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FSW OF LIGHTWEIGHT ALUMINUM STRUCTURES: LAP JOINT DEVELOPMENT

GIANLUCA BUFFA, LIVAN FRATINI

Dipartimento di Tecnologia Meccanica, Produzione e Ingegneria Gestionale
University of Palermo, Italy
Corresponding Author: fratini@dtpm.unipa.it (L. Fratini)

Abstract

Experimental and numerical investigation on the lap joining of 2xxx aluminum alloys blanks by FSW is presented. In particular, the influence of some relevant parameters, both geometrical and technological, is investigated with the aim to maximize the joint strength,. An accurate analysis on the obtained parts and on the numerical results was carried out and the reached results gave important information on the investigated joining technique.

Key words: lap, FEM, tool geometry

1. INTRODUCTION

The joining of aluminum alloys sheets represents still today an open border of the research activity of the scientific community due to the high relevance of such issue for many branches of the industrial environment. The so called un-weldable or difficult to be welded light weight alloys are very common materials in automotive or aerospace industries. Classic welding processes, i.e. TIG or laser, produce joints characterized by mechanical performance to tensile tests lower than the 60% or even 50% of the parent material. Actually such decrease in the joint strength is fundamentally due to metallurgical aspects, namely the increase of the average grain size observed in the melted material up to 10 times with respect to the parent material and to the large thermally affected zones, characterized by dendritic microstructure. What is more, strong precautions have to be considered during classic welding in order to avoid inclusions and other typical defects in the joint core.

On the other hand, friction stir welding (FSW) is a solid state welding process, first proposed at the beginning of the 1990s, in which a specially designed rotating tool characterized by a shaped pin-end is inserted into the adjoining edges of the sheets to be welded with a proper nuting angle and then moved along the joint. A heat flux is generated by frictional forces work and plastic deformation work, but no material melting is observed during the process. Furthermore, as the tool moves, material is forced to flow in a quite complex flow pattern [1]. Considering a section of the joint normal to the tool movement direction, asymmetric metal flow is obtained [2]. Overall, the tool action determines the material softening and, what is more, the metal flow which allows the blanks welding. The process avoiding any melting of the material allows to maintain an effective metallurgy of the material permitting to get mechanical performances of the joints even up to the 90% of the parent material.

In the most recent years several researches have been developed on FSW with the aim to fully high-

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light its process mechanics, material flow and metallurgical aspects. The mechanical behavior of the joints has been investigated from many points of view, namely static, dynamic and fatigue resistance, crack propagation, residual stress state and so on. First of all the influence of the most relevant process parameters on the effectiveness of the obtained joint were studied [3]. In particular geometrical parameters such as the shape and the dimension of the shoulder and the pin, but also the tool sinking into the sheets to be welded, and technological parameters, as the tool rotating speed and the tool feed rate, have to be properly chosen on the basis of the blank material in order to maximize the joint strength.

Furthermore, a few researches have been developed with the aim to highlight the correlations between the measured residual stresses [4-5] and fatigue life [6-7] of the joints, showing the relevance of the residual stress state to the fatigue behavior of the welding [8-9].

Recently a few research activities have been undertaken also on the numerical simulation of FSW processes, in order to develop a proper computer aided engineering of the process. Two main approaches have been followed: first of all thermal models, taking into account the heat generated by both friction force work and the material deformation work, have been proposed [10] trying to highlight the temperature distributions nearby the rotating pin. On the other hand, finite element thermo-mechanical models have been presented [11-13] with the aim to investigate the stress and strain distribution during the FSW process.

Overall, several attempts have been developed in order to fully understand FSW process mechanics and to improve joints performances, but only a few research works can be found in literature on FSW of lap joints.

In the paper the authors present the application of the FSW process to development of aluminum alloy lap joints to be utilized in the automotive, naval and aerospace industry. A wide experimental and numerical investigation on the lap joining of 2xxx aluminum alloys blanks is carried out at the varying of the tool geometry and of the main process parameters. An accurate analysis on the obtained parts was carried out and the reached results gave important information on the investigated joining technique.

2. THE EXPERIMENTAL ANALYSIS

The peculiarities of the FSW process mechanics have to be properly described in order to highlight the effectiveness and the advantages of such technology with respect to other classic welding processes.

FSW of lap joints is obtained fixing the adjoining blank edges on a properly designed fixture, inserting a specially designed rotating pin into the edges of the sheets to be welded and then moving it all along the welding line. In figure 1 a sketch of a fixture to obtain linear lap joints is reported. The tool pin is usually 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, supported by a dedicated clamping fixture, undergoes to a local backward extrusion process up to reach the tool shoulder contact. The tool rotation (R) generates 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 an excessive material reaction force with a feed speed Vf. The tool movement determines heat generation due to both friction forces work and material deformation one. Considering a section of the joint normal to the tool movement direction (figure 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 velocity; on the contrary, in the latter the two velocity vectors are opposite. What is more, in the section a vertical movement of the material is observed, mixing the two sheets parent material.

A detailed observation of the material microstructure in the joint section of two 3.2 mm thick AA2024-T4 sheets utilized allows a few different areas to be discerned moving from the periphery of the joint towards the welding line (figures 2 and 3) as described below [13].

After the parent material (zone d) a heat affected zone (HAZ) is discerned (zone c): in this region the material has undergone a thermal cycle which has modified the microstructure and/or the mechanical properties; no plastic deformation occurred in this area. The next material zone (b) is a thermo-mechanically affected one (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. Finally the nugget zone is found out (a): the recrystallised area in the TMAZ in aluminum alloys is generally called the nugget. In such a zone the original grain and subgrain boundaries appear to be replaced with fine, equiaxed recrystallized grains characterized by a nominal dimension of few mm.

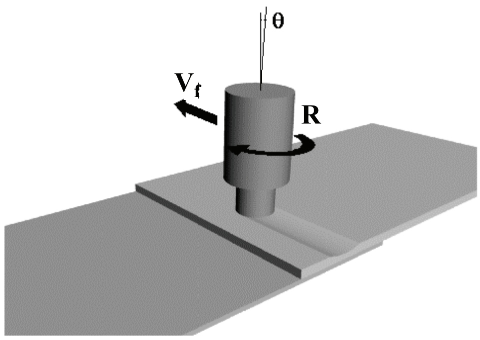

Fig. 1. Sketch of the linear FWS lap joint.

It should be observed that the microstructure observed in the nugget zone is caused by a "continuous" dynamic recrystallization (CDRX) process, 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 (just a few μm), equiaxed grains [12].

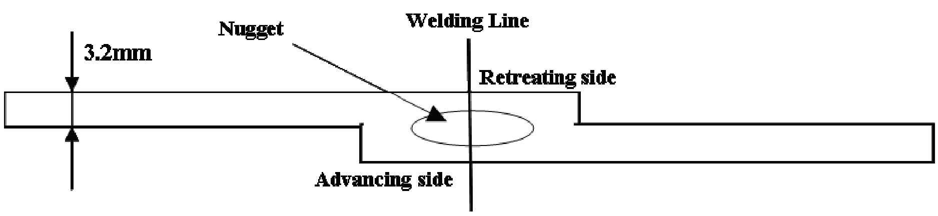

Fig. 2. Sketch of a typical lap joint section.

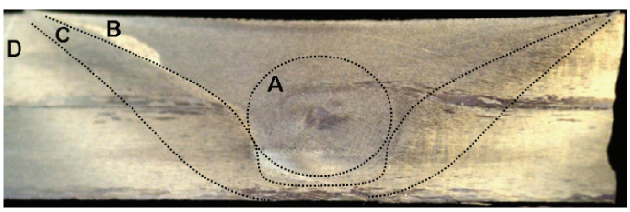

Fig. 3. Cross section of a typical lap joint section (AA2024-T4).

As far as the process parameters are regarded, three different tool geometries, characterized by a shoulder diameter equal to 20 mm, have been tested at the varying of the rotating speed: in particular a cylindrical (T1), a conical (T2) and a cylindrical-conical (T3) pin tool, whose details are given in figure 4, have been used. For all the welds an advancing speed equal to 100 mm/min, a 2° nuting angle and a tool sinking of 5 mm have been selected based on previous preliminary tests. The rotational speed ranged between 500 rpm and 1000 rpm. Every weld has been repeated three times and, from each obtained lap joints, specimens have been cut for the shear load tests.

Finally, from each weld further specimens have been derived, embedded by hot compression mounting, polished, etched with Keller reagent for 45 s and observed by a light microscope.

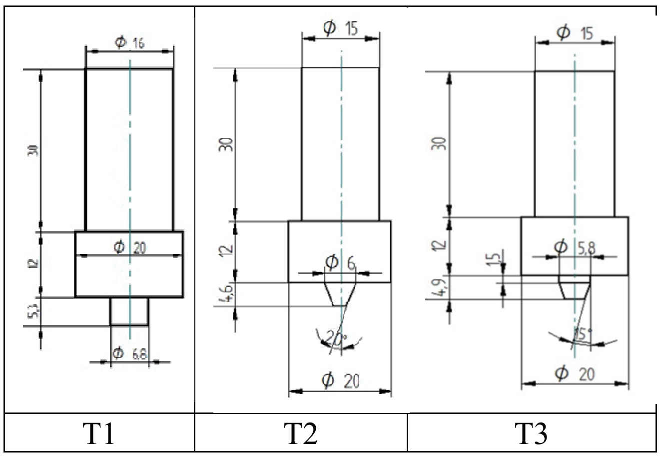

Fig. 4. Geometrical details of the utilized tools.

3. THE FE MODEL

The commercial FEA software DEFORM3D^{TM}, Lagrangian implicit code designed for metal forming processes, has been utilized to model the FSW process. The workpiece was modeled as a rigid viscoplastic material, and the welding tool was assumed rigid.

As far as the thermal aspects of the model are regarded, the temperature levels generated in the FSW process can be quite high, usually ranging from 400°C to 550°C depending on the chosen operative parameters, and have a considerable influence on the mechanical response. It is assumed that the heat generation in the deformation zone is due only to plastic deformation and frictional conditions at the tool-workpiece interface. The fraction of mechanical energy transformed into heat is assumed to be 0.9, as commonly utilized for many plastic deformation processes; such value was kept constant during the subsequent tune operations of the model [16]. The fraction of the rest part of the plastic deformation energy, stored in the body, causes changes in dislocation density, grain boundaries, and phases and so on. This energy is usually recoverable by annealing.

For the thermal characteristics of the considered AA2024-T4 aluminum alloy, the following values were utilized: thermal conductivity k = 180 [N/(s°C)] and thermal capacity c = 2.4 [N/(mm^2°C)] taken from literature; no variation of k and c with temperature was taken into account. This assumption makes the thermal problem linear, speeding up the numerical solution at each time increment. A rigidviscoplastic temperature and strain rate dependent material model was employed, ($\sigma = KT^{A}\left(\dot{\varepsilon}\right)^{B}\left(\bar{\varepsilon}\right)^{C}$) where K = 0.03×10^{3}, A = -0.488, B = 0.0027 and C = 0.124, are material constants determined by a numerical regression based on acquired experimental data [13]. As it can be seen, an increase in temperature leads to a decrease in flow stress ($A < 0$). On the contrary, an increase in both strain and strain rate leads to an increase in flow stress ($B > 0$, $C > 0$). A constant interface heat exchange coefficient of 11 [N/(s mm °C)] was utilized for the tool sheet contact surface. A preliminary sensitivity analysis for different interface heat exchange coefficient values confirmed that there was no significant variation of temperature as interface heat exchange coefficient changes. The tool was modeled as a rigid body and meshed, for the thermal analysis, with about 3,000 tetrahedral elements. As far as the modeling of the workpiece is regarded, a "single block" continuum model (sheet blank without a gap) is used in order to avoid contact instabilities due to the intermittent contact at the sheet-sheet interface. The rotating tool moves forward and welds a crack left behind the pin as it advances along the welding line. The sheet blank, 3.2 mm in thickness, was meshed with about 14,000 tetrahedral elements with single edges of about 1 mm; in this way about six elements were placed along the sheet thickness in the overlap region. A non-uniform mesh with adaptive remeshing was adopted with smaller elements close to the tool and a remeshing referring volume was identified all along the tool feed movement [14]. Experience in previous FEM simulation shows that a coarser mesh leads to incorrect results and a finer mesh results in unaffordable computation time without significant improvement of simulation results. A constant shear friction factor of 0.46 was used for the tool-sheet interface on the basis of a previous experimental thermal characterization and of a numerical sensitivity analysis for the shear friction factor m. Figure 5 shows a sketch of the utilized model during the welding stage.

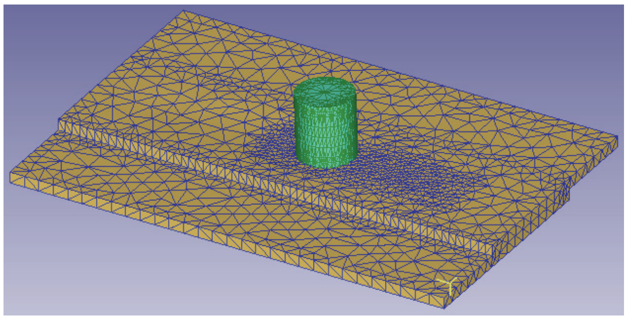

Fig. 5. *The FE continuum model at the beginning of the simulation.*

The presented FE model has been already tuned and verified by the authors for butt joints and the obtained results have been presented in [12-14].

4. RESULTS

In order to evaluate the performances of the three utilized tools, shear test have been performed: the next figure 6 shows the results of such tests in terms of load to failure per millimeter of welding. Nine different case studies have been studied, i.e. for each tool three values of rotating speed – 500 rpm, 700 rpm and 1000 rpm respectively - have been tested. As it can be seen from the figure the T1 tool is significantly less performing at every rotational speed value. This indicates the possibility of an incomplete and unsatisfactory weld. The joints obtained by the T2 and T3 tools present, on the contrary, a better resistance with similar maximum failure load obtained for R = 500 rpm. However, the joints obtained using the T3 tool show acceptable failure load values even at the increasing of the rotational speed, indicating a further improvement in the welding mechanics. It has to be noticed that, for all the considered tools, the joint mechanical resistance decreases at the increase of the rotational speed. This indicates that, for the selected shoulder diameter, at the increase of the rotational speed an excess in the specific thermal contribution conferred to the weld is observed, leading to grain growth and/or even micro-fusion, which have a negative effect on the microstructure and, as a direct consequence, on the joint resistance.

To investigate the causes of such behavior, a comparison has been performed between the transverse sections of three welds obtained with the same process parameters at the varying of the tool. In figure 7 the macro observation of three welds obtained with R = 700 rpm is shown. The above picture makes clear the reasons for the behavior observed in figure 6. As a matter of fact, friction stir welded lap joints resistance is dramatically influenced by the width of the nugget area, which in turn is heavily linked to the resistant section. Taking into account figure 7A corresponding to the weld obtained with the cylindrical pin tool, in spite of a quite large nugget area (L_A distance), a typical tunnel defect is highlighted. Such defect is the cause of an early crack occurrence all along the weld area and of a poor shear test performance. Looking at figure 7B a defect free weld can be observed with a good nugget integrity, and in this way a significant improvement in the joint performance is obtained. This is due to the effect of the conical pin that, beside the horizontal helical material flow given by the cylindrical pin, gives rise to an additional vertical helicoidal material flow [14]. It has to be noticed that such vertical component, whose beneficial effects are known in FSW of butt joints, is even more important in FSW of lap joints where the initial separation line between the sheets is horizontal. On the other hand, a conical pin has a smaller section at the sheet-sheet separation surface, hence the resulting resistant section is smaller as highlighted in figure 7 ($L_B < L_A$). According to these considerations, the T3 tool is able to combine the beneficial effects of the T1 and T2 tools, i.e. a quite large resistant section and nugget integrity, presenting a cylindrical section till the sheet-sheet interface and a conical section at the end in order to create the vertical helicoidal material flow.

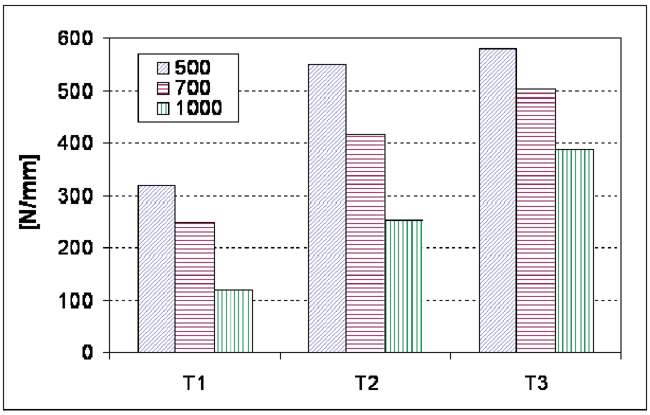

Fig. 6. Shear tests results, expressed as maximum failure load per mm of welding, at the varying of the rotational speed R

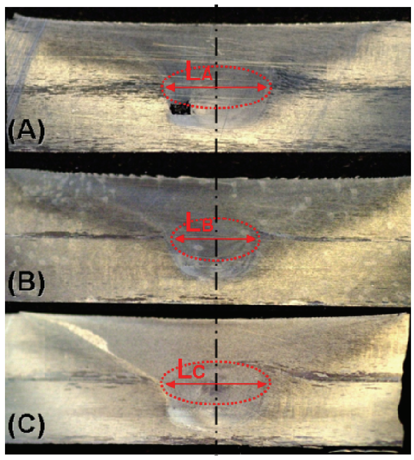

Fig. 7. Macro observation of the transverse sections of welds obtained with R = 700 rpm and the (A) T1, (B) T2, and (C) T3 tool respectively

The above observations are further explained by the numerical analysis developed. In figures 8, 9 and 10 the temperature, strain and strain rate distributions in a joint transverse section are shown, respectively, for the R = 700 rpm case study with reference to the two most performing tools, namely T2 and T3.

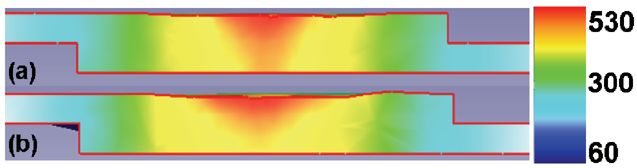

Fig. 8. Temperature distribution in a transverse section for (a) T2 and (b) T3 case studies (R = 700 r.p.m.)

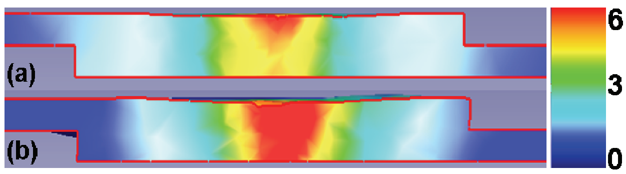

Fig. 9. Strain distribution in a transverse section for (a) T2 and (b) T3 case studies (R = 700 r.p.m.)

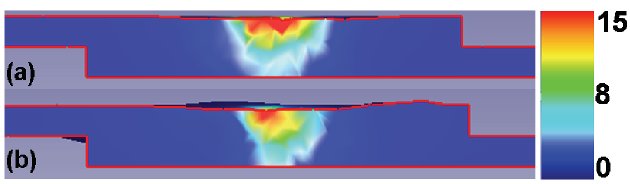

Fig. 10. Strain rate distribution in a transverse section for (a) T2 and (b) T3 case studies (R = 700 r.p.m.)

The reason for the increase in performance observed with the T3 tool are highlighted by the above pictures. First, though the maximum strain values are similar, a wider area characterized by large deformations is found when the T3 tool is adopted (figure 9B), due to the wider pin section near the bottom of the joint. In this way more material is involved in the material flow resulting in a more effective and homogeneous weld. Taking into account the T3 case studies (figures 8B, 9B and 10B) a similar strain rate distribution is observed along the transverse section with respect to the T2 case studies (figures 8A, 9A and 10A) while, at the same time, a lower temperature is observed, especially in the bottom of the joint and at the sheet-sheet interface, due to the smaller contact surface between the tool and the workpieces and to a lower deformation work decaying into heat. Such combined effect of strain rate and temperature results in a more refined grain size in the nugget area, being the latter variable strongly dependant by the Zener-Hollomon parameter ($Z = \dot{\varepsilon} e^{\frac{Q}{RT}}$). In particular, if the strain rate remains constant while the temperature decreases an increase of Z is found with a subsequent decrease of the average grain size due to the continuous recrystallization phenomena.

5. CONCLUSIONS

In the paper a wide experimental and numerical campaign has been developed for friction stir welded lap joints of AA2024-T4. The obtained results permit to draw the following conclusions:

- In order to get effective friction stir welded lap joints an as wide as possible nugget area has to be obtained together with satisfactory nugget integrity.
- Cylindrical pins allow obtaining large nugget areas because of the large section they present at the sheet-sheet interface; in turn, poor material flow is observed due to the absence of a vertical component of material velocity. Conical pins allow obtaining an effective vertical helicoidal material flow, but, due to their smaller section at the sheet-sheet interface, a smaller resistant section is found in the joint.
- Cylindrical-conical pins are able to combine the positive effects of the two tools, and the joint performances are the best, among the analyzed case studies, for every rotating speed value.
- The developed numerical model is able to predict the effect of the tool geometry on the main field variables thus representing an effective tool for the process design.

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ZASTOSOWANIE PUNKTOWEGO ZGRZEWANIA TARCIOWEGO Z MIESZANIEM MATERIAŁU ZGRZEINY DO ŁĄCZENIA LEKKICH STRUKTUR ALUMINIUM: OPRACOWANIE SPOJENIA ZAKŁADKOWEGO

Streszczenie

Tematem niniejszej pracy są badania laboratoryjne oraz analiza numeryczna procesu spawania zakładkowego metodą Friction Stir Welding (FSW) stopów aluminium serii 2xxx. Analizie poddany został wpływ parametrów geometrycznych oraz technologicznych na wytrzymałość uzyskiwanych spoin. W pracy omówiono uzyskane wyniki oraz wynikające z nich wnioski.

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