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Technical Paper

Linking process and structure in the friction stir scribe joining of dissimilar materials: A computational approach with experimental support

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ABSTRACT

Friction stir welding (FSW) is a popular technique to join dissimilar materials in numerous applications. The solid state nature of the process enables joining materials with strikingly different physical properties. For welds in lap configuration, an enhancement to this technology is made by introducing a short, hard insert, referred to as a cutting-scribe, at the bottom of the tool pin. The cutting-scribe induces deformation in the bottom plate which leads to the formation of mechanical interlocks or hook like structures at the interface of two materials. A thermo-mechanical computational model employing a coupled Eulerian-Lagrangian approach is developed to quantitatively capture the morphology of these interlocks during the FSW process. Simulations using this model are validated by experimental observations. The identified interface morphology coupled with the predicted temperature field from this process–structure model can be used to estimate the post-weld microstructure and joint strength.

1. Introduction

Friction stir welding (FSW) is a solid state joining technology patented by The Welding Institute (TWI) in 1991 [1]. It is becoming increasingly popular for joining dissimilar materials [2–9] and has wide spread applications in several industries, including automotive, aerospace, robotics, shipbuilding and offshore energy production. Especially with the automotive industry, the steady push towards energy efficiency is driving research on lightweight vehicle structures necessitating the joining of aluminum alloys to other metals. The process of friction stir welding is illustrated in Fig. 1, where a rotating cylindrical tool plunges at the interface of two metal plates placed in the butt weld configuration. The friction between the tool and the substrate materials generates heat which enhances the plastic deformation in the plates and causes localized softening of the material underneath the tool. This softened material is subjected to extrusion from the rotational and translational motion of the tool. The temperatures in this process are presumed not to reach the melting point of the substrate materials and hence it is considered a solid state joining process. The friction stir welding process has also been successfully demonstrated for metal alloys in lap configuration [10–13]. However, due to the narrow process window, it is difficult to achieve acceptable weld quality owing to undesired melting and the formation of brittle intermetallic compounds. In addition, the joining of vastly dissimilar materials such as aluminum and steel, or plastics to metal using friction stir welding has been quite challenging because of a significant difference in thermal and physical properties of the dissimilar materials. Attempts to utilize FSW method for joining of vastly dissimilar materials often leads to an unstable process, liquefaction, cracking and porosity issues. Another popular technique to join dissimilar materials is called Brazing, in which two or more materials are joined together by melting and flowing a filler material into the joint [14–16].

Recently, an enhancement to FSW was introduced [17] for dissimilar metal welds in lap configuration. It is made by introducing a short, hard insert, referred to as a *cutting-scribe*, at the bottom of the tool pin. A schematic of the process is illustrated in Fig. 2. The cutting-scribe induces deformation in the bottom plate material which leads to the formation of *hook*-like mechanical interlocks at the interface of the two dissimilar metals as shown in Fig. 3. It is expected that these mechanical interlocks between the two materials provide the necessary joint strength for welds in the lap configuration. This enhanced technique involving a cutting-scribe will hereafter be referred to as friction stir scribe joining (FSSJ) and can be considered as a hybrid of mechanical fastening and solid-state joining. In this technique, a small clearance is

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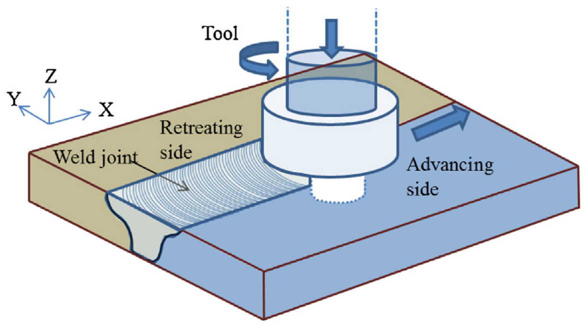


Fig. 1. Friction stir welding process.

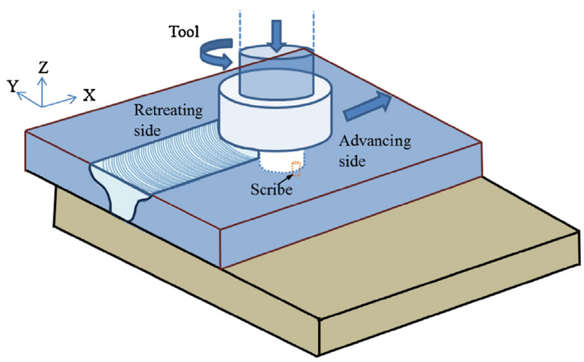


Fig. 2. Friction stir scribe welding process for plates in lap configuration.

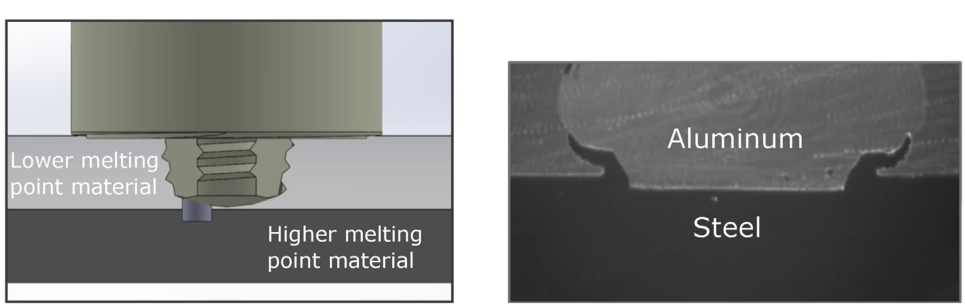
maintained between the FSSJ tool pin and the top surface of the bottom plate which helps in avoiding bulk plastic deformation of the bottom plate material, and thereby diminishing the propensity of melting and associated defect/void formation typically observed in conventional FSW of vastly dissimilar materials. More detailed discussions on the technique can be found in [18–20].

The friction stir welding process involves several key parameters which greatly influence the quality of the produced joint. Over the last two decades, significant progress has been made towards the understanding and optimization of FSW process parameters. Reviews of the extensive research work performed for the traditional FSW process can be found in [21–25]. However, FSSJ, being a relatively newer technique, still requires further understanding of the joint formation mechanism and optimization of weld parameters. The most significant one, amongst other parameters, is the design and positioning of the cutting scribe. The Edisonian approach of conducting several experimental sweep in establishing those weld parameters can be extremely time-consuming and resource intensive. The main objective of the presented work is to establish a validated computational model for the FSSJ process that can be utilized to ascertain some optimal weld parameters and to reduce the cost of experimentation.

Friction stir welding is a highly complex process because of the strong coupling of multiple nonlinear physical phenomena. Simulating this thermo-mechanically coupled process with large deformations and strain rates to predict the resulting joint structure is not straightforward. Many researchers have used either a decoupled or a sequentially coupled approach by separately considering thermal and displacement fields. Deng and Murakawa [26] performed de-coupled thermal and mechanical analyses by applying a moving heat source to the workpiece model. Schmidt et al [27,28] modeled the heat generation from both frictional and plastic dissipation using a surface flux boundary condition at the tool-workpiece interface. Khandkar et al [29] presented a model predicting the thermal signature in the FSW process based on mechanical torque input to the system. Darvazi et al [30] also presented a thermal model where heat transfer between the workpiece and backing plate is modeled using an equivalent convection coefficient. Another thermal analysis for the FSW and the effect of process parameters was presented in [31]. The thermal modeling work presented in [32] shows that the preheat supplied to the workpiece is advantageous for the FSW joint strength. Yang [33] used a decoupled approach to predict the temperature and hardness distribution obtained in the friction stir welding process.

With the advent of new computational methods and increasing computational resources, several research efforts have employed fully coupled thermomechanical models to simulate the FSW process [24,34–38]. The use of Finite Element Method (FEM) in simulating this process is very common [35,39,40]. However, due to the excessive mesh distortion in the stirred zone, traditional FEM in the Lagrangian framework poses a significant challenge. A Coupled Eulerian framework to model such processes is frequently deployed to address this issue [41–44]. As such, these modeling techniques are used in other metal processing applications as well [45,46]. Researchers have also demonstrated the application of other novel numerical methods in modeling this complex process [47,48]. A comprehensive review of the numerical modeling work carried out for FSW is provided in [49,50]. For FSSJ process, however, no computational framework has been reported in the open literature in an effort to predict the mechanical interlock formation. The process development has largely relied on extensive parametric experimental studies which have been reported in the literature.

The properties and performance of a FSSJ joint are governed by its underlying interfacial interlocking mechanism and microstructural morphology, which in turn are determined by the process parameters. The computational capability of predicting the joint morphology from the process is hereafter referred to as the process–structure model. The development and validation of this process–structure model for the FSSJ of dissimilar materials is the primary objective of this work. A Finite Element Method (FEM) based, coupled Eulerian-Lagrangian framework is presented here to model the friction stir scribe joining process. The major outcomes of the model are the prediction of weld interface morphology and the temperature field. The process parameters used for the simulation correspond to an actual FSSJ experiment and the results of the simulation are compared with experimental data.



(a) (b)

Fig. 3. (a) Material configuration in friction stir scribe joining. (b) In-situ mechanical joint: interlock or hooks.