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A selectively-coupled shear localization model for friction stir welding process window estimation

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ABSTRACT

This paper presents a novel computational procedure specifically aimed at gaining modeling capabilities for estimating friction stir welding (FSW) process window. The proposed model first combines a three-dimensional (3D) transient heating effects with a one-dimensional (1D) shear localization process leading to shear band development within one pin revolution. The resulting shear band width is then compared with the minimum material flow layer thickness required for satisfying both mass conservation and velocity continuity conditions in a two-dimensional (2D) planar material flow around the tool pin. If the shear band width formed within one pin revolution is equal or larger than the minimum material flow layer thickness, conditions for developing a quality weld prevail. Otherwise, conditions for developing various forms of weld defects can be identified, depending upon shear localization behavior predicted. Specifically, the proposed model is shown capable of elucidating some of the major defect formation mechanisms observed in experiments, such as "lack of fill", "abnormal stirring", "surface galling", and "excessive flash", etc. As a result, the selectively-coupled shear localization model enables a theoretical estimation of FSW process window typically represented as a regime of welding speed and stir tool rotation speed combination for a given application, within which acceptable weld quality should be expected. Its application in FSW process window estimation is demonstrated by considering three types of aluminum alloys. In all cases, good agreements are achieved between model-estimated and experimentally-determined process windows. In addition, the proposed model also enables a theoretical estimation of optimum welding parameters within an established process window, e.g., for achieving maximum welding speed while maintaining good weld quality.

1. Introduction

Friction Stir Welding (FSW), since its invention in 1991 [1], has been shown to possess numerous advantages over conventional fusion welding processes, particularly for joining metals or dissimilar metals that are difficult to weld with traditional methods [2–4]. As a result, FSW has been viewed as a key enabler for the manufacture of high-performance, lightweight structures [5]. However, FSW process development, i.e., to establish a process window in terms of a proper combination of welding travel speed and pin rotation speed for a given engineering application, relies mainly on Design of Experiments (DoE) which can be rather time-consuming and costly [6]. Once developed, a process window may not be transferable to other welding conditions, e.g., with somewhat different material type, thickness, etc. Therefore, there have been numerous investigations into effective modeling procedures over the past two decades with the aim of estimating welding process window such that the needs for performing costly and time-consuming DoE can be significantly reduced. Although various numerical models for simulating FSW have been proposed over the years and a plenty of insights have been gained, a model-based estimation of process window remains elusive to this day, as recently discussed by Qian et al. [6]. Given the complexity of FSW weld formation process involving multi-physics phenomena at different length scales, the authors have taken the position that an efficient modeling procedure aimed at process window estimation should focus on capturing some of the important phenomena directly relevant to weld formation process and simplifying other aspects of process details that may not significantly impact an overall trend of model-based estimation [7,8].

Through a careful examination of some of the relevant past investigations, particularly those focusing upon important weld formation phenomena related to process window estimation and their modeling procedures, a basic modeling framework for developing an effective

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approach to this challenging problem seems emerging. Research findings to date appear to suggest that a model for FSW process window estimation would require a synergistic consideration of three essential elements that are inter-dependent on one and other in some particular manner in forming a quality weld. They are discussed below:

1.1. Heat generation and 3D heat flow

It has been shown by past numerical and experimental investigations [e.g., 9–22] that two major sources of heat generation must be accounted for in modeling FSW process: One is due to friction heating between stir tool shoulder and workpiece, which plays an important role in establishing a desirable temperature environment within which a well-defined stir zone can develop [e.g. 13,16, 22]. The other is due to interactions at pin/workpiece interface, which tends to generate more localized heating and deformation gradients that can be further intensified through plastic dissipation once plastic strain rate reaches a high level [e.g.,13, 22]. In this regards, most analytical heat flow modeling work to date only considered friction heating between tool shoulder and workpiece using a Rosenthal type solution [9–12], in which heat source is modeled as a line heat source. A this kind of solution only takes into account of overall bulk friction heating effects at shoulder and workpiece interface and cannot provide sufficient spatial resolution of temperature field generated underneath the tool shoulder, e.g., any temperature difference between front and back of stir pin. More refined modeling approaches with numerical implementation considering both shoulder/workpiece and pin/workpiece can be found in Chao et al. [14], Song and Kovacevic [15], Schmidt et al. [16] and others [17–21].

However, it is worth noting that a more recent study by Mendez et al. [22] who introduced a novel scaling analysis method and investigated available experimental data is rather insightful. They pointed out that even though shoulder/workpiece friction contributes to a significant fraction of heat generated during FSW, peak temperature near the pin seems more affected by localized heat generation resulted from localized shear deformation around the pin than by distributed heat generation from shoulder/workpiece interface. With this finding, Mendez et al. [22] then proposed a modeling procedure in which shoulder/workpiece friction heating was treated separately as a secondary heat source that serves as a "preheating" to the thermomechanical interactions of pin and workpiece. They showed that the modeling results from such an approach are pretty consistent with published experimental results [22].

1.2. Shear localization and texture development

Due to the interactions between pin and workpiece within the confine of the thermomechanical environment described in Sec. 1.1, localized shear deformation develops in front of the pin, which contributes to shear texture development as observed experimentally by numerous researchers on aluminum alloys [23–30], and by Knipling and Fonda [31,32] and Plichak et al. [33] on titanium alloys. Such shear textures are also referred to as shear layers [22,24,29] or shear band [34–37] by different investigators, as illustrated in Fig. 1. Guerra et al. [25] further pointed out that shear texture forms a distinct zone referred to as "rotation zone", within which material rotates at the same angular speed of the pin (Fig. 1b). Guerra et al. also identified this zone is about "*three times thicker than the distance that the pin moves in one revolution*" [25]. This observation was further substantiated by Schmidt et al. [24] by investigating material flow using traditional metallography, X-ray, and computer tomography (CT). Therefore, it simply cannot be overstated how important a role that shear localization development plays in weld formation process in FSW.

However, most modeling efforts to date have not directly considered such a shear localization process. Credits should be given to Batra and Wei [37] for first suggesting that the extensive localized shear deformation can be studied by a 1D shear localization model [37–39], but without providing any further details on modeling procedures relevant to FSW process. Two subsequent studies on shear localization modeling of FSW by Pei and Dong [7,8] showed rather promising results, in which both shear band formation time and final shear band width per pin revolution were estimated for computing optimum welding travel speed. However, their shear localization model [7,8] have some significant limitations in process window estimation: (1) lack of considerations of friction stir shoulder/workpiece interactions which defines a thermomechanical environment for shear localization to take place; (2) lack of any material flow description around pin once a shear deformation layer of certain size forms in front of pin.

1.3. Material flow or extrusion leading to banded structure

As consistently observed experimentally in welding trials for high strength aluminum alloys [23,24,28–30] and titanium alloys [31–33], a quality friction stir weld can be characterized as exhibiting an orderly banded structure in the form of overlapping circular rings that are approximately equally spaced at a distance corresponding to stir pin

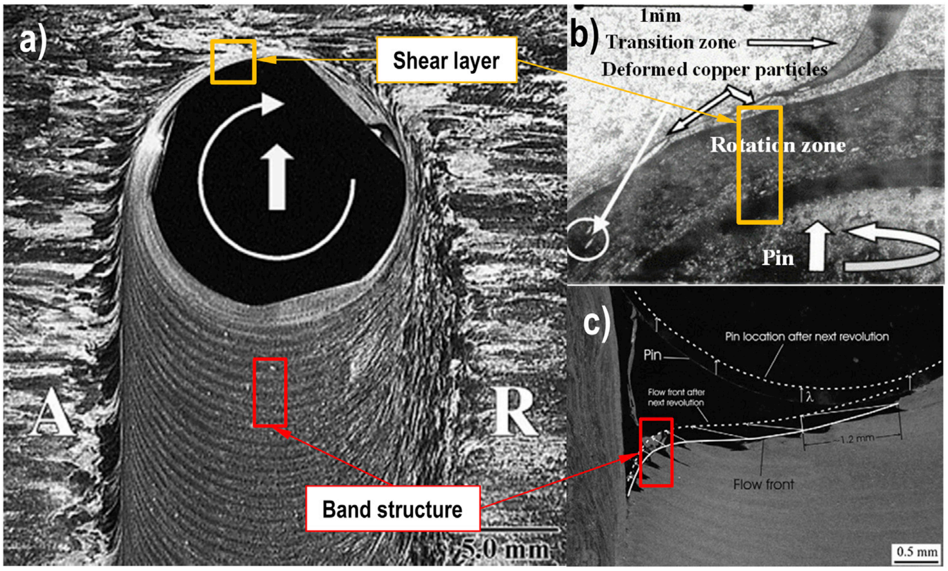

Fig. 1. Typical shear layer and band structure in typical FSW welding a) Planar view [23]; b) shear layer in front of pin [25]; c) band structure behind of pin [26].