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An analysis of through-thickness residual stresses in aluminium FSW butt joints

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Abstract

In the paper, the results of a wide experimental campaign on friction stir welding (FSW) of aluminum alloys are reported. The attention was focused on the through-thickness residual stresses that occur on aluminum joints, after the welding process. In detail, using the hole-drilling method the residual stresses distribution in the zone close to the tool shoulder border of the joint advancing side, has been investigated; four different aluminum alloys and three different process conditions have been considered. The experimental analysis has shown that unlike traditional welding processes, the residual stresses are negative in the surface of the examined zone, and increase with depth until values of about 100–150 MPa that occur at a depth of about 0.5–1.0 mm. As expected, the maximum value of the residual stresses induced by the FSW process influences the mechanical behavior of the joint significantly, as it has been observed for the AA6082-T6 aluminum alloy by considering its static and fatigue resistance.

Such results corroborate that the hole-drilling method, widely employed in the industrial field due to its simplicity and low cost, can be used for an accurate estimation of the maximum residual stresses that occur in an aluminum butt joint obtained by friction stir welding.

Keywords: Friction stir welding; Residual stresses; Hole-drilling method.

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 a 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].

The effectiveness of the obtained joint is strongly affected by several operating parameters [4–6]; first of all geometrical parameters, the height and the shape of the pin as well as the shoulder surface of the tool influence both the metal flow and the heat generation due to friction forces. Furthermore, the force superimposed on the rotating tool during the process itself has to be chosen properly since the generated pressure on the tool shoulder surface and under the pin end determines the heat generation during the process. Rotating speed and feed rate also have to be properly chosen in order to obtain effective joints [7].

In the recent past, a few research activities have been developed on residual stresses occurring in FSW processes with particular reference on aluminum alloys. In particular, some researches developed with the aim to highlight the correlations between the residual stresses and the fatigue crack growth in the welded joints [8,9] have shown the relevance of the residual stress state to the fatigue behavior of the weldings. In detail, it has been observed that in the FSW joints, the crack growth behavior is generally dominated by residual stress and microstructure, whereas hardness changes have a minor influence. Peel et al. [10] investigated the influence of the tool feed rate on the residual stresses of FSW aluminum joints by using synchrotron X-rays measurement; the superficial residual

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stresses were highlighted and it was found out that in FSW the weld zone is subjected to longitudinal (parallel to tool travel) and transverse (perpendicular to tool travel) residual stresses.

Staron et al. [11] utilized the neutron strain scanning technique for the non-destructive determination of stresses in FSW butt aluminum joints: the research was aimed to investigate the possibility to modify the residual stress state in the joint by exerting external mechanical tensioning during the welding process. Low plasticity burnishing has also been utilized in order to modify the residual stress state and improve the fatigue performance of the joints [12]. Finally, steel joints have also been investigated in order to measure the residual stress state occurring after friction stir welding [13].

In the present paper, four different aluminum alloys were taken into account, namely AA6082-T6, AA2024-T4, AA7075-T6 and AA1050-O. Using the hole-drilling method, the variable through-thickness residual stresses occurring in the welded joint were investigated at the varying of the two most important process parameters determining the specific heat contribution [7] conferred to the joint, namely the tool rotating speed and the tool feed rate. In detail, the experimental set-up and the calculation procedure for non-uniform residual stresses allow the user to detect the residual stresses distribution that occurs at the most stressed zone of the joint section.

2. The FSW process mechanics

As briefly described before, FSW of butt joints is obtained by inserting a specially designed pin, rotating with velocity V_r, into the adjoining edges of the sheets to be welded and then moving it all along the joint with velocity V_f (Fig. 1). The pin is characterized by a rather small nuting angle θ (see again Fig. 1) 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

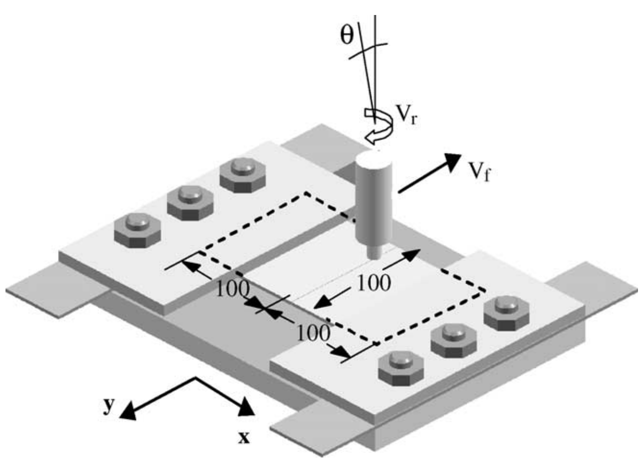

Fig. 1. Sketch of a FSW butt joint during welding processing.

the sheets, the blanks material undergoes a local backward extrusion process to reach the tool shoulder contact. In detail, the pin is inserted into the sheet edges to obtain a proper tool sinking Δh determining the contact between the tool shoulder and the sheets surface. The tool rotation determines an increase in the material temperature due to the friction forces work. As a consequence, the mechanical characteristics of the material decrease locally and the blanks material reaches a sort of 'soft' state; however, no melting is observed, and 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 (see also Fig. 1) determines a peculiar metal flow all around the tool contact surface.

It should be observed that assuming a null nuting angle, the tool composed of movement with respect to a fixed reference system is such that a single point of the tool contact surface moves along a cycloid curve whose shape is related to both the actual values of the tool pin rotation speed V_r and of the tool feed rate V_f. 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 distinguished in the joint section (see Fig. 2): the former is characterized by the 'positive' composition of the tool feed rate and the peripheral tool 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 transverse section of the joint permits to discern some different areas. As an example, Fig. 2 shows the transverse section of an aluminum AA6082-T6 butt joint and the contours of the different areas as:

(a) *Parent material.* No material deformation has occurred; both the microstructure and the mechanical properties of such a remote material have not been affected by the heat flux.
(b) *Heat affected zone (HAZ).* In this region, the material has undergone a thermal cycle, which has modified

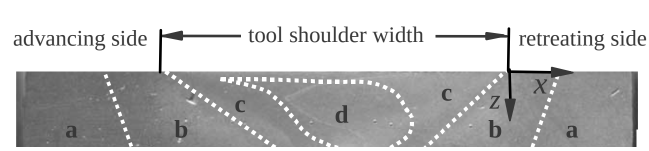

Fig. 2. Material microstructures in a typical transversal section of an aluminum AA6082-T6 welded joint.