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Friction based solid state welding techniques for transportation industry applications

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Abstract

Solid bonding based processes represent an effective solution in terms of both joints mechanical performances and sustainability. In the last years, both the academic and the industrial researchers focused their work on two solid-state processes: Friction Stir Welding (FSW) and Linear Friction Welding (LFW). The former, patented in 1991 by TWI, is used to weld sheet metal in different joint morphologies, i.e. butt, lap T and 3D joints. The latter has been known for several years, but a growing interest is observed in the last years due to the enhancement of the welding machines performances. LFW, used to join bulk components, is particularly suited for aeronautical and aerospace applications.
In this paper, the potential of the two processes is investigated analysing the joints properties and the metallurgical modifications induced by the processes as related to the welded alloy. For both the processes, the effect of the main process variables is highlighted and the impact on industrial production is pointed out.

Keywords: Friction Stir Welding; Linear Friction Welding; Aluminum alloys; light alloys.

1. Introduction

1.1. Weldability of lightweight alloys

In the last years, the development of the manufacturing technologies has led to the wide use of innovative materials in various industry fields. Lightweight alloys, namely aluminium, magnesium and titanium alloys, are characterized by a high strength/weight ratio so that they allow the production of light structures without using expensive composite materials. Such characteristics have been highly appreciated by the transportation industry because of the weight reduction resulting in fuel consumption and emissions drop off. However, the production of these structures could not be pursued without innovative welding technologies that, differently from other joining techniques (i.e. self-piercing riveting, clinching etc.), allows material continuity in the joint. Traditional welding techniques are based on the melting of the base material and a filler along the joining line. The heat flux required by the process is provided by various sources as oxyacetylene torch, electric arc, laser beam, etc. The critic phase of the process is the cooling of the weld that must first be protected by the oxidant effects of atmosphere through melted ceramics floating on it or inert gas blown on it. Besides, during the solidification of the weld other untoward phenomena (such as segregation, dendritic recrystallization, gas bubbles (porosity) and intermetallic formation) may occur compromising the joint resistance.

All these issues are particularly relevant as the welding of lightweight alloys is concerned. Until a few years ago, all the aluminium alloys were considered non-weldable because of the formation of Al_2O_3 during the process. Such ceramic, refractory oxide (commonly called alumina) quickly cover the weld at high temperature and his extreme hardness (and the relative fragility) causes the failure of the joint. The development of TIG and MIG technology partly solved this issue. However, many of the other sources of defectiveness, such as the formation of porosity caused by hydrogen bubbles trapped in the weld (hydrogen is characterized

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by different solubility in solid and melted aluminium), cannot completely overcome. Consequently, some of the cited aluminium alloys remains non-weldable with traditional “melting” techniques (see Fig. 1).

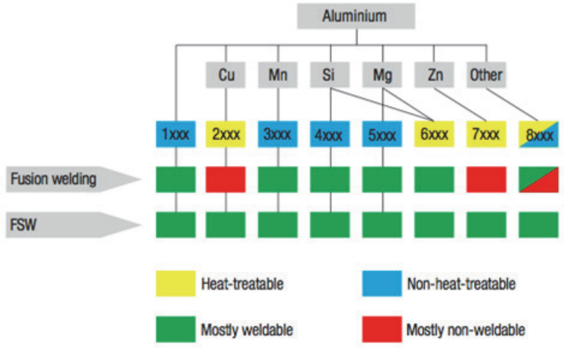

Fig. 1. Weldability of aluminium alloys [1]

Magnesium alloys can also be welded using MIG, TIG and laser technology; in particular, Mg-Al alloys are considered the most weldable of them, while Mg-Zn alloys are often affected by hot cracking defects. Titanium alloys result to be the most complex to be welded because hydrogen and water vapour create brittle structures from about 250°C so that the joint is usually welded under controlled atmosphere. Other innovative technologies used to soundly weld lightweight alloys are the electron beam welding (EBW) and the laser beam welding (LBW). These processes result to be inefficient in terms of joint mechanical properties because of the vaporization of magnesium and zinc and the high reflectivity of the cited alloys [2].

1.2. Solid bonding process

In the last decades, researchers have developed new joining technologies to radically settle all the issues linked to the melting-based welding techniques. The solid-state bonding technology allow to obtain sound weld without reaching the melting temperature of the base material. Solid bonding phenomenon occurs in metal materials when a plastic flow is subjected to high pressure and temperature. The third variable that affects the process is the period of time the cited condition are kept.

Solid bonding process can be sorted depending on the mechanism of generation of the heat flux necessary to the material softening; the most common energy sources are the work of friction forces (friction stir welding (FSW), linear friction welding (LFW) and rotary friction welding (RFW)) and high frequency ultrasound (ultrasonic welding). Indeed, solid bonding phenomenon characterizes other production technologies in the field of plastic deformation such the porthole die extrusion [3]: during extrusion, a mandrel and some spiders divide the plastic flow that is hence collected in a welding chamber, which apply the necessary pressure to form a solid pipe. Although this process is commonly used in many industrial fields, his engineering is still incomplete and based on empirical data rather on solid knowledge of the phenomena that control it [4].

As far as friction based welding processes are regarded, the relative simplicity of manufacturing (in particular for FSW and RFW) and high joint quality are the main reasons for this quick spread in a wide variety of industrial fields: in particular, FSW has been applied in the production of computer cases, aerospace structures and space shuttle fuel tanks. This technology, originally developed to weld aluminium alloys, is also used to weld dissimilar joints and particular joint configuration (tailored, skin/stringer) required for the manufacturing of complex and performant lightweight structures (Fig. 2).

Fig.2 Audi Space Frame (ASF) [5]: chassis of an Audi A8 manufactured with magnesium and aluminium elements manually welded because of the defectiveness of the melting process

On the other hand, one of the most known industrial application of LFW is the production of the so called blisks, i.e. bonding of blades (see Fig. 3) on the rotors of turbine for fixed installation or aeronautic application (often made of different alloys).

Fig. 3 LFWed turbine blades [6]

In this paper, the evolution and the potential of FSW and LFW is analysed describing the welding processes and the parameter of influence that affect them. Future development and industrial application of both the technology were hence highlighted.

2. Friction Stir Welding

Friction Stir Welding is a solid-state welding process developed and patented in 1991 by The Welding institute (TWI) of Cambridge. This technology allow to join sheet metal thanks to a complex plastic flow of material caused by the action of a properly designed rotary tool that is plunged nearby the edges of the sheets and moved along the welding line. During the process, no filler is used and temperature results to be under the melting point of the base material so that all the issues linked to the melting and solidification of the material are avoided.

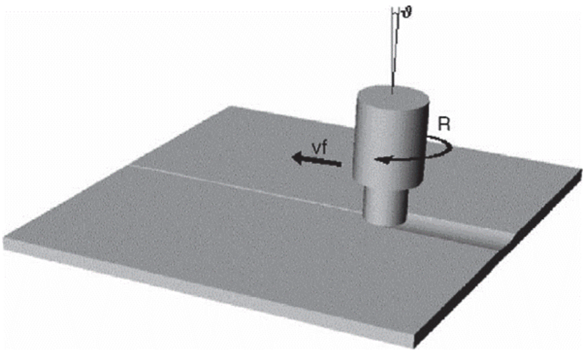

Fig. 4 FSWed butt joint processing

The tool, responsible of both stirring and friction action, is characterized by a "shoulder" and a smaller end-jut called "pin". The shoulder forms a small "nuting" angle with the sheet metal reducing the actual contact to one-half of shoulder's surface. Since the spread of this process, many different and complex tool geometries have been developed in order to optimize plastic flow and heat production. At the beginning of the process, the tool is plunged at constant velocity in the metal until the bottom of the pin is a few tenths of millimetre far from the bottom of the sheets. The initial inverse extrusion caused by the pin plunging is arrested by the shoulder that consequently generates heat by friction. The material softening caused by the heat flux enable an effective stirring action exerted by both the shoulder and the pin. When the material is heated up enough, the tool is moved along the joining line forming the weld (Fig. 4).

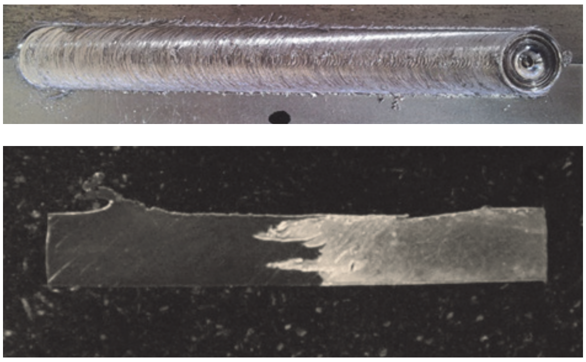

Fig. 5 FSWed butt joint weld and section macrography (2 mm thick AA6016 RS and AZ31B AS)

The trajectory of each point of the tool can be considered (ignoring the nuting angle) a cycloid curve so that the material flow result to be inherently asymmetric; two different zones can be identified in the weld depending on the combined action of the rotary and advancing motions. The side where advancing and rotary velocity are concord is so called "Advancing Side" (AS) while the side where they are opposite is registered "Retreating Side" (RS).

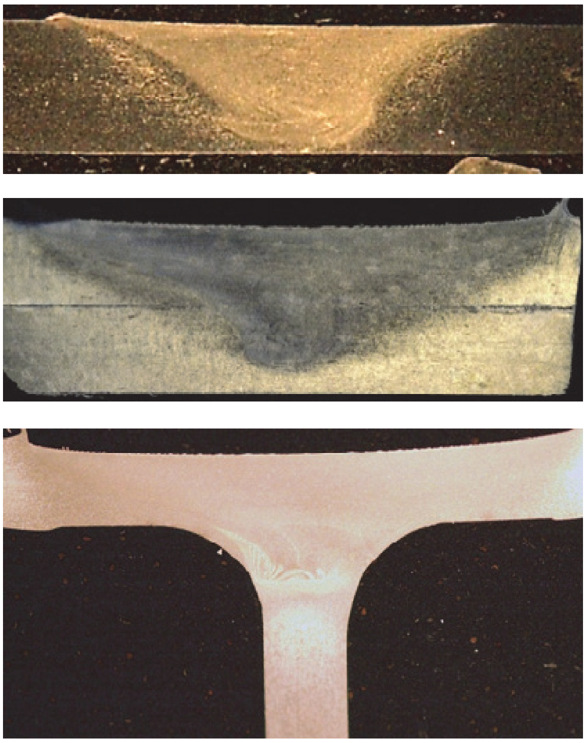

Fig.6 Butt, lap and T joint weld section macrographs (3 mm thick AA6082-T6)

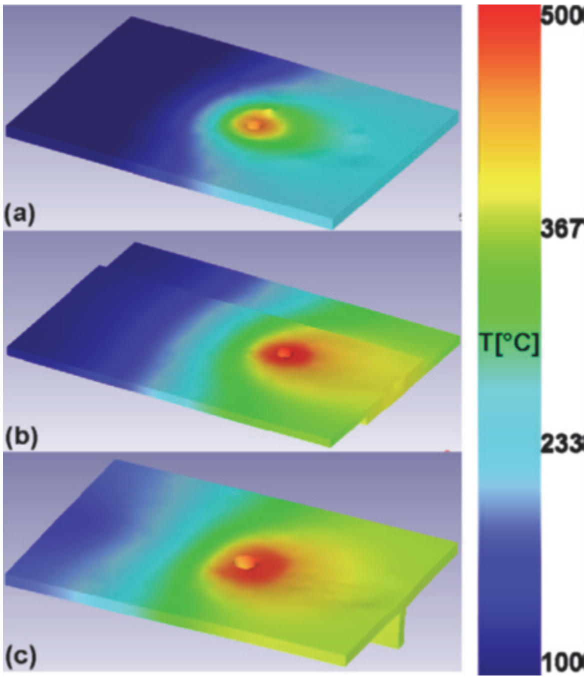

Fig. 7 Temperature distribution obtained by FEM simulations of butt, lap and T FSWed joints (3.2 mm thick AA 2139)

The process parameters commonly varied during experimental campaigns and numerical simulations are the tool rotation and feed rate that directly affect the heat generation and stirring action as well as the tool geometry. Joints produced with different combinations of the cited parameters can hence be analysed in order to find out the best configuration. In particular UTS, the trend of the average grain size and micro hardness on the weld section are commonly investigated. Obtained results show that, optimizing the process, it is possible to obtain UTS of the joints almost equal to the base material one. It is worth noticing that this mechanical resistance cannot be obtained with conventional melting techniques.

Once a consolidated knowledge of the FSW process, as applied to aluminium alloys, has been reached, the researchers focused on different and more "difficult" materials such magnesium [12-13] and titanium [14-15] alloys (see Fig. 8). Titanium alloys cause many problems because of their high strength and require some special arrangements to be soundly welded: the weld have to be protected with inert gas because of the elevate temperature of the process and, for the tool, very hard materials must be used to not be quickly worn out [16]. Recently, the FSW process has been applied on manufacturing dissimilar metal joints (Al-Al, Al-Mg, Al-Ti, Ti-Mg) obtaining encouraging results.

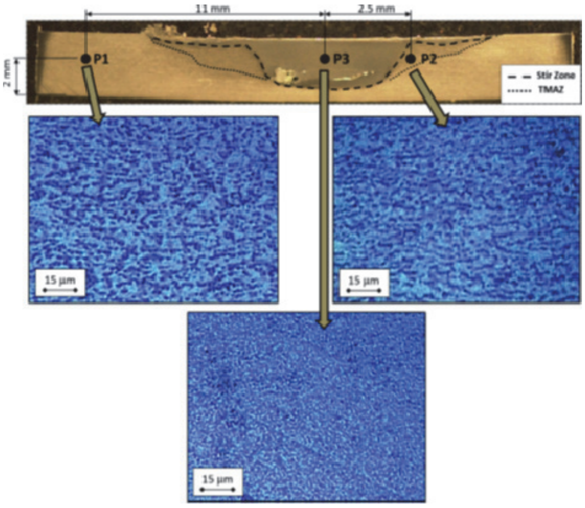

Fig. 8 Butt joint weld section macrograph and micrographs (2 mm thick Ti–6Al–4V)

3. Linear Friction Welding

Linear Friction Welding is one of the oldest friction based welding process. Although the first patent is from the late 60's, the development of this technique started in the 80's. During the last few years, due to the increasing interest of aeronautical and aerospace companies, and to the development of dedicated machines, a few papers have been published by research groups all around the world [17-18]. LFW can be divided in four distinct fundamental phases (see Fig. 9); first the workpieces are brought into contact (the initial contact surface is actually less than the areas of welding because of the micro-roughness). Because of the onset of an oscillatory motion and the application of the closing pressure the roughness is quickly reduced increasing the contact and the heat generation caused by friction actions. If the generated heat flux is adequate, the process goes by the successive step of "transition" in which the increase of temperature causes the softening of the metal. The softening obtained causes the sideward extrusion of the material that produces the typical "flash" reducing the height of the workpieces (equilibrium phase). Finally, the relative motion of the pieces is quickly arrested (in less than 0.1 s) and the closing pressure is increased in order to complete the welding process. The main process parameters affecting LFW are interface pressure, oscillation frequency, oscillation amplitude (commonly sinusoidal) and duration of the process. Surface finish of the workpieces and friction coefficient between the materials have to be properly taken into account.

It is notable that, even if the LFW has been quickly developed in the last years, there are only few papers in literature. This lack of knowledge is mainly imputable to the machines needed to study the process. In fact, LFW machines cannot be easily produced adapting common machine tool such milling machines or lathes (used to made FSW and RFW machines respectively) while dedicated commercial machines are often too expensive and unsuited to experimental studies. Research institutes working on LFW has often manufactured prototypal LFW machines themselves.

In particular, the DICGIM researcher of the University of Palermo developed, basing on previous knowledge [19-20], a LFW machine (see Fig. 10) characterized by a kinematic desmodromic chain with trefoil cams [21] that transmit the oscillation to one of the specimens. A hydraulic actuator, applying the needed pressure, moves the other workpiece. The device is hence fitted out with a pneumatic clutch (that separates it from the engine in order to reduce the inertia in the deceleration phase) and a few sensors to measure torque, temperature and acceleration of the oscillating specimen.

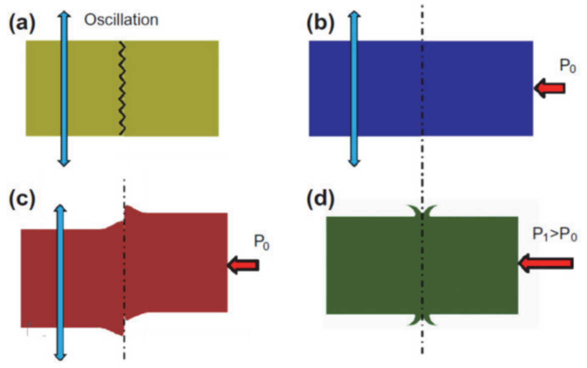

Fig. 9 The four phases of LFW: (a) initial, (b) transition, (c) equilibrium, (c) deceleration

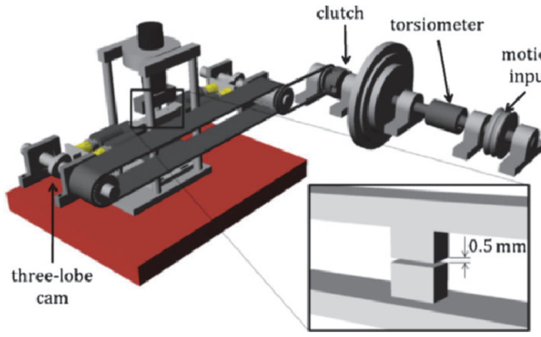

Fig. 10 LFW machine

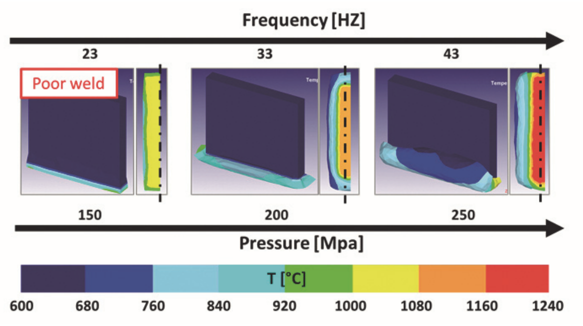

Fig. 11 FEM analysis on temperatures distributions (ASTM A285 steel)

As for FSW, experimental campaigns and numerical simulations [22] (see Fig. 11) have been carried out in order to find, for each studied material, the best combination of process parameters with the aim to maximize the joint mechanical properties. Both aluminium alloys (Fig. 12) and steels were analysed. Future developments include further improvement of the machine in order to investigate titanium alloys welding and mixed joints.

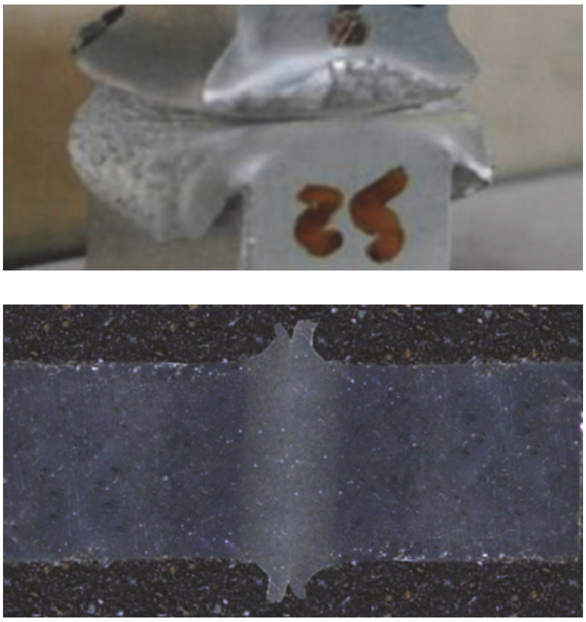

Fig. 12 LFWed AA6082-T6 joint and macrograph of the weld section

4. Conclusion

Solid-state welding technology represents an important research field for the production of high performance components due to the excellent characteristic of mechanical strength of the joints.

Moreover the absence of filler material, consumable tools, staking, protective gasses and dangerous products of the weld makes these processes "eco-friendly" and safer for the operator. Different materials can be successfully welded and the numerical simulation was demonstrated to be an effective tool for the prediction of the distribution of the main field variables, of the microstructural evolutions during the weld and of the final mechanical properties of the joints. In this way, a further use of this technique in actual production is expected in the next few years.

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