9] and without [10] considering metal flow. In the thermomechanical methods considering material flow, large deformation causes distortion in Lagrangian elements [11]. Various techniques are applied to prevent element distortion. Although the Lagrangian method has high accuracy in following different nodes in a deforming material, in high deformation rate processes where the rate of change of the element shape is very high and re-meshing is required almost continuously, accuracy is not maintained [12,13]. Therefore, for high deformation rate processes, other methods such as the coupled Eulerian-Lagrangian (CEL) method is used [14]. In CEL, the material which is under high deformation (or high deformation rate) is modeled by the Eulerian method. While the hard and solid tool is modeled by the Lagrangian method. Different researchers have used the CEL method for simulating different high deformation rate manufacturing processes, such as orthogonal cutting [15] and friction stir welding for similar [13,16,17] and dissimilar joints [18,19].

The authors have previously studied the effect of welding parameters on microstructures and mechanical properties of DSS to Cu-alloy [20]. In the present paper, a CEL method is used to predict the effect of different welding parameters on the material distribution and residual stresses in FSW of a dissimilar joint between a copper alloy and a duplex stainless steel (DSS). Results are compared with the experimental data to verify modeling.

2. Experimental procedure

Cu-alloy and DSS 4 mm thick plates were cut into 50 × 300 mm rectangles to perform FSW experiments. The joining sides were flattened by machining then cleaned and degreased before welding. A mica plate was placed beneath the two sheets to prevent sticking of the weld zone to the machine table. In Fig. 1a the welding setup is shown. Force and temperature were recorded experimentally during the tests to evaluate the simulated results. The temperature was logged using a 4-channel CENTER 309 data logger and two k-type thermocouples. The thermocouples were positioned beneath the sheets in a 3 mm distance from the weld line (Fig. 1b and c). Welding

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https://doi.org/10.1016/j.jmapro.2017.11.004
1526-6125/

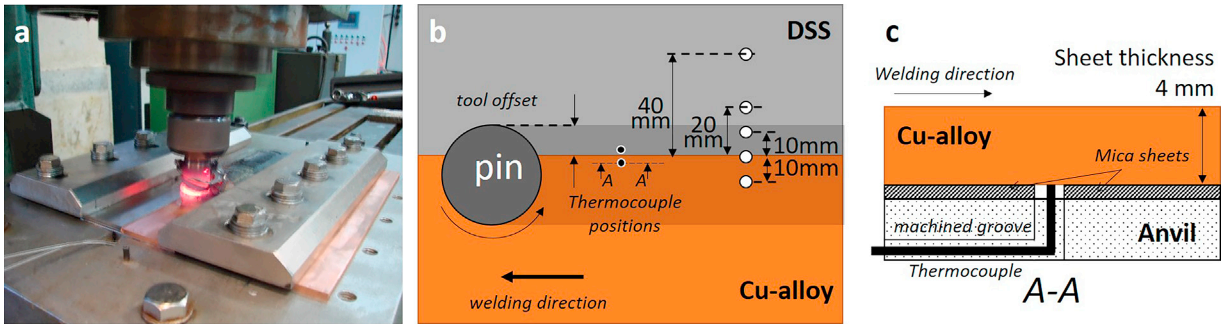

Fig. 1. (a) welding setup, (b) position of thermocouples and strain-gauges (c) side view cross-section showing the relative position of the thermocouples.

Table 1
Split Hopkinson test conditions for the strain rate of 1000 s^{-1}

Input bar length (mm)	Output bar length (mm)	Bar diameter (mm)	Striker bar velocity (m/s)
1700	1200	19.8	7.6

force was recorded using a Kistler piezoelectric dynamometer. To validate the simulated results, a sample was welded using rotation speed of 1200 RPM, the travel speed of 30 mm/min and 0.5 mm tool offset. After model calibration, different welding conditions were simulated to compare results with previously reported experimental work [20].

To experimentally measure residual stresses, the hole-drilling strain gage method (ASTM E837) was used at welding line neighboring regions. To measure strain, 1.6 mm holes were drilled at the center of three-element strain gage rosettes (Tokyo Sokki Kenkyujo, type TML FRS-2-17). As shown in Fig. 1b, strain gauges were attached at different distances from the weld line.

Split-Hopkinson test was performed to measure dynamic mechanical properties of the studied material. 8 mm diameter 8 mm high cylinders of both DSS and Cu-alloy were placed between two incident and transmitted bars. Then a gas gun fires the striker and causes plastic deformation in the specimen. Considering uniform deformation in the samples, stress, and the strain was calculated from the amplitudes of the incident, transmitted and reflected waves by strain gauges. The split Hopkinson test conditions used for this study are presented in Table 1.

3. Simulation method

As previously introduced, in the present study, FSW process is simulated by CEL method. By using this approach for FSW of dissimilar metals, movement of different material could be easily distinguished and observed. Moreover, the formation of defects, especially voids, could be visualized and predicted.

Owing to the high strains and strain rates in the deforming material, Euler method is considered for the two sheets. While, for simplification and reduction of solving time, the tool is set as solid in this method. Since the yield strength of the tool material is much higher compared to the workpiece, rigid tool assumption is valid. The original sheet is a 150 × 100 mm rectangle with 4 mm thickness while the mesh has an extra 1 mm thickness in the space to visualize the out of plane material flow and flash formation. Fig. 2a shows the three-dimensional model of the sheet, highlighting the contrast between the surface layer (blue) and the base material (red). The three-dimensional model of the tool pin and its reference point are shown in Fig. 2b. The pin is modeled considering discrete rigid criteria. Different methods have been used for simulating the tool movements in FSW [3,15,16,21]. In this research, vertical (indentation inside the sheets) and rotational movements for the tool have considered. The advancing of the tool inside the sheet is modeled as material flow from inside the mesh. In this method, the software compute and update information for all nodes in each time section.

3.1. Geometrical conditions

For the sheets, which is described in the Eulerian system, EC3D8RT elements are used. These elements which are also coupled with the temperature freedom degree have three dimensions and eight nodes. For the tool, which is described by the Lagrangian system, R3D4 elements are used. These elements are three-dimensional and have four solid nodes. The element size of the Eulerian sheet and lagrangian pin are 2 mm and 1 mm respectively.

3.2. Boundary conditions

Euler method based on hydro-codes is used for boundary condition of the sheet which contains speed at the boundaries [22]. As shown in Fig. 3a, the red regions (1 mm above the surface) are locations where the speed in the normal direction is zero. This condition prevents material to flow into and out from the surface. To simplify calculations, the rotating tool location is considered fixed while material flows into the Eulerian mesh using boundary conditions in the y and z direction for the penetration of the shoulder and the tool travel on the seam line respectively. Fig. 3b shows only the boundary condition of the welding stage. Considering this boundary condition, the applied speed on the boundaries is equal to the travel speed of the tool in the FSW process. Important to note that in the Eulerian and Euler-Lagrangian analysis, there is no mesh movement and material flows inside the mesh grid.

Another important parameter in FSW simulation is the tool inclination angle. A coordinate system is considered on the tool axis to simplify the application of tool rotation conditions. In Fig. 3c the pin boundary conditions are shown. In complex simulations, such as dissimilar FSW presented in this paper, heat transfer properties are variables unique to the model.

3.3. Material properties

In the present CEL study, instead of describing two parts on the two sides of the interface, a single region with a step profile representing material properties of Cu-alloy and DSS is used. The applied material properties are density, elastic modulus, Poisson ratio, thermal diffusivity coefficient, heat capacity and plasticity properties. All the mentioned properties are a function of temperature. Different constitutive material models and their influence on the output responses of the FSW process have been studied by various researchers [23]. In this paper, the Johnson-Cook (JC) plasticity