EFFECT OF FSPW PARAMETERS ON MICROSTRUCTURE AND LAP SHEAR STRENGTH OF AA5754 ALUMINIUM ALLOY[1]

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Abstract

Currently there is a lot of pressure in the transport section to reduce the fuel consumption and consequently cost and gas emissions. This measure has increased in the last years the use of light alloys, as the alluminium's alloys and of more efficient methods for joining them. Nevertheless, there is some difficult in joining these alloys using the conventional methods. The Friction Spot Welding (FSpW) is a solid state joining technique derived from Friction Stir Welding (FSW), which has great advantages regarding the other joining techniques, hence can be a viable alternative to replace the established spot joining technologies as Resistance Spot Welding (RSW) and riveting. The present work aims the study of the parameters influence in the microstructure and Lap Shear Strength (LSS), through the comparison of two different welding conditions, one good and one bad. Therefore, FSpW were performed in two lapped plates of 2 mm-thick AA5754 aluminium alloy. Mechanical tests, as hardness and tensile were realized, as well as microstructure analysis by optical microscope. Furthermore, it was observed that the welded region is larger in the good condition, than in the bad one. This result showed that the increase in the dwell time from 0 second to 1 second caused a larger bonded area, leading to a higher shear strength.

Key words: Aluminium alloy; Friction spot welding; Lap shear strength.

EFEITO DOS PARÂMETROS NA MICROESTRUTURA E RESISTÊNCIA AO CISALHAMENTO DA LIGA DE ALUMÍNIO AA5754 SOLDADA POR *FSpW*

Resumo

Atualmente existe uma grande pressão no setor de transportes a fim de reduzir o consumo de combustíveis, e consequentemente, o custo e as emissões de gases. Essa medida aumentou, nos últimos anos, o uso de ligas leves como as de alumínio, bem como métodos mais eficientes de uni-las. Porém, existem certas dificuldades em se unir essas ligas através de métodos convencionais. A Soldagem por Fricção por Ponto (*FSpW*) é uma técnica de soldagem no estado sólido derivado da Soldagem por Fricção e Mistura (*FSW*), a qual possui ótimas vantagens com relação a outras técnicas de soldagem, podendo portanto, ser uma alternativa viável para substituir as tecnologias de soldagem por ponto já estabelecidas, tais como a Soldagem por Resistência por Ponto (RSW) e Rebitagem. O presente trabalho visa estudar a influência na microestrutura e na resistência ao cisalhamento (LSS), através da comparação entre duas condições de solda diferentes, uma boa e uma ruim. Para isso, as soldas com *FSpW* foram realizadas em duas chapas sobrepostas da liga de alumínio AA5754 com 2 mm de espessura cada uma. Testes mecânicos, como dureza e tração foram realizados, assim como a análise da microestrutura através de microscópio ótico. Além disso, foi observado que a região soldada é maior na condição boa do que na condição ruim. Esse resultado mostrou que o aumento no tempo de operação de 0 para 1 segundo causou uma área soldada maior, levando a um aumento na resistência ao cisalhamento.

Palavras-chave: Liga de alumínio; Soldagem por fricção por ponto; Resistência ao cisalhamento.

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1 INTRODUCTION

The demand for lightweight structures is increasing in aeronautical industries as well as in the automotive aiming fuel consumption reduction and also to attend gas emission protocols. In these industries, certainly the connection of lightweight structures must be done during the production cycle. Resistance spot welding (RSW), riveting, clinching, self piercing riveting and fusion welding are the most common techniques used for spot-like connections.(1)

However, weight penalty, difficulty of automation, requirement for sealants and corrosion problems are strongly associated to its applications. Also aluminum alloys are difficult to weld using RSW and are likely to produce poor weld quality. High energy consumption as well as high investing costs are other problems related to these conventional techniques.

The Friction Stir Spot Welding (FSSW) is a solid state joining process that could be a possible replacement for rivet technology in the automotive and aerospace industries and derivate from Friction Stir Welding (FSW). FSW was developed in 1991 for *The Welding Institute* (TWI) in England,(2) and it has been applied with success in the union of lots of metallic alloys, including dissimilar ones. The process, performed in the solid state, involves basically frictional heat and severe plastic deformation, resulting from the interaction of a not-consumable tool and the surface to be welded.(3)

Mazda reported the first application of FSSW on one of its mass production vehicle where rear doors were welded using the plunge FSSW process. One disadvantage of the FSSW process is that the pin leaves a key hole in the middle of the joint during the retract stage which can act as a stress raiser.(4)

Differently from FSSW, Friction Spot Welding (FSpW), developed and patented by Helmholtz-Zentrum in Germany, doesn't leave a key hole in the joint. It is characterized by a defect-free and a strong spot-lap joining technology that presents a great potential for replacing the mechanical fastening and fusion based spot welding and it is suitable for welding lightweight materials, such as Al and Mg. Also it has some advantages over conventional spot joining techniques, like high energy efficiency, reduction in the number of process step, no post-processing, high welding speed, reproducibility as well as high environmental compatibility.(4,5)

FSpW is performed using a special tool comprised of three pieces tool system: clamping ring, pin and shoulder. Each component can be moved independently of the other, since they comprise a separate actuation system. The clamping ring has the function of keeping the plates to be joined held tightly, while the pin and shoulder rotate and have the ability to plunge into the plates.(1,6)

There are two variants in the process associated with the way of the tool can penetrate into the plates: pin plunge and sleeve plunge. In both variants, while one of the parts plunges into the plates, the other one is moved up creating a space for accommodating the flash generated during the process.(1) In the sleeve plunge variation, sleeve is plunged into the material while pin is retracted until a specified plunge depth. Plasticized material is squeezed into the space left by retraction of the pin. Both sleeve and pin retract back toward the sheet surface, pushing the plasticized material that was originally displaced back into the plate. Finally, the clamping is released once the pin and sleeve reach the upper surface, concluding the weld. The advantage of the sleeve plunge over the pin plunge variant is the biggest welded area, which might leads to higher joint strength.(7,8)

A schematic representation of the shoulder plunge FSpW process is presented in Figure 1.

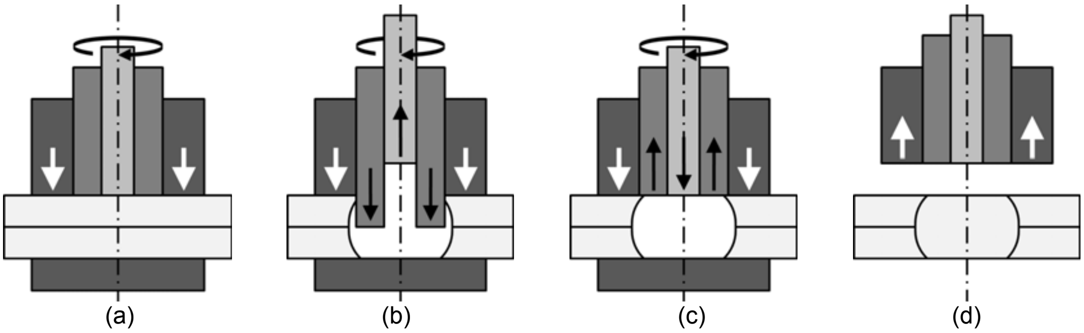

Figure 1. Schematic illustration of the FSpW sleeve plunge variant with the 4 main stages: (a) tool rotation; (b) sleeve plunging and pin retraction; (c) pin plunging and sleeve retraction; and (d) tool removal.(3)

2 MATERIALS AND EXPERIMENTAL PROCEDURE

Sheets of 2 mm-thick AA5754-H111 aluminium alloy were cut to 100 mm long and 25 mm wide. The specimens were prepared in lap-shear configuration with 25 mm overlap to produce joints using the FSpW/sleeve plunge process. The process was made using a RPS 100 machine, which was developed by Helmholtz-Zentrum GmbH. The maximum plunge force and rotational speed permitted for specimens are, respectively, 7.8 kN (vertical axis) and 3,000 rpm. A monitoring system is responsible for record the parameters: rotational speed, torque, axial load, plunge, welding time, as well as, pin and sleeve position. The welding tool consist of a clamping ring, Ø 9 mm threaded sleeve and Ø 6 mm threaded pin and was made of tool steel. Details of the FSpW tool geometry and the tool assembly are shown in Figure 2.

Figure 2. FSpW tool: (a) components (pin, sleeve and clamping ring); and (b) tool assembly.

Series of welds were performed with a range of parameters, set in order to find the levels for three factors: rotational speed (RP), plunge depth (PD) and dwell time (DT). The parameter matrix definition was based on results of a preliminary investigation with Taguchi method to develop the design of experiments (DOE), which will be explained in a future work. Taguchi method was applied to define both the optimal result from finite analytical data and the dominant factors involved in the optimization of FSpW. The result was the optimized condition predicted by the method (WC 10) and more six conditions achieved by keeping two variables constant and varying the levels of the other, in order to study the influence of each individual variable on Lap

Shear Strength (LSS) behavior. The welding specimens were produced and studied through macro and microstructural analysis, as well as, mechanical testing (each experiment was carried out in triplicate).

The resulting parameters varied during welding were RS (1,700 rpm, 2,000 rpm and 2,300 rpm), PD (2.7 mm, 2.8 mm and 2.9 mm), DT (0 s, 1 s e 2 s) and the clamping force (12.0 kN), that was maintained fixed, comprising 7 conditions. See Table 1 for process parameter matrix. The specimens were prepared for metallographic examination such that the polished transverse cross section passed through the weld centre. Samples were prepared according to standard metallographic procedures and etched using Barker's reagent (1.8% fluoboric acid in water).(9) In order to investigate the macrostructure features a Leica DM IRM optical microscope (OM) was used.

Table 1. Process parameter matrix

Welding Condition	Rotational Speed (RPM)	Plunge Depth (mm)	Dwell Time (s)	Clamping Force (kN)	Lap Shear Average (kN) and Standard Deviation
10	2,000	2.8	1	12.0	**7.58 (0.14)**
11	2,300	2.8	1		**7.55 (0.04)**
12	1,700	2.8	1		**7.26 (0.30)**
13	2,000	2.9	1		**7.57 (0.14)**
14	2,000	2.7	1		**7.47 (0.01)**
15	2,000	2.8	0		**6.81 (0.28)**
16	2,000	2.8	2		**7.17 (0.06)**

The welding specimens were produced and studied through macro and microstructural analysis, as well as, mechanical testing. The microhardness tests (Vickers) were performed across the joint transverse section with a Zwick/Roell-ZHV machine, using a conventional indenter with 0.2 kgf load. The Lap Shear Strength (LSS) tests were performed using a screw-driven Zwick/Roell testing machine with a load capacity of 200 kN at room temperature and a constant cross head speed of 2 mm/min were used.

3 RESULTS AND DISCUSSION

3.1 Macrostructural Characterization

Macrographies of the welds were prepared in order to investigate their features and relate it to the mechanical behavior of the joints. After the new experiments carried out to evaluate the effect of each individual variable, it was chosen only the best (WC 10) and the worst condition (WC 15) to make the metallographic characterization. The study of these conditions was shown to be enough to understand the reason that one of them achieved a very good value of LSS and the other a low value.

According to the macrostructural features of the similar welds, three distinct welding regions are found in FSpW process: stir zone (SZ), thermo-mechanically affected zone (TMAZ) and heat-affected zone (HAZ). The cross section of the welding conditions (WC) 10 and 15 are presented in Figure 3.

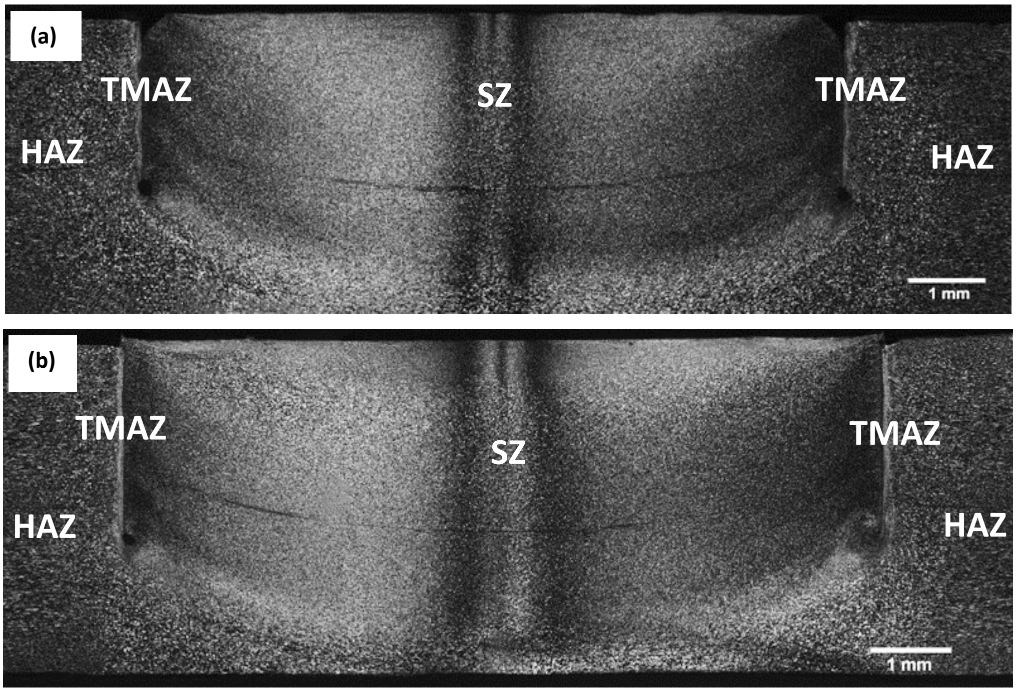

Figure 3. (a) Macrograph of welding condition 10; (b) macrograph of welding condition 15.

Some defects associated to the material flow were also found to be present in the connections. In WC 10 at the top interface between SZ and TMAZ a lack of refill can be found, which is a small volumetric defect. Another geometric pattern that can be seen is the hook formation (Figure 4). The hooking is formed because of the upward bending of the sheet interface due to the tool penetration into the bottom sheet.(10) The hook presents an upside down V shaped appearance and its final dimensions will be controlled by the energy input.(11)

Volumetric defects in welding condition 15 are presented in Figure 5. A small group of voids can be seen at the top region of the SZ, near the TMAZ/SZ boundary. However, here the lack of refill is almost inexistent compared with the same region in WC 10. Also, the same metallurgic pattern of WC 10 can be seen at the bottom of the SZ, which are the hook formation.

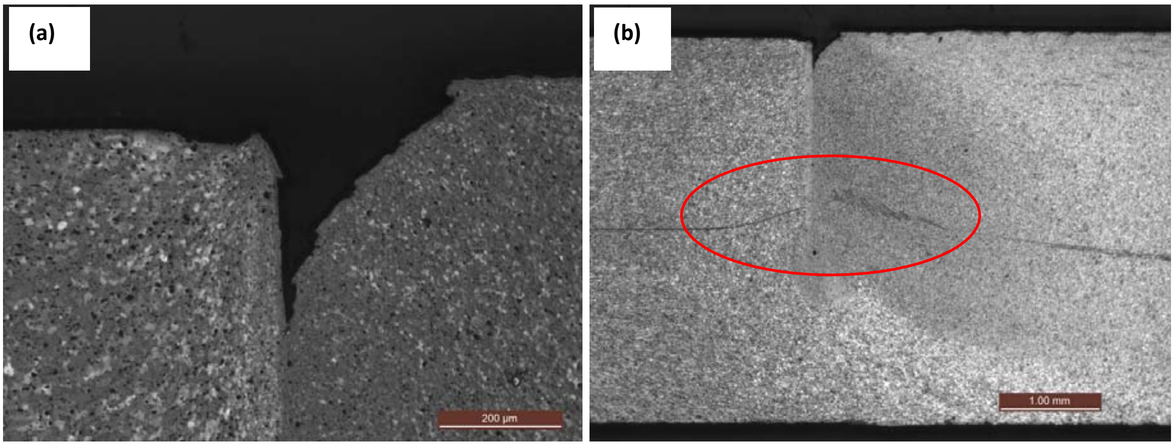

Figure 4. Defects in WC 10: (a) Lack of Refill – 100X; and (b) Hook formation on the left side of SZ – 16X.

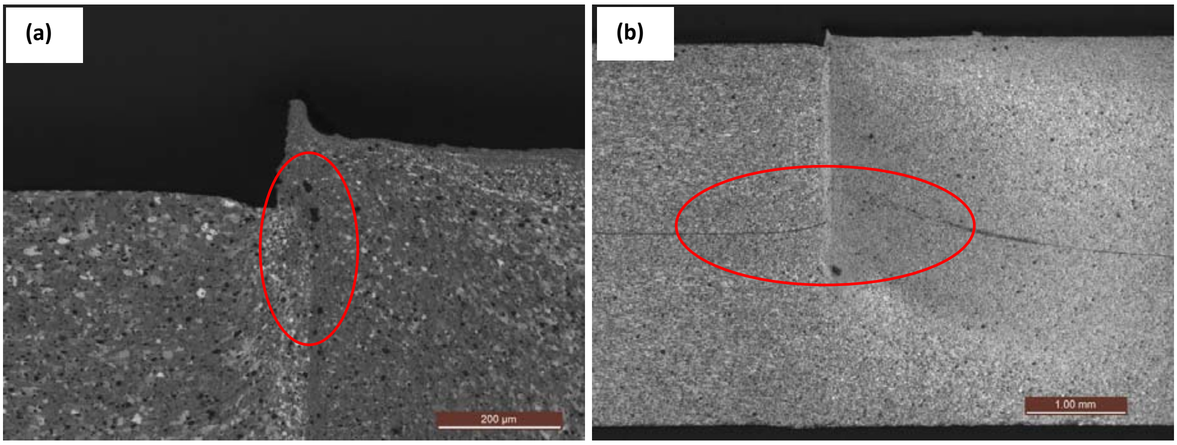

Figure 5. WC 15: (a) Voids in top of transition region between SZ/TMAZ - 100X; and (b) hook formation on the left side of SZ - 50X.

Nevertheless, the presence of these defects does not mean poor weld strength. In WC 10 there was a big lack of refill at the top interface that was not found in WC 15, however LSS of WC 10 was the highest one. Kyffin et al.(12) and Feng et al.(13) studying FSSW process of automotive steel reported the presence of a hook interface in the weld. Kyffin et al.(12) proposed that the "hook" feature between the two sheets acts like a mechanical interlock in the shear direction, resulting in an additional contribution to the failure load. Ikegami et al.(14) cited by Tier et al.(15) showed that a tool with threaded pin produced joint with "hooking" at the interface and had higher strength while a tool with smooth pin (no "hooking"). Nonetheless, Schilling(16) investigating the FSSW of AA6061-T4 proposed that to safeguard joint performance the interface between the sheets should be linear and parallel to the surface.

The different reports about the effect of hooking are contradictory. While some authors consider its effects beneficial to mechanical properties of the weld, others observed a detrimental effect. Hence, it was concluded that, for these welding conditions, volumetric defect cannot explain the difference in the mechanical performance of the welds.

3.2 Microhardness Testing

The microhardness profile was carried out through the weld in both welding condition in the middle of the top plate as well as in middle of the bottom plate. The mechanical and thermal inputs provided by the welding tool in friction based welding processes have been proven to affect the weld in different forms, leading to different welding zones. Nevertheless, the microhardness profile of the cross section of the FSpW connections can also be used to infer these effects (Figures 6 and 7).
It can be observed in the Figure 6 of welding condition 10 (best LSS), that in SZ the hardness values remain constant, both in the bottom and in the top plate. The intense plastic deformation and high temperatures cause the microstructure in the SZ to undergo dynamic recrystallization, reducing the grain size. This would lead to a hardness increasing of this region. However the SZ achieved lower values of hardness than TMAZ, that could have been caused by the presence of precipitates of Al3Mg2. Senkara and Zhank(17) discovered precipitates inside the grains and intergranular of AA5754. EDX and WDX analyses revealed an increased amount of Mg in these regions, which it is most probably due to an Al3Mg2 secondary phase. So, in the TMAZ the hardness begins to rise until reach the interface between TMAZ/HAZ. The deformation of the grains in TMAZ can produce some strain hardening in this region, which can cause the increase in the hardness values. So, it starts to decrease until reach the BM, where the average hardness is about 75 HV0.2. The hardness loss at the outer limits of the HAZ is associated mainly to recovery of the as rolled BM microstructure since the temperature reached at this specific region is not so high during welding.(11)

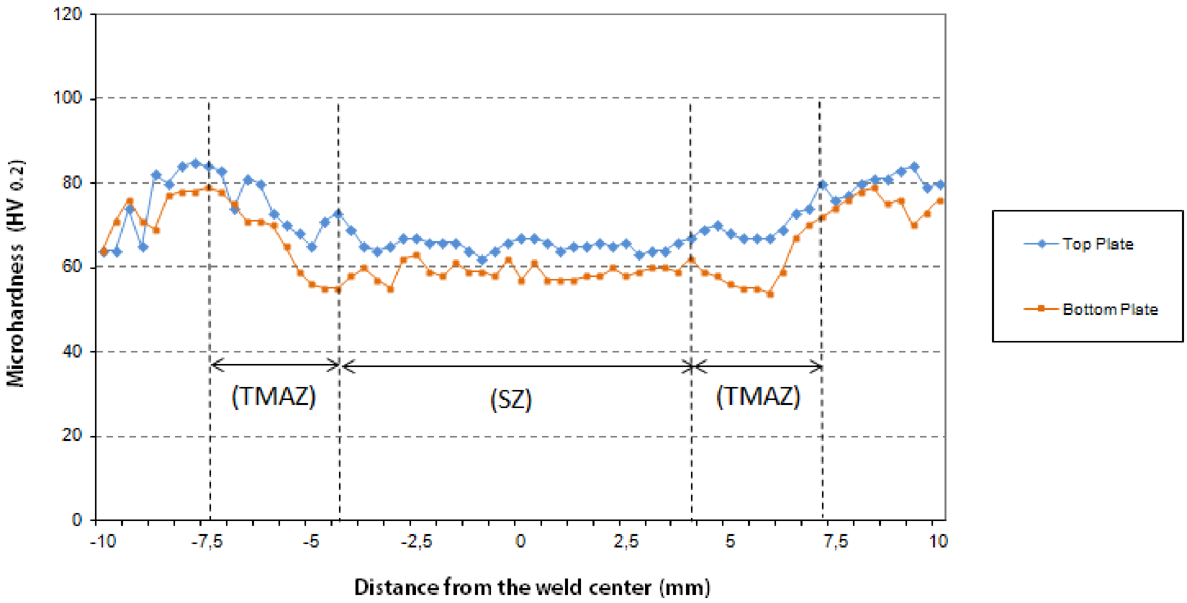

Figure 6. Microhardness Profile of Welding Condition 10.

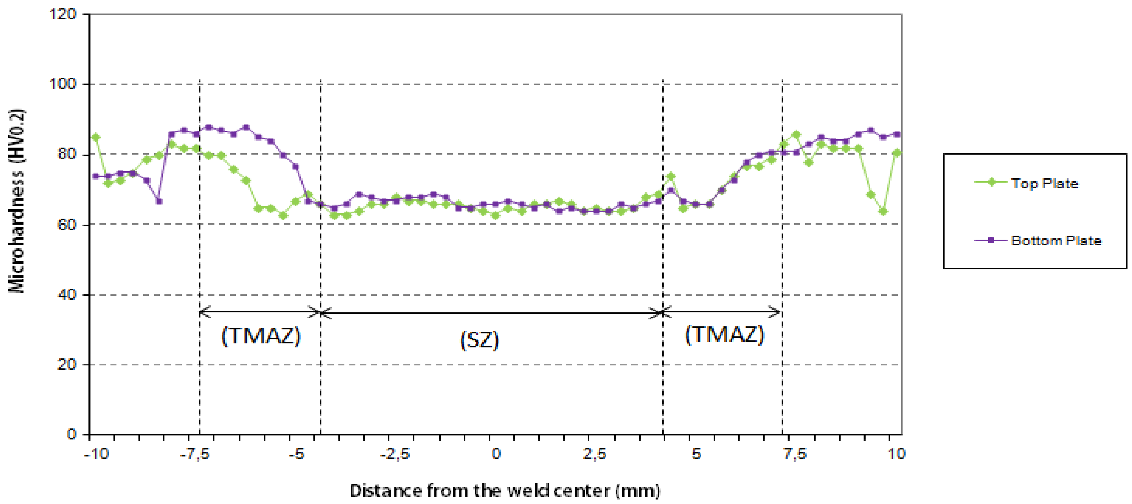

Figure 7. Microhardness Profile of Welding Condition 15.

Almost the same behavior happens in profile of the welding condition 15 (worst LSS) (Figure 7). However, the microhardness profile of the WC 15 appears to be a little higher than the WC 10 in all regions, SZ, TMAZ and HAZ and specially in the bottom plate. This increase in the hardness of WC 15 has slightly contributed for the lower values achieved in shear strength test.

3.3 Lap Shear Tensile Testing

The views of the lower and upper sheets of a shear failed specimen, representing both welding conditions 10 and 15, can be observed in Figure 8a. In both welding conditions, the fracture mode in tensile shear corresponded to a circumferential nugget pull-out. A similar failure mechanism was also observed in 6061 lap-shear specimens by Wang and Lee.(18) They found that under lap shear loading conditions, the failure is initiated near the possible original notch tip in the SZ and the failure propagates along the circumference of the nugget up to final fracture. The close-up view of nugget pull-out is in fact a stir zone pullout (Figure 8b).

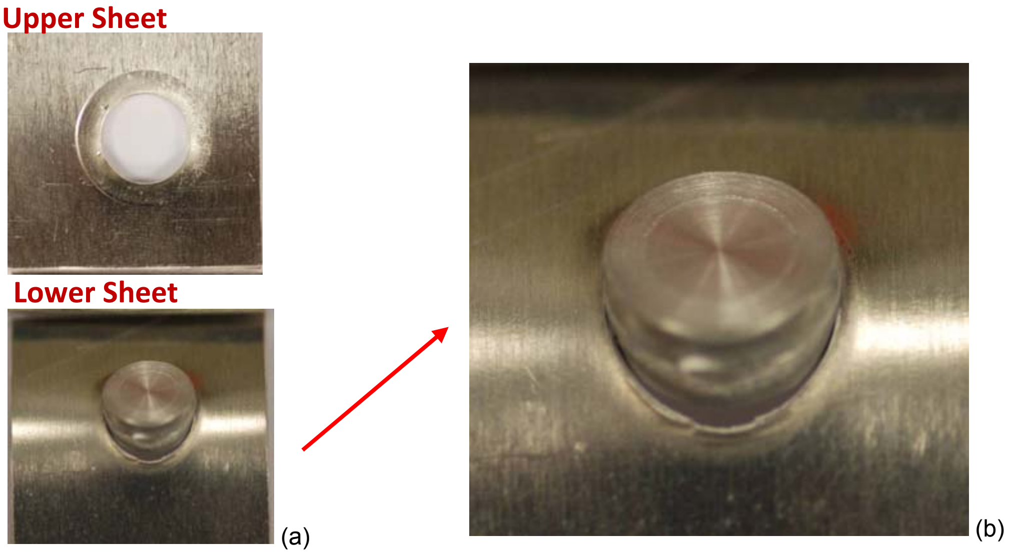

Figure 8. Failure mode after LSS testing showing (a) the upper and lower sheets of a shear failed specimen; and (b) a close-up view of the nugget pull-out on the lower sheet.

Rosendo(1) have observed that the plug pull-out is preferable than other failures since the mechanism in these fracture modes is ductile associated with plastic deformation around the stir zone prior to failure. Specimens presenting this fracture mode had a large area under the load displacement curve in the tensile shear tests which means high degree of energy absorption prior to failure.

Observing the low magnification overview (Figures 9a and 9b), can be seen that the bonding ligament length (BLL) is larger in the WC 10 (BLL = 9,31 mm) than in the WC 15 (BLL = 9,19 mm). Tier, Rosendo and Mazzafero(15) have reported that low strength FSpW connections presented a shorter BLL when compared to high strength connections. Furthermore, Su, Gerlich and North(19) have showed that the bonded area is positively correlated to LSS and energy into weld/specimen. The less heat energy into the specimen will result in a smaller bonded area and lower LSS.

The welding parameters showed that WC 10 had a longer dwell time (DT = 1 s) than WC 15 (D = 0 s) (Table 1). This longer dwell time causes a larger BBL (SZ) of the WC 10 than WC 15, leading to higher LSS of the condition 10.

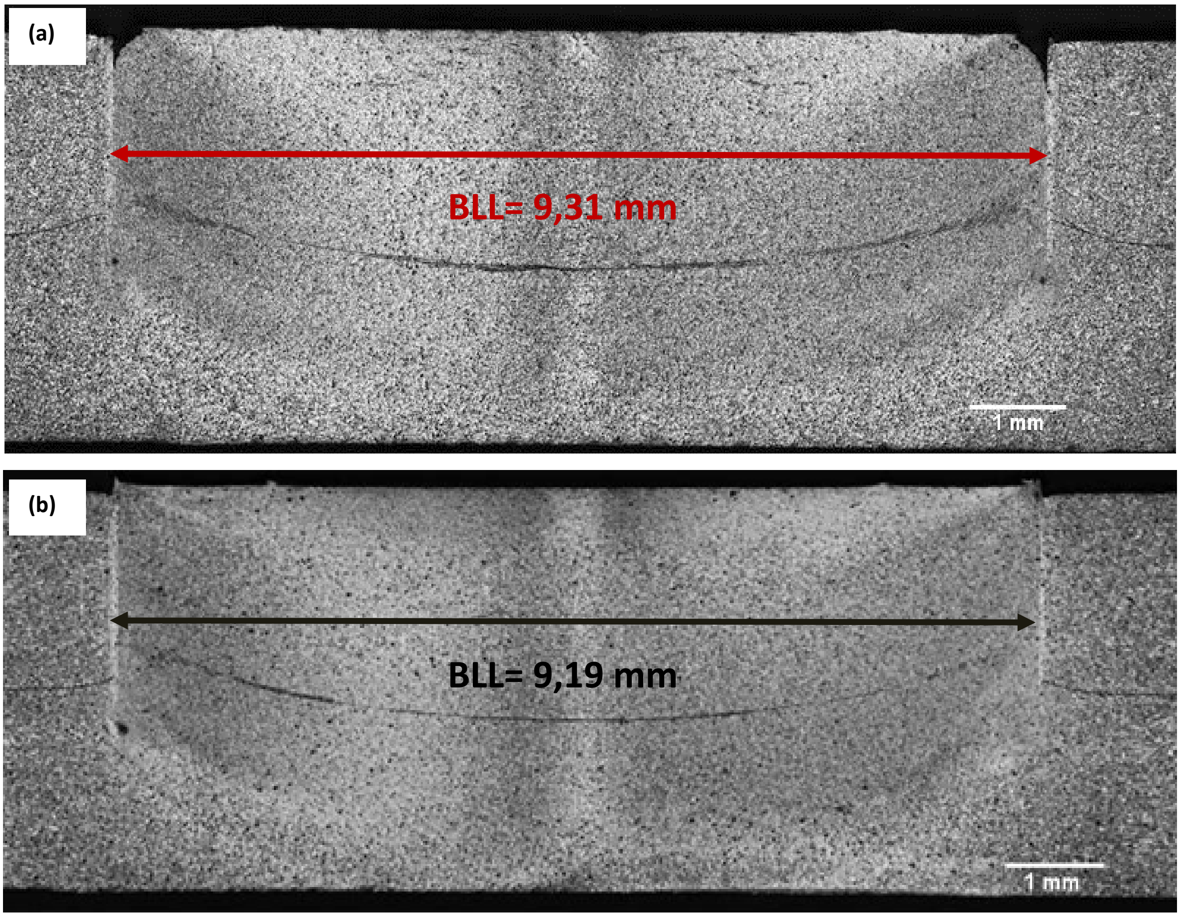

Figure 9. Low magnification overview showing the bonding ligament length (BLL) of (a) WC 10; and (b) WC 15.

4 CONCLUSIONS

Macrostructures and mechanical tests of friction spot welds in aluminium 5754 specimens were investigated.

- The dwell time has showed to play an important role in Lap Shear Strength (LSS) of FSpW AA5754;

- the small increase in the hardness of WC 15, compared with WC 10, has slightly contributed for the lower values achieved in WC 15 LSS test;
- the nugget pull-out failure mode was observed. This failure mechanism in the fracture mode is ductile associated with plastic deformation around the stir zone prior to failure;
- the bonding ligament length (BLL) was higher for the WC 10 (best condition) produced with dwell time (DT) of 1s than the WC 15 (worst condition) without dwell time (0 s).

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REFERENCES

1 ROSENDO, T. S. Preliminary Investigation on Friction Spot Welding of Alcad 2024-T4 Aluminum Alloy, Consolda. 2008.
2 THOMAS, W.M. et al. Friction Stir Butt Welding. GB Patent 9125978-8, 6 dez. 1991.
3 CAMPANELLI, L. C., ALCANTARA, N. G. et al. Soldagem por Ponto no Estado Sólido de Ligas Leves. Soldagem & Inspeção, vol.16, no 3. São Paulo. July/Sept. 2011.
4 KALAGARA, S.; MUCI-KUCHLER, K. H. Numerical Simulation of a Refill Friction Spot Welding Process. TMS (The Minerals, Metals & Materials Society). 2007.
5 DA SILVA, A. A. M. et. al. Performance Evaluation of 2-mm thick alclad AA2024-T3 Aluminium Alloy Friction Spot Welding. 2007.
6 DA SILVA, A. A. M. et al. Friction Spot and Friction Stir Spot Welding Processes – A Literature Review. In The Bulletin of National R&D Institute for Welding and Material Testing. Timişoara: ISIM. p. 36-44. 2007.
7 TIER, M. et al. The Influence of Weld Microstructure on Mechanical Properties of Refill Friction Spot Welding of 5042 Aluminum Alloy. In Proceedings of the 7th International Friction Stir Welding Symposium. Awaji Island, Japan. 2008.
8 MAZZAFERRO, J.A.E.; ROSENDO, T.S. Preliminary Study on the Mechanical Behavior of Friction Spot Welds". Soldagem Insp. Sao Paulo, vol. 14. p.238-247. 2009.
9 ASM INTERNATIONAL HANDBOOK COMMITTE. ASM Handbook. Buehler Ltd, vol. 9: Metallography and Microstructures. p. 496-498. 2004 Edition.
10 HAGHAYEGHI, R.; ZOQUI, E.J.; BAHAI, H. An investigation on the effect of intensive shearing on the grain refinement of A5754 aluminium alloy. Journal of Alloys and Compounds, vol. 481, p. 358-364. 2009.
11 ROSENDO,T.; PARRA, B. et al. Mechanical and microstructural investigation of friction spot welded AA6181-T4 aluminium alloy - Materials and Design 32. p. 1094–1100. 2011.
12 KYFFIN W.J, THREADGILL P. L, LALVANI H, WYNNE B. P. Progress in FSSW of DP800 High Strength Automotive Steel, 6th International Symposium of Friction Stir Welding, 6th ISFSW 10-14. Canada. September 2006.
13 FENG Z., SANTELLA M. L. et al. Friction Stir Spot Welding of Advanced High-Strength Steels – A Feasibility Study, SAE technical paper No 2005-01-1248, Society of Automotive Engineers. Warrendale, USA.
14 IKEGAMI I, TSUMURA T. YE. F, NAKATA K. Effect of tool geometry on joint strength of Mg alloy by spot friction welding, preprints of the national meeting of Japan welding society, no. 78. 2006.
15 TIER, M.; ROSENDO, T.; MAZZAFERO, C. et al. The Influence of Weld Microstructure on Mechanical Properties of Refill Friction Spot Welding of 5042 Aluminium Alloy - 7th International Symposium on Friction Stir Welding. Awaji Island, Japan, 20-22nd May 2008.

16 SCHILLING C. A preliminary investigation on the static properties of friction stir spot welding, 2nd International Symposium of Friction Stir Welding, June 26-28, 2000, Gothenburg, Sweden.
17 SENKARA, J. and ZHANG, H. Cracking in Spot Welding Aluminum Alloy AA5754. Welding Research Supplement. p. 194-201. July 2000.
18 WANG, D.A., LEE, S.C. Microstructures and failure mechanisms of friction stir spot welds of aluminum 6061-T6 sheets. J. Mater. Proc. Technol. 186, 291–297. 2007.
19 SU P, GERLICH A AND NORTH T.H. Friction Stir spot welding of Aluminum and Magnesium Alloy Sheets, SAE Technical Paper 2005-01-1255, 2005 SAE Congress, Detroit, SAE, p 127-134.