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On material flow in Friction Stir Welded Al alloys

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ABSTRACT

AA6082-T6 joints were produced using a trigonal shape pin. The influence of Friction Stir Welding (FSW) process parameters on the formation of banded structures was predicted using numerical modeling and then experimentally validated by optical and electron microscopy. Special attention was paid to the formation and evolution of banded structures observed in the plane of the welded sheets. A finite element (FE) analysis based on the Coupled Eulerian–Lagrangian formulation was developed to predict and quantify the influence of FSW process parameters on the formation and extent of the banded structures. The combination of the experimental and numerical analyses showed that the formation of the banded structures is mainly related to the geometry of the pin whereas the friction conditions have a much smaller effect.

1. Introduction

Friction Stir Welding (FSW) is a solid state joining process in which a rotational tool moves along the interface of the parts to be welded. Joining is performed by stirring the interface, which is facilitated by heating due to plastic dissipation as well as friction between tool and workpieces. Friction stir welds have superior mechanical strengths when compared to conventional welding processes. MIG, TIG and FSW welds of aluminum alloy 5086-H32 have been studied by Taban and Kaluc (2007). The comparison shows that FSW welds are the strongest ones both for bending and tensile tests. Fatigue tests carried out by Ericsson and Sandström (2003) on welds made of aluminum alloy 6082 showed that the fatigue strength of FSW welds is higher than that of MIG and TIG welds. For FSW welds, the material forming the joint undergoes different thermomechanical histories depending on its location in the joint. This gradient in thermomechanical history results in various microstructural features and plays major role in determining the mechanical strength of the joint. The microstructure of the joint exhibits a number of characteristic features such as:

- Kissing bonds which correspond to a specific type of solid-state bonding defect where the two materials to be welded are in contact with little or no metallic bond as reported by Xu and Deng (2008). Crack growth along the kissing bonds have been observed by Jene et al. (2006) on friction stir welds made of aluminum alloy 5454.
- Banded structures consisting of alternating clear and dark bands. This phenomenon leads to the formation of onion rings which can be observed on the cross section of the weld joint, as studied by Krishnan (2002), using semicylinder clay model. The periodical material deposition has also been observed with a high speed camera by Gratecap et al. (2011) during FSW of plasticine.
- Void defects such as porosities or tunnel defects as observed by Kumar and Kailas (2008) which correspond to the lack of material flow in the retreating side of the joint.

Therefore, understanding material flow during FSW is crucial for controlling the weld quality, especially for complex tool geometries. In literature, a number of techniques have been used to study material flow during FSW. Steel balls have been used by Colligan (1999) as markers in the weld seam. Liechty and Webb (2007) carried out FSW welds by using plasticine with dissimilar color in order to observe the material stirring during the process. Even though the information provided by these techniques is valuable, it is not accurate enough to explain specific phenomena observed in metallic FSW welds such as the contrast difference between the bands. For FSW welds made of aluminum alloys, material flow during the welding stage can be reliably described by analyzing the elements in the weld microstructure. This approach was used by few authors in the literature. The formation mechanism of kissing bonds was investigated by Xu and Deng (2008) by inserting a thin

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sheet (0.1 mm) of pure aluminum at the interface of the AA6061-T6 plates to be welded, in order to increase the visibility of the resulting kissing bonds. In their study, the evolution of the kissing bonds as well as banded structure shapes as a function of the welding speeds was investigated. They reported that kissing bonds are often dragged into the banded region. This indicates that banded structures are highly related to the mixing of materials across the width of the weld. The formation mechanism of void defects was studied extensively by Kumar and Kailas (2008). The authors showed that void defects decrease when the welding force increases. Cui et al. (2008) used the stop action technique to study the material layer deposition mechanism. The technique is experimental and consists in leaving the tool inside the weld and observes the joint using optical and/or electron microscopy. However, an “a posteriori” description of the material flow during FSW welding must be checked through numerical investigations such as those carried out by Xu and Deng (2008) to predict banded structures produced by a cylindrical pin.

The main approach used for simulation of the FSW process is a solid mechanics type including large strains and strain rates. Several finite element formulations have been applied to simulate material flow during FSW. With a Lagrangian formalism, a step by step analysis needs to be performed to follow the movement of the tool and especially, the rotation of the pin. If such simulations seem to be very useful to study the process step corresponding to the penetration of the pin into the material, it is very time consuming to get the material flow during steady state welding conditions. In addition, as the mesh follows the material flow, the large distortions lead to unacceptable finite element distortions. The local modeling of mechanical effects requires refined meshes along the trajectory of the stirring zone which leads to significant size of the numerical problems that need to be solved. This can be avoided by means of refining discretization only in the vicinity of the welding zone using a re-meshing procedure. However, this approach increases the computational cost. The Arbitrary Lagrangian–Eulerian approach (ALE) can be used to obtain realistic computation times as suggested by Assidi et al. (2010) and Timesli et al. (2012). It consists in introducing a relative movement between the mesh and the welded material in order to decrease mesh distortions. The main drawback of this approach remains in the choice of the relative movement. Despite the complexity of such an approach, the formation of void defects has been well predicted by the model developed by Schmidt and Hattel (2005). An alternative approach consists in using meshless techniques such as the Smoothed-Particle Hydrodynamics (SPH) applied by Lorrain et al. (2009) and Tartakovsky et al. (2006), or the Moving Particle Semi-implicit (MPS) method used by Yoshikawa et al. (2012). However, as transient simulations must be performed, these approaches are complicated to implement and very time consuming as shown by Assidi et al. (2010) and Schmidt and Hattel (2005).

Like most welding processes, the FSW process involves a small size welding zone compared to that of the studied structure. It is very often assumed that a periodic state is reached when the welded structure displays a translational geometry over a long distance. Therefore, the material flow during the welding phase of the process can be calculated using an analysis with a reference frame linked to the welding velocity in an Eulerian formalism as used by Colegrove and Shercliff (2004), Jacquin et al. (2011) and Bastier et al. (2006), thus significantly reducing the computational efforts by avoiding the transient analysis. For non-axisymmetric tools, the periodic phase of the process can be simulated within an Eulerian formalism coupled with a simple moving mesh technique as proposed by Feulvarch et al. (2012) and latter applied by Dialami et al. (2013). The mesh is composed of two parts: a first one which is fixed around the stirring zone and a second one which includes the material under the tool and moves with a rotational solid motion

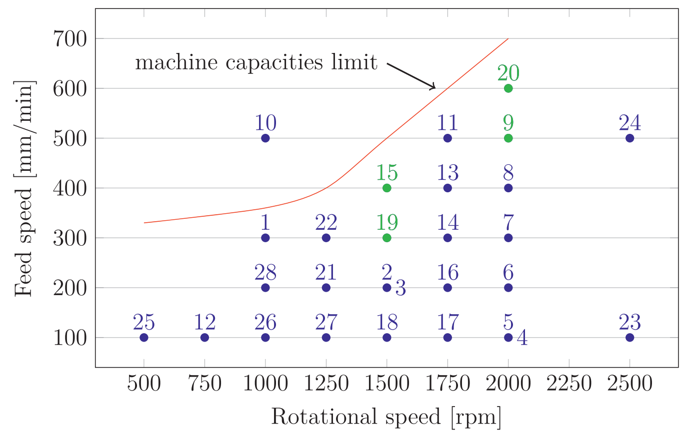

Fig. 1. Welding configurations (defective welds are indicated in blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

corresponding to the tool rotational velocity. Using the above approach, the mesh distortion problem is solved. The Eulerian formalism has the advantage of requiring much lower computation time as underlined by Tutum and Hattel (2011). With the mixture theory developed by Benson (1997), an enhanced boundary method can also be used to model the tool rotation. The geometrical volume of the pin is considered as a void inserted at each time step in the Eulerian media, where the welded material can flow. The contact mixture theory provided by Benson (1997) automatically computes and tracks the interface between the Lagrangian tool and the Eulerian welded material. Therefore, it is possible to simulate complex tool geometries as there is no requirement for fitting Eulerian mesh boundaries to the tool geometry. This approach is referred to as the Coupled Eulerian–Lagrangian (CEL). Recently, it has been used by Al-Badour et al. (2013) to predict void defects and flashes in FSW welds. Malik et al. (2014) have investigated the effect of various tool pin profiles using this approach. However, the CEL method has never been used to study the formation and evolution of the banded structures in FSW joints.

In the present paper material flow during FSW of 6 mm thick AA6082-T6 sheets using a trigonal shape pin is investigated by experimentation and modeling. In the first part, the influence of welding speed on the characteristics of the banded structure in the plane of the welded sheets is investigated. In the second part of the paper, a 2D numerical analysis based on the CEL formulation is used to analyze and predict the formation of banded structures and kissing bonds in the investigated material.

2. Experimental analysis

The details of the FSW experiments have been already provided in a previous publication of Tongne et al. (2015). The plates are made of aluminum alloy 6082-T6 with a thickness equal to 6 mm. Welding is carried out by means of a carbide trigonal tool. The height and the mean diameter of the pin are equal to 5 mm and 5.5 mm, respectively and the tool shoulder diameter equals 12 mm. The tilt angle is 1°. The total weld length is about 25 mm to be sure of achieving the stationary state as shown by Giraud et al. (2016) for the same welding setup. Fig. 1 summarizes the FSW processing map where the sound and defective welds are identified as a function of tool rotational speed and welding velocity. The red line denotes the welding limit of the testing machine according to the vibrations and forces which occur during the welding experiments.