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CDRX modelling in friction stir welding of aluminium alloys

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Abstract

In the paper a numerical model aimed to the determination of the average grain size due to continuous dynamic recrystallization phenomena (CDRX) in friction stir welding processes of AA6082 T6 aluminum alloys is presented. In particular, the utilized model takes into account the local effects of strain, strain rate and temperature; an inverse identification approach, based on a linear regression procedure, is utilized in order to develop the proper material characterization.
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1. Introduction

Friction stir welding (FSW) is a solid state weld process invented in 1991 in which a specially designed rotating pin is first inserted into the adjoining edges of the sheets to be welded with a proper nuting angle and then moved all along the joint. Such pin produces frictional and plastic deformation heating in the welding zone; actually no melting of material is observed during friction stir welding. Furthermore, as the tool moves, material is forced to flow around the tool in a quite complex flow pattern [1–3].

Actually the effectiveness of the obtained joint is strongly affected by several operating parameters [4–6]; first of all geometrical parameters, such as the height and the shape of the pin and the shoulder surface of the tool, have got a relevant influence both on the metal flow and on the heat generation due to friction forces. Furthermore the force superimposed on the rotating tool during the process itself has to be chosen, since the generated pressure on the tool shoulder surface and under the pin end determines the heat generation during the process. Finally both rotating speed and feed rate have to be properly chosen in order to obtain effective joints.

In the recent past, a few research activities have been developed on the numerical simulation of FSW processes. Thermal models, taking into account the heat generated by both friction forces work and the material deformation one, have been proposed [7–9] trying to highlight the temperature distributions nearby the rotating pin. Finite element thermo-mechanical models have been presented [10,11] with the aim to investigate the stress and strain distribution during the FSW process. In particular, Deng et al. [12–14] presented the results of both 2D and 3D thermo-mechanical analyses based on the finite element method. The researches were aimed to the investigation of the material flow, in terms of material circumferential speed all around the rotating pin; what is more a correlation was developed between the material final microstructure and the plastic strain distribution.

In this paper, the results of a FE analysis developed with a commercial code on the friction stir welding of AA6082-T6 sheets, are presented. The material microstructure evolution was taken into account through a proper model of grain size evolution due to recrystallization phenomena. It should be observed that in FSW processes, a continuous dynamic recrystallization phenomenon [15,16] occurs due to the tool pin disruptive mechanical action. The tool stirring action generates the formation of fine, equiaxed, recrystallized grains; such new microstructure determines the local material mechanical properties and the overall joint resistance.

The obtained results were compared with the ones derived by a set of experimental tests and allowed to

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highlight the process mechanics at the varying of the most important operative parameters.

2. The FSW process mechanics

As briefly described before, FSW of butt joints is obtained inserting a specially designed rotating pin into the adjoining edges of the sheets to be welded and then moving it all along the joint. The pin is characterized by a rather small nuting angle (θ) limiting the contact between the tool shoulder and the sheets to be welded just to about one half of the shoulder surface. As the pin is inserted into the sheets, the blanks material undergoes to a local backward extrusion process up to reach the tool shoulder contact. The pin is inserted into the sheet edges up to obtain a proper tool sinking (Δh) determining the contact between the tool shoulder and the sheets surface. The tool rotation determines an increase of the material temperature due to the friction forces work. As a consequence, the material mechanical characteristics are locally decreased and the blanks material reaches a sort of 'soft' state; no melting is observed, a circumferential metal flow is obtained all around the tool pin and close to the tool shoulder contact surface.

As such material softening is obtained, the tool can be moved along the joint avoiding the pin fracture due to excessive material reaction. The tool movement determines heat generation due to both friction forces work and material deformation one. Furthermore the composition of the tool spin vector and of the feed rate vector determines a peculiar metal flow all around the tool contact surface (Fig. 1).

It should be observed that the tool composed movement with respect to a fixed referring system is such that, assuming a null nuting angle and on the basis of the actual values of the tool pin rotation speed (R) and of the tool feed rate (V_f), a single point of the tool contact surface moves along a cycloid curve. As a consequence, considering a section of the joint normal to the tool movement direction (Fig. 2), an asymmetric metal flow is obtained. An advancing side and a retreating one are observed in the joint section: the former is characterized by the 'positive' composition of the tool feed rate and of the peripheral tool

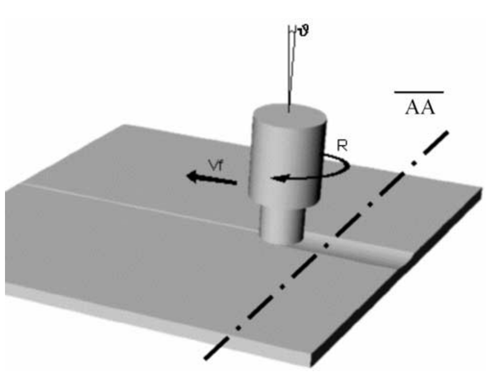

Fig. 1. A sketch of the FWS butt joint.

velocity; on the contrary, in the latter the two velocity vectors are opposite. Overall, the tool action determines the material softening and, what is more, the metal flux which allows the blanks welding.

A detailed observation of the material microstructure in the joint section of two AA6082-T6 sheets allows also to discern a few different areas (Fig. 2) as described below.

(a) *Parent material*. No material deformation has occurred; such remote material has not been affected by the heat flux in terms of microstructure or mechanical properties and shows an average grain size of 80 μm.
(b) *Heat affected zone (HAZ)*. In this region the material has undergone a thermal cycle which has modified the microstructure and/or the mechanical properties. However, no plastic deformation occurred in this area (Fig. 2b).
(c) *Thermo-mechanically affected zone (TMAZ)*. In this area, the material has been plastically deformed by the tool, and the heat flux has also exerted some influence on the material. In the case of aluminium, no recrystallization is observed in this zone; on the contrary, extensive deformation is present (Fig. 2c).
(d) *Nugget*. the recrystallised area in the TMAZ in aluminum alloys is generally called the nugget. In such zone, the original grain and subgrain boundaries appear to be replaced with fine, equiaxed recrystallized grains characterized by a nominal dimension of few micrometers (Fig. 2d).

A few considerations have to be developed on the recrystallization phenomena occurring in the nugget zone [15,16]. Several authors suggest that the microstructure observed in the nugget does not result from a discontinuous dynamic recrystallization phenomenon characterized by recrystallization nuclei formation and gross grain-boundary migration occurrence (DRX). In turn, the microstructural evidence suggests that a 'continuous' dynamic recrystallization (CDRX) process, analogous to that which gives rise to subgrain formation during hot rolling, occurs. Apart from specific microstructural considerations, it should be observed that the 'continuous' dynamic recrystallization phenomenon is due to the tool pin disruptive mechanical action. Actually, no time is given for grain-boundary recrystallization phenomena, even if dynamic. On the other hand, the thermo-mechanical action of the tool pin rather determines a grains demolition in the blanks material up to a microstructure characterized by very fine, equiaxed grains. CDRX process, as the more known DRX, is affected by a few variables; in other words, the final dimension of the continuously recrystallized grain is influenced by the local value of a few field variables, such as the strain, the strain rate and the temperature levels, and, of course, by the considered material. These last consideration fully explain the final microstructure observed in the nugget zone of a FSW joint section.

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