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AN INVESTIGATION ON FRICTION SPOT WELDING IN AA6181-T4 ALLOY

Bruno Parra [1]
Vinícius Toledo Saccon [2]
Nelson Guedes de Alcântara [3]
Tonilson Rosendo [4]
Jorge Fernandes dos Santos [5]

Abstract

Friction spot welding is a new solid state welding process, invented and patented by the GKSS Research Centre GmbH in Germany, suitable for spot joining lightweight low melting point materials such as Al and Mg alloys. The process is performed with an especially designed rotating tool (comprised by a clamping ring, sleeve, and pin) that creates a joint between sheets in overlap configuration by means of frictional heat and mechanical work. The result is a spot welded lap joint with minimal material loss and a flat surface with no keyhole. In this work the application of Friction Spot Welding for spot joining the AA6181-T4 is investigated. Different rotational speeds (1900 to 2900 rpm) and welding times (2 to 3.4 s) were tested with the objective of finding the best suited ones for producing high quality joints in terms of microstructure and mechanical performance. Welds with strength in the order of 6.8 kN were obtained with high reproducibility. The results also show that geometric elements of the weld play an important role on the fracture mechanisms and hence on the mechanical performance of the joints. In sum, the results reveal the potential of this process for industrial applications.
Keywords: Friction; Aluminnum; Welding.

INVESTIGAÇÃO DO PROCESSO DE SOLDAGEM POR FRICÇÃO POR PONTO PARA A LIGA AA6181-T4

Resumo

Soldagem por Ponto por Fricção (SPF) é um novo processo de solda ponto no estado sólido patenteado no Centro de Pesquisas alemão GKSS, que permite se unir pontualmente ligas metálicas com baixo ponto de fusão como as ligas de Al e Mg. O processo é realizado com uma ferramenta especialmente desenvolvida (composta por anel de retenção, camisa e pino) que une as partes em configuração sobreposta por calor de fricção e deformação mecânica. O resultado é uma junta soldada sobreposta com mínima perda de material e superfície lisa sem buracos deixados pela ferramenta. Neste trabalho, é investigado o processo de SPF para a união da liga AA6181-T4. Diferentes velocidades rotacionais (1900 a 2900 rpm) e tempos de soldagem (2 a 3,4 s) foram testados com o objetivo de se encontrar as melhores condições de se produzir juntas de qualidade em termos de microestrutura e desempenho mecânico. Foram obtidas soldas com resistência na ordem de 6,8 kN, com alta reprodutibilidade. Os resultados também mostram que elementos geométricos das juntas têm importante papel nos mecanismos de fratura e, portanto no desempenho mecânico das juntas. Em suma, os resultados revelam potencial do processo para aplicações industriais.
Palavras-chave: Fricção; Alumínio; Soldagem.

[1] *Mestre em Ciência e Engenharia de Materiais. Programa de pós-graduação em ciência e engenharia de materiais – PPGCEM, Universidade Federal de São Carlos – UFSCAR, Rod. Washington Luís, Km 235, Cep 13565-905, São Carlos, SP, Brazil. E-mail: brunoparra@gmail.com*
[2] *Mestre em Ciência e Engenharia de Materiais. Programa de pós-graduação em ciência e engenharia de materiais – PPGCEM, Universidade Federal de São Carlos – UFSCAR, Rod. Washington Luís, Km 235, Cep 13565-905, São Carlos, SP, Brazil. E-mail: vinicius.saccon@yahoo.com.br*
[3] *Professor Doutor em Ciência e Engenharia de Materiais. Programa de pós-graduação em ciência e engenharia de materiais – PPGCEM, Universidade Federal de São Carlos – UFSCAR, Rod. Washington Luís, Km 235, Cep 13565-905, São Carlos, SP, Brazil. E-mail: nelsong@ufscar.br*
[4] *Doutor em Ciências dos Materiais. Programa de pós-graduação em engenharia de materiais – PPGEM, Universidade Federal do Rio Grande do Sul – UFRGS, Av. Osvaldo Aranha, 99/610, Cep 90035-190, Porto Alegre, RS, Brazil. E-mail: tonilson@gmail.com*
[5] *Doutor em Engenharia de materiais. Universidade Federal do Rio de Janeiro – UFRJ. GKSS Research Centre, Institute of Materials Research, Materials Mechanics, Solid State Joining Processes, Max Planck St, 1.21502, Geesthacht, Germany. E-mail: jorge.dos.santos@gkss.de*

1 INTRODUCTION

Nowadays, as it has been presented by Pan, Zhu and Wchwarz,[1] spot joints in structural components are achieved mainly by mechanical fastening and fusion based techniques such as resistance spot welding (RSW) and laser spot welding. Mechanical fastening suffers from a weight penalty, difficulty of automation, requirement for sealants, and corrosion issues. Fusion based spot welding has problems associated to material melting and low weldability issues presented by some high strength lightweight alloys.

Taking this scenario into account, a relatively new technology, friction spot welding (FSpW) comes as an alternative to overcome these issues. FSpW is a solid-state welding process that produces spot connections suitable for joining parts in overlap configuration. The appearance of the final weld resembles that of a resistance spot welding (RSW) – the surface of the joints is likely to be flat without defects. This process was invented and patented by the GKSS Research Centre in Germany, as reported by Schilling and Santos.[2,3] The absence of keyhole characterizes the FSpW joints as being almost defect free with enhanced mechanical strength. Some other advantages of the process are: environment friendly (no fumes are generated), no additional material is required, minimal or no waste products, energy efficient, no pre-cleaning necessary as well as no post processing due to good surface quality, fast processing speeds, and ease of automation.

As previously reported by Rosendo et al.,[4,5] sound welds can be obtained with good mechanical behavior and reproducibility by this process, provided that appropriate process parameters and tool configuration are employed. Finally, the mechanical nature of this welding process makes it applicable to any alloy which presents some degree of plasticity, as explained by Schilling, Strombeck and Santos.[6]

FSpW is performed using a tool assembly comprised of three parts: clamping ring, sleeve, and pin. The Pin and sleeve are operated by separate actuators in such a way that they can be moved up and down independently. The clamping prior to welding is performed by means of a third actuator moving the entire welding head against the work pieces. The clamping ring has two functions: to keep the sheets to be welded held tightly during the process and work as a barrier to avoid plasticized material to be lost in the form of flash.

The process is performed in four stages (Figure 1). On stage one, the sheets are clamped together by the clamping ring against a backing anvil and both pin and sleeve start to rotate producing frictional heat on the upper sheet surface (Figure 1a). On stage two, the sleeve is plunged into the sheets while the pin moves upwards creating a cylindrical cavity to accommodate the plasticized material displaced by the sleeve (Figure 1b). After a predetermined plunge depth is reached, the process is reversed marking the third stage where both pin and sleeve retract back to the surface of the upper sheet. The retraction of the pin brings the plasticized material initially displaced back to the hole left by the sleeve, refilling it completely (Figure 1c). Stage four is marked by the withdrawal of the entire welding head from the work pieces, and the result is a flat surface with minimum material loss.

In this work, FSpW/sleeve plunge process is used with the objective of investigating the effects of different welding parameters on the microstructural features and mechanical performance of an Al alloy 6181 in T4 condition. This alloy has strong application in the automotive industry due to its good heat treating properties end ease of recycling. According to Hofmann,[7] these two reasons led to the trend to use only alloys of the 6xxx-series in the automotive structures.

2 MATERIALS AND METHODS

Rolled sheets 1.7 mm thick of AA6181-T4 were used to produce overlap joints using the FSpW/sleeve plunge process. Welds were performed using an FSpW prototype machine capable of applying forces up to 15 kN

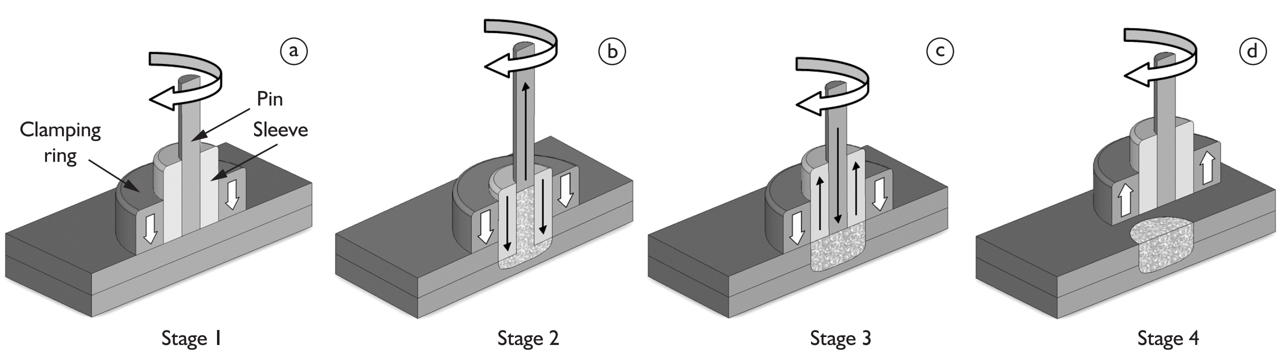

Figure 1. Schematic representation of the FSpW/sleeve plunge process: a) clamping and spindles rotation, b) sleeve plunges into the sheets while pin moves upwards, c) spindles retract back, and d) withdrawal of welding head.

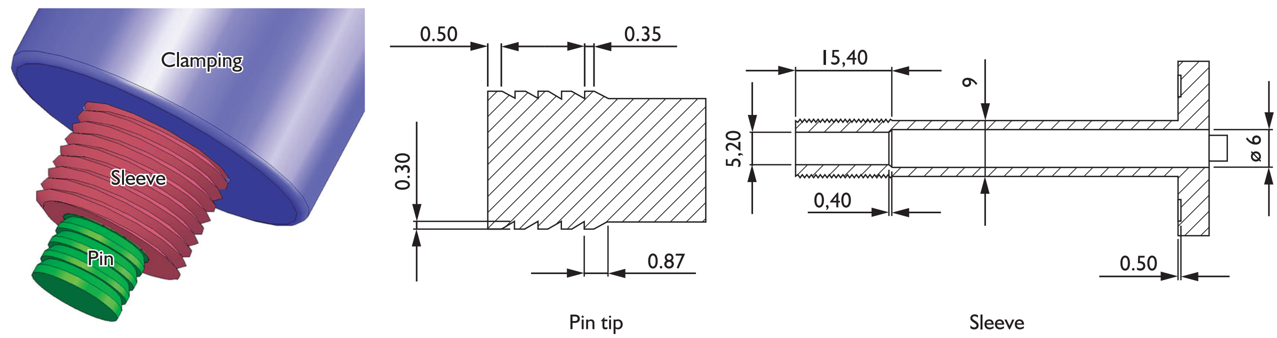

Figure 2. Details of the welding tool used to produce the joint investigated in this work.

(vertical axis) and reaching a maximum rotational speed of 3000 rpm. A monitoring system recorded the rotational speed, torque, axial load, welding time as well as pin and sleeve position. Details of the tool geometry are shown in Figure 2.

A total of 15 different welding conditions were investigated including rotational speed and welding time as process parameter variables. The parameter ranges definition as well as the plunge depth was based on the results of a preliminary investigation performed by Knoll,[8] Table 1 presents the process parameter matrix used to produce the joints investigated.

For each welding condition four overlap joints were produced in the form of samples for shear tensile testing according to the DIN EN ISO 14273 standard.[9] One of the samples was then cut in the centre of the joint for metallographic characterization and hardness evaluation. The other three were submitted to shear tensile testing in order to assess the mechanical resistance of each welding condition. The shear test samples had a dimension of 230 x 60 mm with 46 mm of overlapping and were tested using a screw-driven testing machine. For the assessment of the weld zones and microstructure of the final joints, the standard metallographic procedure was used to produce samples that were then etched using Kroll solution and electrolytically etched using Barker solution.

3 RESULTS

Some defects associated to the material flow were found to be present in some joints depending on the welding parameters selected (Figure 3).

The micrograph shown in Figure 4a presents the different welding zones, with a detailed image of the SZ in Figure 4b.

Vickers 0.5 microhardness profile is shown in Figure 5, of the cross section of the weld joint.

The results of the shear tensile tests, with different welding parameters, are shown in Figure 6.

Analyzing the fractured shear tensile testing samples, three different fracture modes are observed, as shown Figure 7.

In Figure 8, it is schematically showed the tearing mechanism and the effective shear zone in the crack propagation in shear tensile test.

4 DISCUSSION

Optical microscopy (OM) investigation of the welded joints cross section revealed two distinct weld zones: the stir zone (SZ) and the thermo-mechanically affected zone (TMAZ), as shown in Figure 3, similarly to what is described by da Silva et al.[10,11] Nevertheless, a heat affected zone (HAZ) although not resolved with OM is also present, as evidenced by the microhardness profiles across the joint (Figure 5).

The examination of the cross sections also revealed some geometric patterns common to all the joints, as shown in Figure 3, which are referred to as joint elements denominated: *Hooking*, caused by the plastic deformation of the lower sheet, and its final dimensions will be controlled by the energy input. It presents an upside down V shaped appearance; *Partial Bonding*, a kind of transition region where the bonding between the upper and lower

Table 1. Welding parameter matrix used to produce the FSpW connections investigated

Process parameters for a sleeve plunge depth of 1.75 mm*															
Welding time [s]	2			2.2			2.6			3			3.4		
Rotational speed [x1000 rpm]	2.9	2.4	1.9	2.9	2.4	1.9	2.9	2.4	1.9	2.9	2.4	1.9	2.9	2.4	1.9
Welding condition	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

*Taking the upper sheet surface as reference.

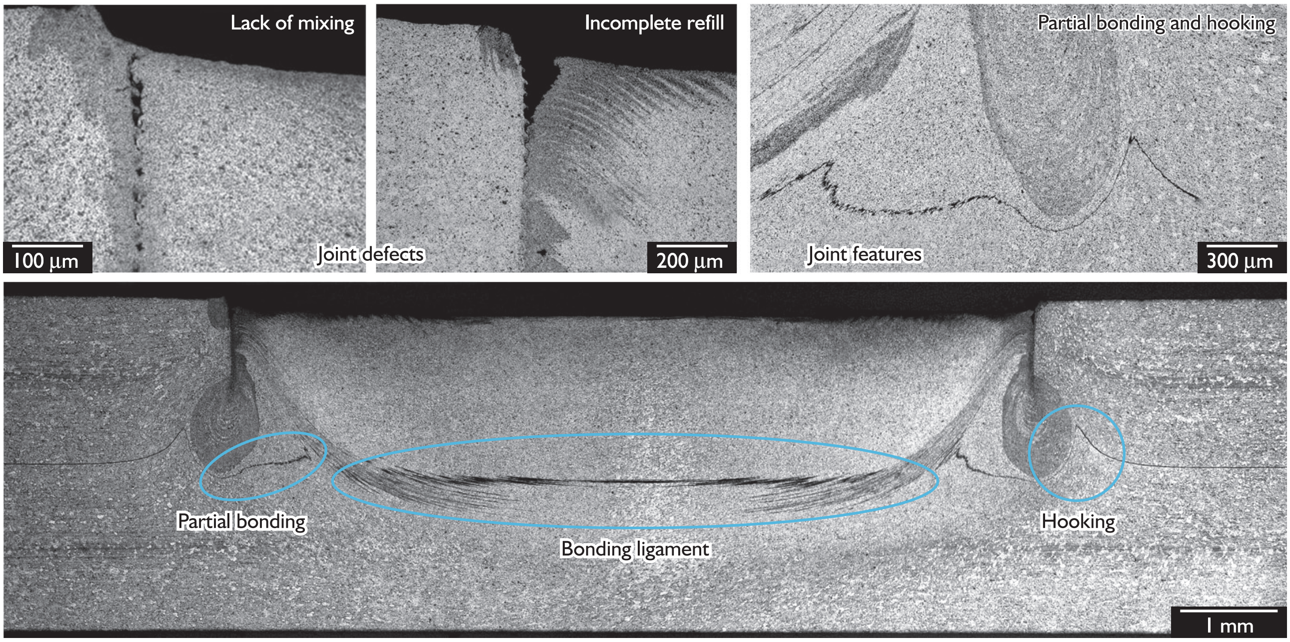

Figure 3. Macrographs of a typical FSpW joint cross section etched with Kroll solution showing the weld zones, joint features, and weld defects.

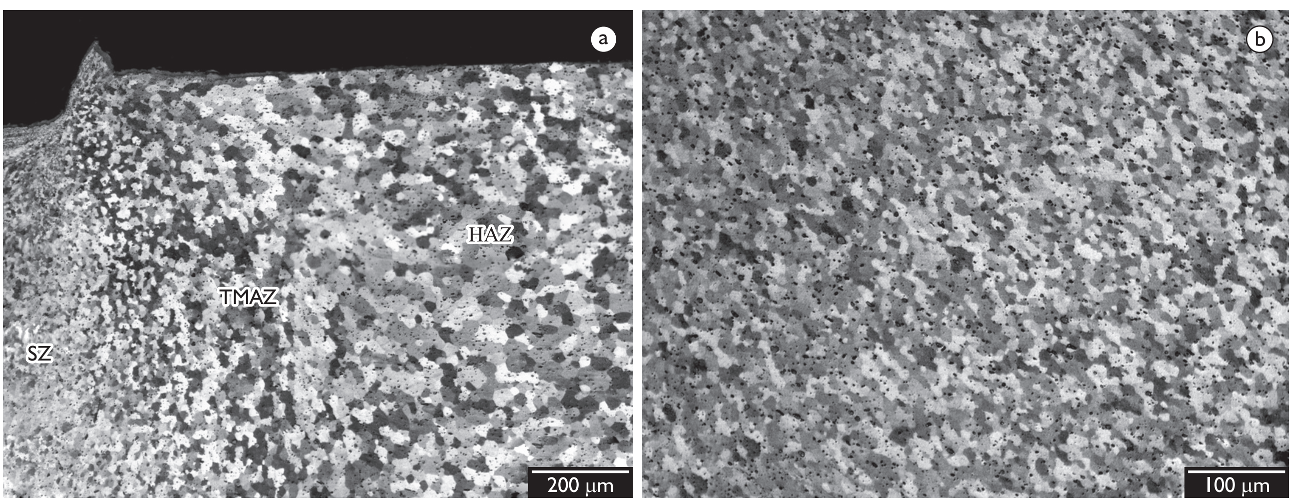

Figure 4. Optical micrographs obtained by electrolytic etching using Barker solution and viewed with polarized light showing details of: a) distorted grains in the TMAZ, and b) refined microstructure in the SZ.

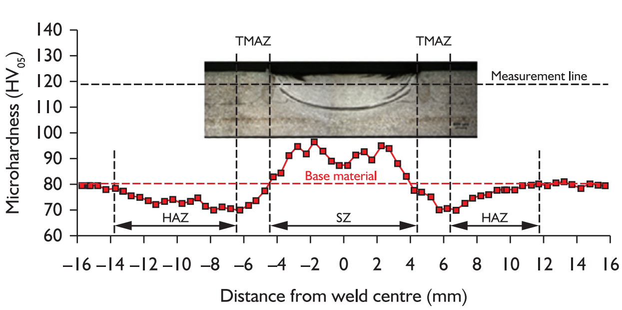

Figure 5. Microhardness profile measured in the middle of the upper sheet at the cross section of a FSpW joint welded according to the welding condition number 10 (2900 rpm / 3 s).

sheet is not so strong. It appears as a short and usually uneven line on the joint cross section; and *Bonding Ligament***,** a region of good adhesion between the upper and lower sheet with strong resistance. Its characteristic shape on the edges is a result of the material flow, especially on the third stage of the process, when the pin pushes the plasticized material (displaced on the second stage) back to its original position.

The defects associated to the material flow (Figure 3) are referred to as lack of mixing and incomplete refill, both located at the path through which the sleeve plunges into the upper sheet. Their occurrence is found to be associated to improper combination of the rotational speed and welding time.

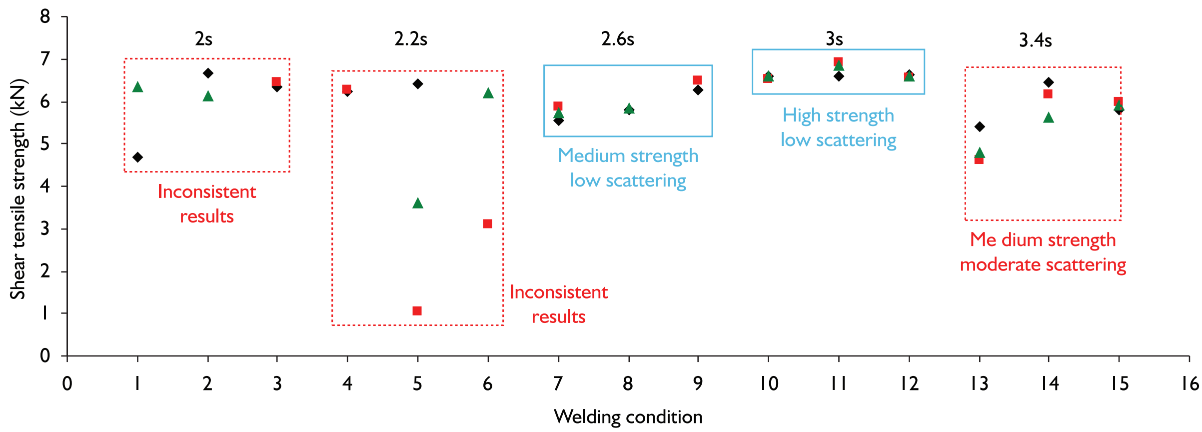

Figure 6. Shear tensile testing results for each welding condition.

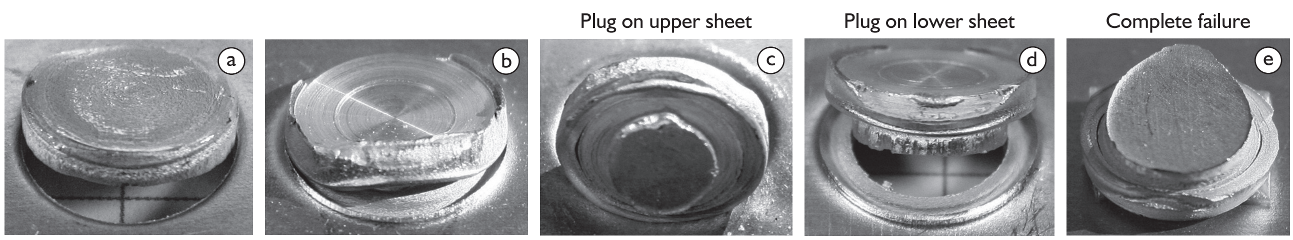

Figure 7. Fracture modes in shear tensile test: a) through weld with circumferential crack, b) plug pull-out with nugget tearing, and c) plug pull-out with back plug variations.

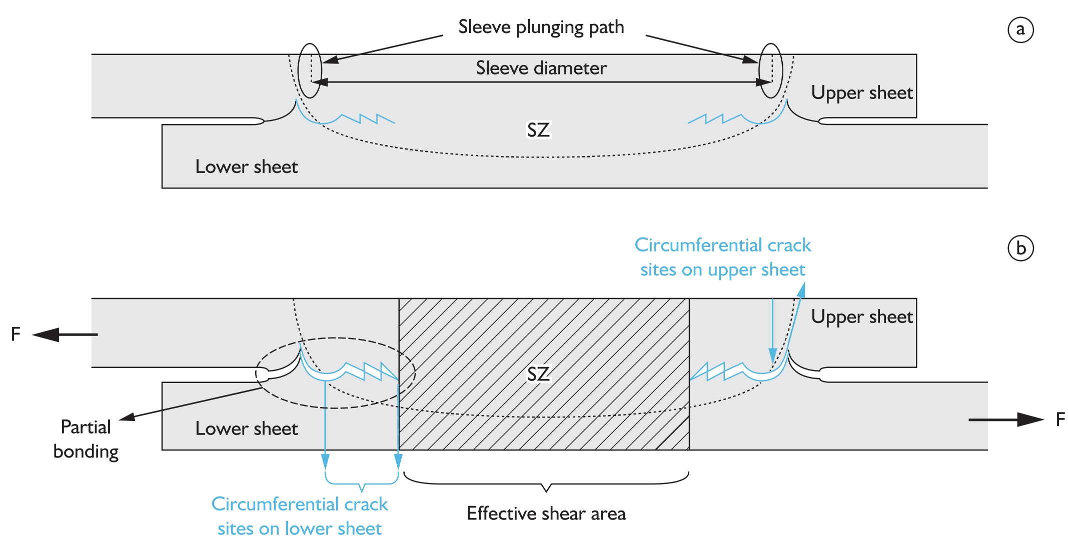

Figure 8. Schematic drawing showing the fracture development of FSpW joints under shear tensile loading. Notice that the joint dimensions are out of proportion for clarity.

The TMAZ is characterized by grains distorted in comparison to the base material. Moderate strain rate accompanied by moderate temperature are responsible for the microstructural changes in this zone. Higher magnification micrographs of this weld zone revealed elongated grains pointing upwards at the vicinity of the SZ, see Figure 4a.

The SZ is characterized by very refined and rather equiaxed grains as shown in Figure 4b. This microstructure appearance is associated to dynamic recrystallization caused by the high strain rate during the plunging stage and the thermo cycle imposed by the process, as explained by Gerlich et al.[12]

Since the AA6181 is a precipitation hardening alloy, the changes of the precipitates during and after welding will be the most important phenomena dictating the resulting hardness and strength of the different weld zones. The mechanical and thermal inputs provided by the welding tool in friction based welding processes have proven to affect the original state and distribution of the precipitates.

Such changes were evidenced by TEM observations of the different weld zones by Olea et al.[13] Nevertheless, the microhardness profile at the cross section of the welded specimens (Figure 5) can also be used to infer these changes. The base material presents an average hardness of 80 $HV_{0.5}$ which starts to decrease in the HAZ to a minimum of 70 $HV_{0.5}$ at the interface between HAZ and TMAZ. The hardness loss at the outer limits of the HAZ is associated mainly to the recovery of the rolled microstructure of the base material since the temperature reached at this site is not so high during welding. However, the closer to the centre of the weld, the higher is the peak temperature reached, and the strengthening particles can be subjected to coarsening and even solubilization. Coarsening has shown to be the predominant phenomenon in the TMAZ due to the thermocycle in this weld zone according to the TEM observations reported by Olea.[14] The deformation level can also produce some strain hardening in the TMAZ although not enough to suppress the softening due to precipitate coarsening.

The shear tensile tests reveal that some sets of welding parameters resulted in high strength joints with reproducibility while others are associated to weak joints and/or scattering. Figure 6 presents the maximum load achieved during shear tensile testing of each welding condition. It can be seen that the best welding conditions were those with total welding time between 2.6 s and 3 s (conditions 7 to 12), that is, welds with slower plunge rates. Condition 11 presenta a little bit higher scatter (std dev = 0.17) with practically the same average joint resistance (6.8 kN against 6.6 kN of both conditions 10 and 12).

Based on these results and considering the equation proposed by North et al.,[15] which shows the rotational speed and welding time as the two process parameters that affect mostly the energy input, it can be said that the 3 s welding time provides the amount of energy necessary to produce sound joints for this alloy. Based on a standard nomenclature adopted by Koch et al.[16] and Allen and Arbegast,[17] the fracture modes observe in this work are referred to as: a) through weld with circumferential crack (Figure 7a), b) plug pull-out with tearing (Figure 7b), and c) plug pull-out with back plug; this last one presents three variants, see Figure 7c. These fracture modes are observed both in sound and poor joints with the exception of the plug pull-out with back plug variants: plug on upper sheet and plug on lower sheet, see Figure 7c. These two variants are associated to sound and poor joints, respectively.

All the fracture modes are associated to the same fracture initiation mechanism. In this fracture initiation stage, the Partial Bonding region plays an important role. When a sample is loaded during the shear tensile test, the two sheets tend to get separated at the Partial Bonding by a tearing mechanism, as schematically indicated in Figure 8. This separation (tearing) leads to the formation of an annular crack surrounding the SZ. Depending on the properties of the other weld zones, this annular crack may grow through the Bonding Ligament. As a consequence of this annular crack, the effective shear area of the joint becomes smaller (Figure 8b).

Following the Partial Bonding tearing, it was observed that circumferential cracks may nucleate on just one or on both sheets. On the upper sheet, the only two nucleation sites observed were the Hooking tip and the welding defects (lack of mixing and incomplete refill) at the sleeve plunging path, see Figure 8a. On the lower sheet, it usually initiates at two sites as well, one is the tip of the annular crack (formed by the tearing of the Partial Bonding feature) and the other is the interface between the Partial Bonding and the Hooking (Figure 8a). The overall properties of the joint will determine the subsequent fracture mechanisms that will lead to the final fracture of the joint. An in depth explanation of these fracture mechanisms is not within the scope of the present study and will be published elsewhere.

Since the Hooking works as a crack nucleation site, when it becomes too sharp a crack can nucleate and grow on the upper sheet under small loading levels. The micrographic analysis showed that the Hooking sharpness is strongly related to the welding time, getting too sharp for welding times longer than 3 s due to the high level of plasticity of the lower sheet caused by the intense energy input provided by such long welding times. This observation explains the deterioration of the joint mechanical strength when the welding time was increased from 3 s to 3.4 s, as previously shown in Figure 6.

5 CONCLUSIONS

In this study, the applicability of the new Friction Spot Welding process for producing overlap joints of an AA6181-T4 is investigated. A welding parameter matrix is established based on previous experiences of the group, and the joints produced are characterized in terms of metallurgical and mechanical performance.

The results reveals that sound joints can be produced, and the strongest joints are associated to welding time between 2.6 s and 3 s, especially when accompanied by slow rotational speed (1900 rpm). The joint cross section reveals the joints are formed by three elements: Partial Bonding, Bonding Ligament and Hooking. The combination of the welding time and rotational speed (i.e. energy input) shows strong influence on these elements as well as eventually causing some weld defects (lack of mixing and incomplete refill).

Welding times shorter than 3 s led to high strain rate in the material surrounding the tool (due to the fast plunge rate) causing weld defects. At the optimum welding time range of 2.6 s and 3 s, the rotational speed shows to have little effect on the joint strength indicating that the welding time is the major parameter providing the energy input necessary to produce a proper connection between the upper and lower sheet. Finally, the Hooking geometry plays an important role in the development of the fracture, and it is responsible for the decrease of the strength in the joints produced with welding times longer than 3 s.

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