Materials and Design 108 (2016) 400–410

Contents lists available at ScienceDirect

Materials and Design

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

Simulation of material plastic flow driven by non-uniform friction force during friction stir welding and related defect prediction

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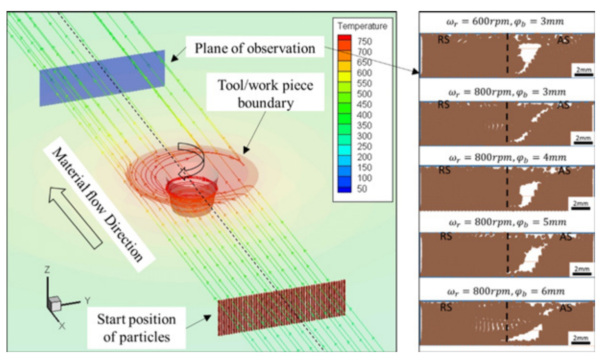
HIGHLIGHTS

- Non-uniformly distributed friction force on tool/work piece interface is considered in computational fluid dynamics models.
- Defects under various welding parameters are graphically predicted by distribution of tracing particles added in models.
- Formation mechanism of defects is discussed based on the change of flow velocity caused by distribution of friction force.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 12 April 2016
Received in revised form 26 June 2016
Accepted 28 June 2016
Available online 1 July 2016

Keywords:
Computational fluid dynamics
Friction stir welding
Coulomb friction
Defect prediction

ABSTRACT

Material flow during welding is an important factor that affects the quality of friction stir welding (FSW) joints. In this study, a new welding tool/work piece contact model is proposed to simulate material flow near the FSW tool. The material around the tool flows under the driving force of friction non-uniformly distributed on the interface. Friction force is calculated based on modified Coulomb friction law in this model. Wormhole defects under various welding parameters are graphically predicted by the distribution of tracing particles added in numerical models. Five groups of FSW experiments were conducted to obtain temperature and joint morphology results. Simulation results, including temperature and wormhole defects prediction, corresponded with the experimental results. Further analyses imply that under the process parameters selected in this study, an area with very low friction force occurred behind the tool pin. When the material in front of the tool pin moved to this area from the retreating side, the material speed significantly decreased due to the insufficient driving force, and it became difficult for the material to move to the advancing side along the circular path. The study reveals that the non-uniform friction force model provides a potential tool for predicting FSW defects.

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http://dx.doi.org/10.1016/j.matdes.2016.06.119
0264-1275/

1. Introduction

Friction stir welding (FSW) is a solid-state welding technology and was first developed by The Welding Institute (TWI) in 1991 [1]. Since materials do not melt during welding, defects like porosity and hot cracks can be effectively avoided, and high-quality welding joints can be obtained. Thus, it has been widely applied in industries, especially aluminum alloy welding [2]. Materials in welding zones experience severe plastic deformation during FSW. Materials move from the front side of the tool pin to the rear side and form dense joints after cooling. The plastic flow of welded materials is the key factor in determining joint quality. Insufficient material flow leads to wormholes and surface grooves, which obviously reduce joint strength [3]. Investigations on the material flow in FSW is beneficial to determining suitable welding parameters and optimal tool shapes. Since the invention of FSW, there have been many studies concerning material flow regularity during FSW. Field [4] utilized the orientation imaging analysis method to study the dimension and arrangement direction of grains in the welding of nuggets made from AA1100, AA6061-T6, and C458 aluminum lithium alloys after FSW. The material flow state during welding was reversely inferred according to the welded structures and textures. Seidel [5] embedded the AA5454-H32 as markers in the FSW experiments of AA2195-T8. By analyzing the plastic deformation and position distribution of markers after welding, the material flow regularity in FSW was discussed. However, the methods mentioned above can only obtain material state information after welding. Until 2011, Morisada [6–8] used several 300 μm diameter tungsten spheres as tracing particles in FSW experiments, and two sets of X-ray transmission real-time imaging systems were symmetrically placed above and below the welding apparatus. During welding, the 3D spatial positions of these tungsten spheres were recorded in real time. By using this apparatus, Morisada obtained the flow track of materials in specific sites during welding. However, the amount of tungsten balls was limited, resulting in difficulties in collecting full-field information.

Compared to experimental methods, numerical simulation methods can obtain full-field and full-process information such as material flow, heat input, and temperature distribution, which makes it possible to conduct analyses of the evolution and interaction regularity between key physical parameters. At present, the modeling methods for numerical simulation can be classified into two parts: computational solid mechanics (CSM) and computational fluid dynamics (CFD). Schmidt [9] used the ABAQUS/Explicit software to establish the 3D thermal–mechanical coupling model of FSW based on the arbitrary Lagrangian–Eulerian (ALE) method. Schmidt discussed the material properties using the Johnson–Cook constitutive equation and defining the contact relationship between the tool and work piece using the Coulomb friction law, the heat generation, material flaw regularity, and weld nugget defect. Zhang [10] also utilized the CSM method to construct a 3D numerical simulation model and investigated the FSW of AA6061-T6. The equivalent plastic strain in the material was obtained via numerical simulation, and the correspondence between the contour line of the equivalent plastic strain and different welding zone boundaries were analyzed. Paulo [11] studied the residual stress distributions in the blanks after FSW and the influence of residual stress on the mechanical behavior of the plates and the collapse load via on the CSM method. Citarella [12] constructed a numerical model and analyzed the influence of residuals stress in blanks after FSW on fatigue crack growth, in combination with the dual boundary element method (DBEM). The simulation results agreed with the experimental results. By using CSM methods to simulate FSW processes, it is possible to favorably present the friction relationships between the tool and work piece; thus, the influence of residual stress can be effectively characterized. However, the tool pin is required to penetrate the welded blank during ALE model construction to eliminate computation misconvergence. Thus, a distinct

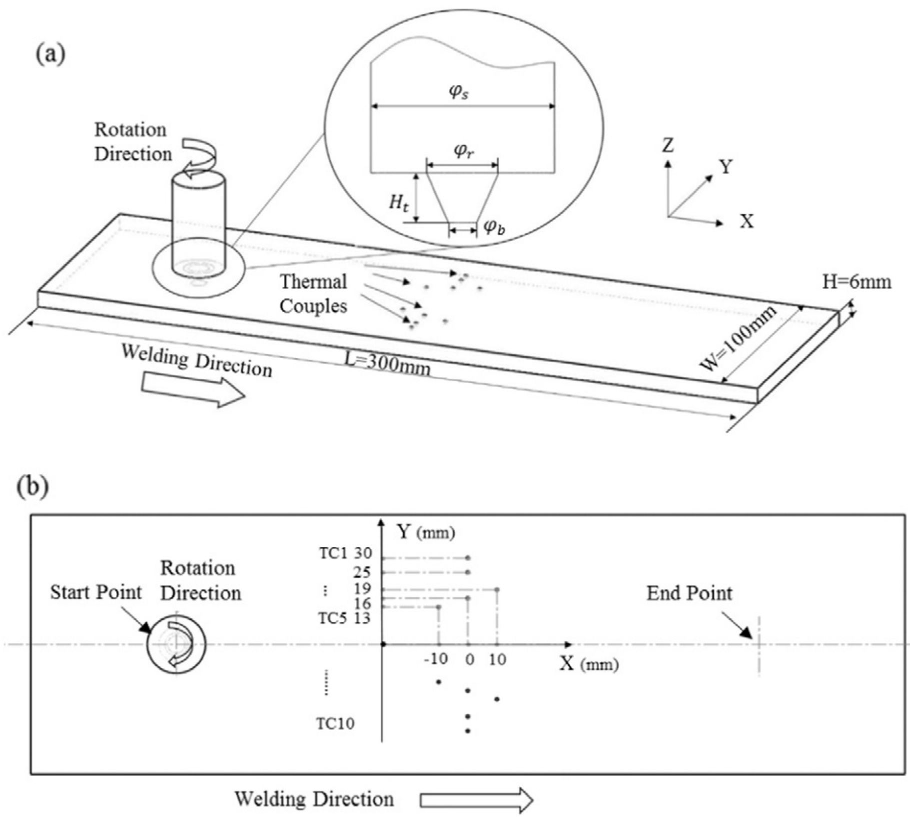

Fig. 1. Illustration of FSW experiment, (a) workpiece and welding tool, (b) thermocouple locations