Publishing House
AKAPIT

COMPUTER METHODS IN MATERIALS SCIENCE
Informatyka w Technologii Materiałów

Vol. 11, 2011, No. 1

MECHANICAL AND METALLURGICAL PROPERTIES OF TITANIUM ALLOY FRICTION STIR WELDED BUTT JOINTS

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Abstract

Friction Stir Welding (FSW) is a solid state welding process patented in 1991 by TWI; initially adopted to weld aluminum alloys, is now being successfully used also for magnesium alloys, copper and steels. Recently, research is focusing on titanium alloys thanks to the high interest that such materials are getting from the industry due to the extremely high strength-weight ratio together with good corrosion resistance properties. Welding of titanium alloys by traditional fusion welding techniques presents several difficulties due to high material reactivity resulting in bonding with oxygen, hydrogen, and nitrogen with consequent embrittlement of the joint. In this way FSW can represent a cost effective and high quality solution. In the paper the effect of the tool rotational speed on welding temperatures acquired during FSW of the widely commercially diffused Ti-6Al-4V alloy is analyzed. Experimental results are correlated to the mechanical and metallurgical properties of the obtained joints. The study of the temperatures reached leads to a deeper knowledge of the process as well as to the possibility to predict the microstructural evolutions occurring during the weld and dramatically influencing the mechanical properties of the obtained joints.

Key words: friction stir welding, titanium, temperature

1. INTRODUCTION

During the last decade, the use of alloys characterized by large resistance-weight ratios appears as the best technical solution for automotive, naval and aeronautical industry as well as a big challenge for engineers. Such materials present several advantages and a few drawbacks that must be overcome. In particular, as far as industrial needs are regarded, through a proper design it is possible to address three of the main issues: increase in the active and passive safety, reduction of fuel consumption and environmental impact. However, such materials are characterized by lower ductility with respect to steels, anisotropy and are often considered difficult to be welded or "non weldable".

At the moment, traditional fusion welding processes for materials as aluminum, magnesium and titanium alloys is often characterized by the insurgence of defects like porosities and inclusions (Liu et ali., 2003; Winter et ali., 1990). As a consequence, a few researches have recently been proposed with the aim to improve the efficiency of the joints. Among the continuous joining techniques, Friction Stir Welding (FSW) appears as one of the most promising. Friction stir welding is a solid state weld process invented in 1991 in which the effectiveness of the obtained joint is strongly affected by several geometrical and technological parameters; in particular both rotating speed and feed rate have to be properly chosen in order to obtain effective joints (Rhodes et ali., 1987, Guerra et ali., 2003). During the process, the tool rotation speed (R) and feed rate

ISSN 1641-8581

(Vf) are combined in a way that an asymmetric metal flow is obtained. In particular, an advancing side and a retreating side are observed: the former being characterized by the "positive" combination of the tool feed rate and of the peripheral tool velocity while the latter having velocity vectors of feed and rotation opposite to each other. Hence the tool action is the main responsible for both the material softening and the material flow resulting in the weld of the two workpieces.

Based on the above description, it is clear why the process can be successfully utilized for "difficult to be welded" alloys and, as far as aluminum alloys are regarded, can ebe considerd mature as it is already being utilized for automotive, aeronautical, civil and naval industrial applications for different joint morphologies (Fratini et ali. 2010a; Buffa et ali. 2010; Fratini et ali. 2009).

In the very last years, the process versatility has leaded to new researches focused on materials like steels, magnesium and copper alloys, MMCs, thermoplastics, mixed joints made of two sheets of different material and titanium alloys.

As far as the latter are regarded, difficulties arise for the application of the process because of the chemical, mechanical and thermal peculiar properties. In particular, titanium alloys present high reactivity with atmospheric gas as oxygen, hydrogen and nitrogen, resulting in a significant joints performance reduction. Besides, the use of traditional fusion welding processes as TIG, MIG, EBW and LBW results in extremely high temperatures and, consequently, in large distortions and residual stress in the welded joints. FSW, as a solid state process, can effectively solve most of these drawbacks. It should be observed that during the FSW of titanium alloys additional difficulties arise with respect to the same process applied to aluminum alloys. Due to the high temperatures and contact forces between the sheets and the tool, the tool material choice is limited to high resistant refractory materials as tungsten carbides, Rhenium and Molybdenum based alloys and pcBN (Zhang et ali. 2008a; Pasta et ali. 2008; Mironov et ali. 2008). Other difficulties are due to the low thermal conductivity [7 W/mK], resulting in a non uniform temperature distribution and in a significant thermal gradient along the joint thickness. That may severely compromise the effectiveness of the joint as most of the heat is generated on the top surface of the joint, i.e. the contact surface between the tool shoulder and the sheets. For such reasons a specifically designed clamping fixture has been designed for the FSW of butt joints in titanium alloys, featuring, as detailed in the fooling paragraphs, a proper cooling system, both for the tool and the clamping fixture, together with a shielding gas continuous flow.

As known by the authors, only a few papers can be found in literature on the FSW of titanium alloys; in (Lee et ali. 2005) and (Zhang et ali. 2008b) the main mechanical and metallurgical properties of joints obtained from commercially pure titanium sheets are analyzed, highlighting the main difference occurring with the same process applied to aluminum alloys. In (Mironov et ali. 2008) the residual stresses effect on the crack growth during fatigue tests is studied by means of a numerical simulation.

In the present paper temperature histories during the FSW of the widely commercially used Ti-6Al-4V titanium alloy sheets are recorded and analyzed. Different tests have been carried out at the varying of the tool rotating speed in order to understand the micro structural evolutions occurring during the process that deeply influence the joint mechanical performances.

2. EXPERIMENTAL PROCEDURE

2.1. Experiments

As far as the welds are regarded, 200 x 100 mm Ti-6Al-4V titanium alloy sheets, 2.5 mm in thickness, have been selected. Different tests have been developed at the varying of the tool rotational speed; in particular 340-500-700-1000 rpm have been chosen for the above parameter. The remaining technological parameters of the process have been kept constant as follows: tool advancing speed equal to 35 mm/min, nuting angle equal to 3° and tool sinking equal to 2 mm.

2.2. Welding fixture development

As briefly discussed in the introduction, the main advantage characterizing the use of FSW for titanium alloys is the possibility to get rid, or significantly mitigate, most of the problems arising during the welding of such materials by traditional fusion welding processes. On the other hand, because of the mechanical and physical characteristics of titanium alloys, tool and clamping fixture must be able to resist to the significant welding forces and temperatures (Fratini et ali. 2010b). The solid model of thee developed fixture is shown in the next figure 1:

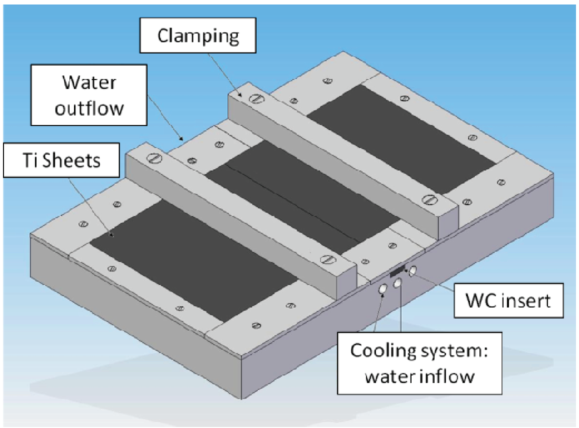

Fig. 1. Sketch of the developed fixture.

On a solid steel backplate, directly fixed on the utilized CNC milling machine table, a rectangular pocket was milled in order to place a tungsten carbide (WC) insert, 6mm in thickness. During the process, temperature can easily be over 60% of the welding temperature of titanium, resulting in values of about 1000°C. At such high temperatures the mechanical properties of the steel backplate decade and undesired binding phenomena between the titanium sheets and the backplate itself may be observed. On the other hand, WC, being characterized by a melting temperature of about 2800°C can prevent such detrimental phenomena. Additionally, steel can easily react with titanium alloys at high temperatures resulting in joint contamination while, on the contrary, WC has an inert behavior. Due to the extremely low thermal conductivity of titanium alloys (about 16% with respect of steels), a cooling system was introduced in the backplate with the aim to enhance the thermal flow from its main source (the tool shoulder) to the bottom of the joint also avoiding detrimental local overheating. More in detail, three holes, 16 mm in diameter each, were drilled in the backplate and connected to a cooling water pumping system. It should be observed that the sheets to be welded must be rigidly fixed to the backplate in order to counteract the vertical, the advancing and the lateral forces that can be observed during the welding process. The selected tool (figure 2) is characterized by a 16 mm shoulder and a 30°conical pin, 2.1 mm in height and 5 mm in major diameter. A key-factor for the process design is the choice of the tool material; as briefly discussed before, titanium alloys maintain good mechanical resistance even at high temperatures. In this way, the tool must be able to undergo severe thermo-mechanical loads and, at the same time, must be inert to titanium which, on the contrary, is extremely reactive at those temperatures. For such reasons a molybdenum based tungsten carbide tool, obtained by EDM, was selected.

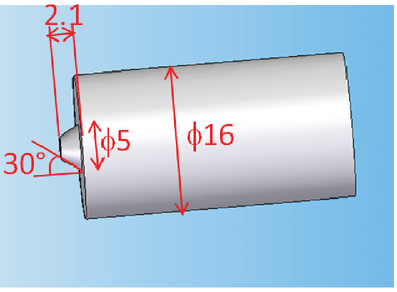

Fig. 2. Sketch of the utilized tool.

Finally, because of the already described reactivity of titanium alloys, a dedicated structure was designed in order to refrigerate the non working surface of the tool by means of a water flow and, at the same time, able to guarantee the desired inert gas flow on the welding area. A steel collar was developed and through a few o-rings the proper water flow was obtained around the tool upper part while the proper argon flow was obtained in its final part thus protecting the joint (figure 3).

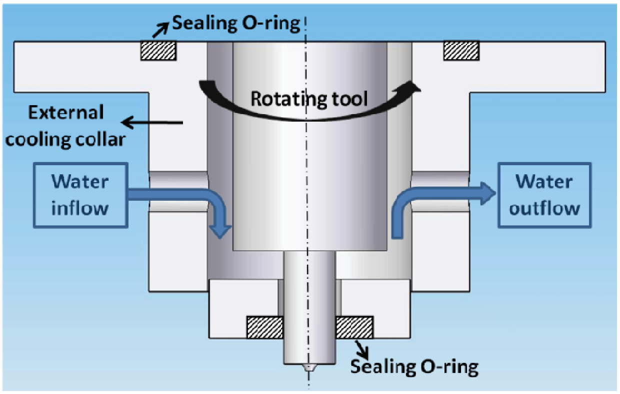

Fig. 3. Sketch of the utilized tool collar (Fratini et ali. 2010b).

2.3. Temperature measurement

In order to acquire the process temperatures K type thermocouples, characterized by a measuring range of 0-1300°C, were selected. In particular, for each experimental test, two thermocouples were positioned and mechanically fastened between the sheets to be welded, i.e. along the welding line, at middle thickness.

As far as the longitudinal position is regarded, the first thermocouple (T1) was placed at 5 mm from the joint edge, behind the initial tool sinking position; the second thermocouple (T2), was positioned at a distance of 0 mm from the same edge (figure 4). As a consequence, temperatures measured by T1 will show a decreasing trend, while, on the contrary, temperatures measured by T2 will show an increasing trend till the moment the leading edge of the tool comes in contact with it making the measurement no more reliable or destructing the thermocouple itself.

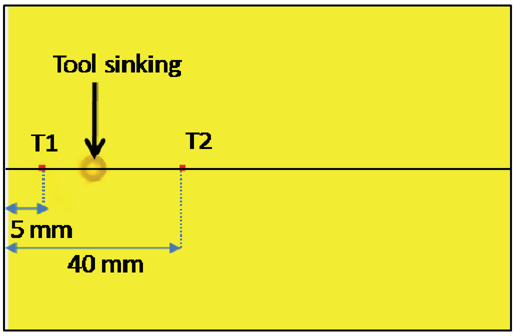

Fig. 4. Thermocouples positioning.

3. OBTAINED RESULTS

First, the temperatures acquired during the process are shown in the next figure 5.

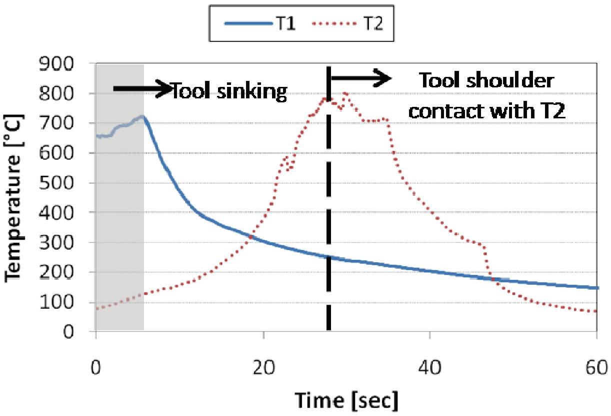

Fig. 5. Temperature measured during the welding process – 700 rpm.

Figure 6 illustrates maximum temperatures measured during the welds at the varying of the rotational speed. From the figure it can be clearly seen ho the thermal contribution conferred to the welding increases at the increasing of the tool rotational speed reaching quite large values, especially for the 1000 rpm case study, in which the maximum value exceeds 1000°C.

Acquired data have then been relate to the main mechanical and metallurgical properties: first the mechanical resistance of the joints have been tested through tensile tests; in the next figure 7 the obtained results, in terms of percentage of the tested specimen with respect to the base material, are presented.

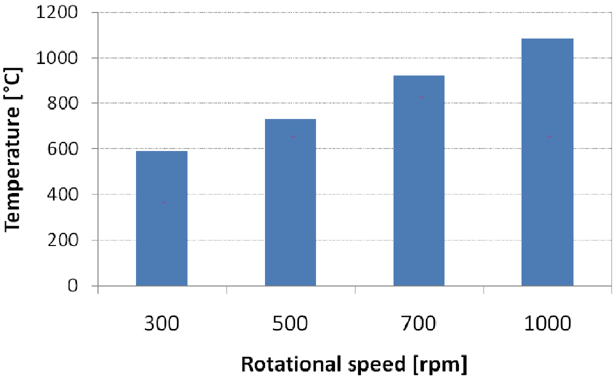

Fig. 6. Maximum temperatures measured from the T2 thermocouple at the varying of the tool rotational speed.

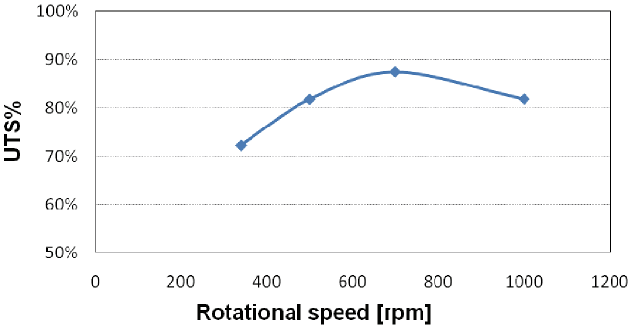

Fig. 7. Joint mechanical resistance at the varying of the tool rotational speed.

As it can be observed from the previous plot, the maximum resistance is found for the 700 rpm case study. As the rotational speed further increases, i.e. as the thermal contribution further increases, a decrease in the failure resistance is observed.

Microstructural analysis can help to explain the links between the process parameters effect, in terms of temperature reached in the joints, and the mechanical performances. In particular, the utilized base material is a biphasic α–β alloy, as it contains both α stabilizing and β stabilizing elements (aluminum and vanadium, respectively). In figure 8 a macro image of the transverse section of a welded joint is shown. The etching process highlighted the typical "open V" shape of the area involved in the metallurgical modifications; on the other hand, it should be observed that a typical "closed V" shape is usually observed in FS welded aluminum joints.

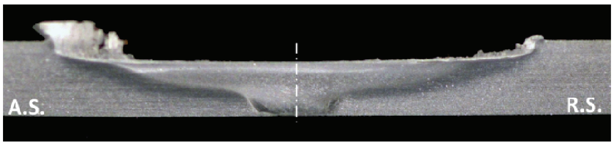

Fig. 8. Macro image of a transverse section of a welded joint – 500 rpm.

The maximum reached temperature determines, in the central area of the joint, both the volumetric fraction and the final dimension of the primary α grains; getting closer to the β-transus temperature, i.e. the temperature at which α phase transforms in β phase (equal to about 1000°C for the considered alloy), the percentage of α phase drastically decreases.

The wide range utilized in this research for the tool rotational speed (340-1000 rpm), resulted in significant differences in the final microstructures obtained in the welded joints. In particular, important differences can be observed both in the average grain dimension and in the microstructure found in the stir zone. For the 340 rpm case study a bimodal structure is observed with low percentage of lamellar structure. The reason for the development of such a microstructure is the relatively low temperatures observed, by far lower than the β-transus temperature, but still high enough to induce microstructural changes. The average grain dimension in the SZ is smaller than the base material one, due to the continuous recrystallization process induced by the disrupting action of the welding tool during the process.

The larger temperature values reached for the 500 rpm case study resulted in a larger dimension of the grains. Temperature is lower than the β-transus one also for this case study, and the final microstructure is bimodal characterized by a larger percentage of equiaxic α phase. The formation of the bimodal structure can be described as follows: during the heating up stage the α phase present in the base material transforms in β phase, as the latter is more stable at high temperatures. Being maximum temperature reached lower than the β-transus temperature a certain percentage of the α phase does not transforms; such percentage decreases at the increasing of the maximum temperature value reached. During the cool down stage α grains undergo a coarsening process while β grains evolve in a lamellar structure.

With a further increase of the rotational speed till the value of 700 rpm, the β-transus temperature value is reached in the whole sir zone. The resulting microstructure is quite a totally lamellar one, characterized by an average grain size of 12 µm, that is larger with respect to the two previous case studies. Temperature distribution is quite uniform along the whole stir zone with a certain decrease only at the very bottom of the joint, where no lamellar structure is found. Finally, due to the strain induced by the pin action, the average grain size in the advancing side is slightly smaller than the one observed in the retreating side. When the tool rotating speed is equal to 1000 rpm temperature values in the whole stir zone are definitely larger than the β-transus temperature value. At these temperatures a growth of the β grains is observed in the stir zone. The larger grain dimension with respect to the base material can be observed because the strain action of the pin starts and ends at temperatures well above the threshold one and the thermal cycle ends with a cool down phase that begins at temperatures larger than the one corresponding to the allotropic transformation. His results in a full lamellar structure and grain growth. Next figure 9 shows micro images from the stir zones of the obtained joints; the previous metallurgical observations are well highlighted:

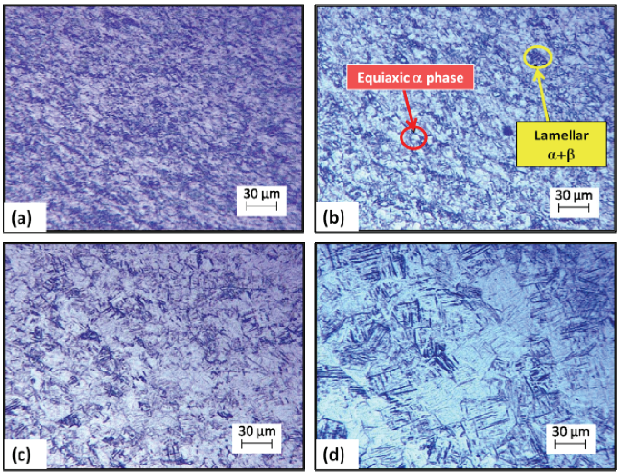

***Fig. 9.** Micro image of a transverse section of a welded joint at the varying of the rotational speed: (a) 340 rpm, (b) 500 rpm, (c) 700 rpm and (d) 1000 rpm.*

4. CONCLUSIONS

In the present research the FSW of butt joints obtained from Ti-6Al-4V titanium alloy sheets has been analyzed. In particular, for each case study obtained at the varying of the tool rotational speed, temperatures have been measured in two different points by means of two thermocouples embedded in the sheets to be welded. Finally both a mechanical and a metallurgical characterization has been performed through tensile tests and micro and macro observations, respectively. Based on the obtained results the following conclusion can be drawn:

– Due to the high temperatures reached it is necessary take into account the strong thermo-mechanical solicitations that tool and clamping fixture parts will undergo; in this way particular attention must be paid to the choice of the proper materials and to a correct design of a cooling system or both the tool and the clamping fixture;

- Joints mechanical performances strongly depend on the microstructural evolutions taking place during the welding in the stir zone; in turn, the latter are strictly linked to the temperatures reached as a consequence of the utilized process parameters;
- When the chosen process parameters set results in a temperature in excess of the β-transus one a mostly lamellar structure is observed together with an increase in the average grain dimension. This represents a detrimental and thus undesired effect for the mechanical performances of the obtained joints.

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MECHANICZNE I METALURGICZNE WŁASNOŚCI STOPÓW TYTANU ŁĄCZONYCH METODĄ ZGRZEWANIA TARCIOWEGO Z MIESZANIEM

Streszczenie

Zgrzewanie tarciowe z mieszaniem (FSW) jest metodą zgrzewania materiałów w stanie stałym opatentowaną w 1991 roku przez TWI. Początkowo wykorzystywana była do zgrzewania stopów aluminium, a obecnie z powodzeniem stosowana również do stopów magnesu, miedzi i stali. Niniejsza praca skupia się natomiast na zgrzewaniu stopów tytanu. Stopy te są bardzo obiecującym materiałem charakteryzującym się wysoką wartością współczynnika wytrzymałości w stosunku do masy oraz odpornością na korozję. Zgrzewanie stopów tytanu metodami tradycyjnymi niesie ze sobą kilka trudności spowodowanych łatwością wchodzenia materiału w reakcję z tlenem, wodorem i azotem, powodując tym samym kruchość zgrzewu. Alternatywą jest metoda FSW, która jest tanim i zapewniającym wysoką jakość rozwiązaniem. W artykule przedstawiono analizę wpływu prędkości kątowej narzędzia na osiąganą temperaturę podczas zgrzewania metodą FSW stopu Ti-6Al-4V. Uzyskane wyniki badań eksperymentalnych przeanalizowano pod kątem otrzymywanych własności w obszarze zgrzewu.

Received: September 27, 2010
Received in a revised form: October 18, 2010
Accepted: October 18, 2010