A methodology for the study of Friction Stir Welded butt joints applied to unweldable aerospace aluminium alloys

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Abstract: Weight reduction is a constant improvement point for the aerospace sector. The joining of difficult to weld materials such as 2xxx and 7xxx aluminium series alloys has attracted the attention to Friction Stir Welding (FSW) in this field. This solid state welding process has already been presented as an environmentally friendly alternative for riveted joints and conventional welding operation in the automobile sector. Unfortunately, its application on the aeronautical sector is not completely studied at the moment and concerns about its quality and in-service behaviour have delayed its implementation. This paper established a methodology to study the effect of the welding parameter and applied it to a structural aluminium AA2024-T3, covering the design of the testing bench, the tool, the process monitoring and the analysis of the quality and main mechanical properties of the joint. The results showed the impact of the welding parameters on the quality of the joint. The burr and the roughness were optimised for 850 rpm and the forces were reduced up to 30% for this rotational speed. Similarly, the mechanical properties were reduced by up to 61.5% and 45% compared to the base material for the UTS and microhardness respectively.

Keywords: FSW, Al2024-T3, Butt-joints, Mechanical properties.

1. Introduction
Patented in 1991 by The Welding Institute (TWI) [1], Friction Stir Welding (FSW) has been studied for several authors due to their advantages and possible applications [2,3]. This solid welding technology has been presented as a weight reduction alternative for both aerospace and automobile industries. Allowing to join up to 50 mm thick in different positions without needing a double-side welding [4,5], it has been particularly applied to materials such 2xxx and 7xxx aluminum series. These materials are commonly known by their poor welding properties and the use of FSW avoids riveting joints and reduces the total weight of the structure. Additionally, compared to conventional welding technologies, FSW is an environmentally friendly process not producing gases or chemical wastes. It reduces the process operation time, not needing a careful previous preparation of the surface, and it is easy to automatize [6,7].
FSW is a solid state welding process that uses the heat produced by the friction and plastic deformation generated on the contact of a rotating tool and the workpiece [8]. A non-consumable tool is plunged between the two plates to join the material by softening it but not melting it [9]. Then, the tool moves forward stirring the plates together [10]. The quality obtained in the butt weld depends on the tool design, the process parameters and the temperature achieved.

The tool geometry can be divided in shoulder and pin geometry and their design is critical to improve the material flow and generate heat. The shoulder keeps the material against the surface and avoid burr and similar defects while the pin influences on the metallurgical bond [10]. Their design depends on the application, having a wide range of diameters and pin shaped such as threaded or conical shapes [11]. Additionally, tool wear must be controlled due to its impact on the final weld properties[12].

Process parameters are limited by the formability and ductility of the material as well as by the tool design. They can be divided in rotational speed, traverse or welding speed, plunge depth and tool tilt angle [13]. Like the tool geometry, they also have an impact on the heat generation. Higher rotational speeds are usually related to higher heat generation. Although, an increase on the welding speed generally leads to lower temperature values. Both rules are applicable up to a limit, where excessive plastic deformation takes place and small voids appear in the joint [11]. The most common parameters for AA2024-T3 are: rotational speed between 400 and 1200 rpm achieving up to 2400 rpm; 2° of the tilt angle, and welding speed between 30 and 400 mm/min. However, few studies were found analyzing the combining the effect of rotational and welding speed.

The temperature generated in the process is usually between a 60-90% of the melting temperature in the nugget zone (NZ) [14]. There are also two other zones to consider, the heat affected zone and the thermomechanical affected zone. The temperature in these two zones has an impact on the material deformation and its microstructure affecting the mechanical properties. For this reason, it should be kept as low as possible and one of the techniques is to use high thermal conductivity baking plates [15].

This work presents a methodology to study the combined effect of rotational and welding speed. For this purpose, a conventional vertical milling machine was adapted designing a clamping system. A FSW tool was designed and manufactured to perform the test. The tests were monitored studying the forces involved in the process and the superficial temperature for different rotational and welding speeds. Finally, the effect of the welding parameters on the workpiece were studied through two different quality parameters (roughness and burr) and three mechanical properties (microhardness, elastic modulus, and tensile strength).

2. Methodology

2.1. FSW process

AA2024-T3 alloy sheets of 150 x 150 mm² and 3 mm thickness were friction stir welded and analysed following the experimental methodology shown in the diagram presented in figure 1(a). The material composition is shown in table 1. The process was carried out on a manual milling machine Heller FU1120 with an automatic axis in x and y direction. This machine was adapted to the FSW process designing a clamping system that ensured the stiffness of the sheets during the process and provided a high rigidity to the system. Both the backing plate and the clamping were manufactured in stainless steel.

|                  | Al     | Cr       | Cu | Fe | Mg      | Mn | Si   | Ti    | Zn   | Others |
|------------------|--------|----------|----|----|---------|----|------|-------|------|--------|
| AA2024-T3        | 90.7-94.7 | <0.1      | 3.8 - 4.9 | <0.5 | 1.2 - 1.8 | 0.30 - 0.90 | <0.50 | <0.15 | <0.25 | <0.15  |

The selected tool was a PH17.4 stainless steel tool with 2° tilt. It had 18 mm of shoulder diameter and a conical probe with an in root diameter of 3 mm, 11.3° and 2.5 mm length. The process parameters, spindle speed and feed rate, are shown in table 2. The plunge stage was manual and the dwell time was
set up to 20 s. The rotational speed was selected in two different ranges of heat input, 850 rpm for a low heat input and 1660 for a high heat input [17]. FSW process steps are shown in figure 2.

| Tool nº | Rotational speed (rev/min) | Welding speed (mm/min) |
|---------|---------------------------|------------------------|
| 1       | 850                       | 42                     |
| 1       | 850                       | 55                     |
| 1       | 850                       | 74                     |
| 2       | 1660                      | 42                     |
| 2       | 1660                      | 55                     |
| 2       | 1660                      | 74                     |

The process was characterized online through the temperature and the forces produced. They were monitored using a thermographic camera Flir T440 and a dynamometric table Kistler 9255B placed under the backing plate. The acquisition system is shown in figure 1(b).

Figure 1. (a) Experimental methodology diagram. (b) Experimental set up.

Figure 2. Process steps.

2.2. Tool recovery
The welding tool shape was recovered between each test using a chemical milling bath. This step reduced the variability of the results in the initial steps of the welding process. It was based in two steps. Initially the tool was submerged in a basic solution of 140g/L NaOH at a temperature range between 85 °C and 100 °C for 5 to 10 minutes. Time was experimentally determined depending on the initial state of the tool. Then the tool was cleaned in a water immersion. Secondly, the tool was submerged in
acid solution prepared with a nitric acid at a 30% for 30 seconds. Finally, the tool was cleaned again in a different water tank to finish the chemical reaction.

The state of the tool before and after the chemical cleanness was register using an optical stereoscopic microscopy device Nikon SMZ-800.

2.3. Joints analysis

The effect of the welding parameters was also studied analysing the quality and the mechanical properties of the joints. The quality parameters were established as the burr aspect and joint roughness while the measured mechanical properties were the tensile properties and micro hardness. For each type of analysis, the sample was divided in three areas -start, medium and exit (figure 3(a))- and three measurements were taken in each area.

![Figure 3. (a) Analysis areas for measurements. (b) Tensile samples geometry (in mm).](image)

Roughness measurements were carried out using a roughness measurement station Mahr Perthometer PGK 120. The cut-off was selected at 0.8 µm for 850 rpm tests and 2.5 µm for 1660 rpm tests, following the ISO 4288 standard [18]. Burr aspect was studied as a visual comparative of the images taken with a stereoscopic microscopy device Nikon SMZ-800.

Tensile strength samples had a geometry adapted from the ISO 25238 (figure 3(b)) and similar to the used by other researchers [19]. These samples were cut using the abrasive water jet machining technology to avoid an increase on the tensile strength of the sample. Tensile tests were performed in a Shimadzu AG-X at 1 mm/min. Microhardness measurements were obtained with a load of 1.961N and waiting time 8 s using a Shimadzu HMV-2ADW. Three tensile samples were tested for each operative condition.

3. Results and discussion

3.1. Temperature

The temperatures obtained during the process are represented in figure 4. Generally, it was observed that the initial temperature was the highest for every set of parameters, while after the medium area seemed to stabilise. Those initial values are related to the initial time needed to ensure the fluidity of the material. Moreover, an increase of the welding speed considerably reduced the temperature acquired during the first area of the welding process. As R D Fu et al. [17] presented, higher rotational speed increased the heat generation but up to 72 mm/min, where the combination of welding speed and rotational speed do not have a significant impact.

3.2. Forces

An example of the registered forces is shown in figure 5, where the manual plunge stage, the dwelling time, the welding stage and the retracting stage were identified. The average vertical force during the plunge was around 1.5 kN and it increased up to the defined plunge depth. During the next stage, the force value was stabilized and decreased with the increase of the fluidity of the material. Then, when the advancing movement of the tool started, the forces increased achieving the initial dwelling force value or even a new maximum value that slightly decreased during the welding length.
As a consequence of the lower heat generation, the tests carried out at the lower rotational speed registered a higher force, with values up to 30% higher. This difference was reduced with the increase of the welding speed, where for 74 mm/min the average no significant effect of the rotational speed was noticed. A similar force pattern was registered for the welding force but in this case the difference was unnoticeable above 55 mm/min welding speed. This values are consistence with the study presented by D G Moghadam et al [20], where a decrease of the vertical force value was registered for higher rotational speeds.

Figure 4. Temperature vs. welding parameters.

Figure 5. (a) Vertical and welding forces for N= 1660 rpm and f=74 mm/min tests. (b) Average welding forces as a function of the welding parameters.

3.3. Welding surface quality

The first quality parameter analysed was the burr generated on the external sides of the joint. This is an avoidable defect that can be considerably reduced depending on the parameter selection. As is shown in figure 6(a), the burr generated in using a rotational speed of 850 rpm is negligible and do not present any anomaly, except for 74 mm/min welding speed, where a slight burr was observed. However, for a rotational speed of 1660 rpm the agitation increase and though the fluidity of the material increasing, its plastic deformation and as a consequence the burr height [11].

The second quality parameter to be studied was the roughness. It was measured in terms of Roughness Average (Ra) obtaining stable values for the start, medium and exit areas. Similarly, the measurement position (advancing side, weld centre line or retreating side) did not have a significant influence on the Ra values with homogenous standard deviation for the different welding parameters.

Although, the welding parameters had a higher effect on this quality parameter, as is shown in figure 6 (b). Reversed trends were found for the different rotational speed. On the one hand, higher rotational speeds with a higher surface temperature during the process, which increased the fluidity of the material and produced deeper marks on the welding surface. On the other hand, an increase of the feed rate was
related to an increase of the deviation of the results obtained for the lower spindle speed, probably caused by an increase on the plastic deformation. Both trends were opposed to the ones obtained during the force analysis. This fact could mean that a decrease on the forces of the process, related to an increase of the ductility of the material, leaded to less homogenous surfaces and probably to the need of finishing operations.

Figure 6. (a) Burr at different welding parameters on the retreating side. (b) Ra mean values.

3.4. Tensile tests
Most tensile samples presented a low ductile fracture, which always took place in the nugget zone. The fracture presented an irregular shape (figure 7(a)) compared to the base metal fracture. These irregular patterns may be caused by the appearance of small holes or cavities in the centre of the tensile sample, which are commonly known as worm hole (figure 7(a)).

Figure 7. (a) Representative example for the tensile samples fracture and worm defect (b) Elastic modulus and Ultimate Tensile Strength for the performed tests.
This type of defect also affected the reduction of the elongation, obtaining a maximum value of 4%, which represent up to 80% reduction compared to the base material. This fact was related to the low temperature obtained during the process, it reduced the hardness of the material and as a consequence make easier the fracture of the joint [6,15]. However, the Ultimate Tensile Strength (UTS) presented similar values to the obtained by other authors [21]. In average the welded tensile samples UTS was up to 61.5% lower than the base metal UTS (figure 7(b)). This initial value can only be achieved if the internal defects are avoid [19]. Furthermore, the elastic modulus was improved regarding the base material, and the results reflected a possible trend improvement for low rotational speeds.

3.5. Microhardness

The selected welding parameter range did not have a significant effect on the microhardness. The values obtained covered the range between 70-90 HV which represents a 45% reduction considering the base metal. A slight increase of the hardness value for a higher feed rate, especially for 850 rpm can be appreciated in figure 8(a). There is no significant decrease on the microhardness in the nuzzle zone figure 8(b). S Kundu et al. [21] presented similar behaviour where no significant difference between the rotational speed was found when the grain structure was not refined properly.

Figure 8. (a) Microhardness for the medium area section. (b) Average depending on the welding parameters.

4. Conclusions

This paper presented a successful methodology for the study of the FSW process in a structural aeronautical alloy, AA2024-T3. Different set of parameters varying the welding and rotational speed were analysed studying the forces, temperature during the welding process, the burr, the roughness, the tensile properties, and the microhardness.

FSW is a suitable process for the joint of AA2024-T3 alloy, although the process selection is basic to ensure the quality of the joint and avoid cavities and defects.

Burr and roughness were optimized for low rotational speed (850 rpm) and low welding speed (42 mm/min) without having an impact on the tensile properties or the microhardness. However, these parameters were related to the higher forces during the process.

Finally, most of the parameters presented similar values for the elastic modulus and microhardness due to the lack of temperature and grain refinement, which may be solved with a lower range of the welding speed than the selected.

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