

FRICION STIR SPOT WELDING OF ALUMINIUM-ALLOY TO STEEL DISSIMILAR OVERLAP JOINTS

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Abstract. *The Friction Stir Spot Welding (FSSW) process allows overlapped dissimilar metals to be joined in the solid state, avoiding common complications associated with conventional fusion-based welding processes. In FSSW, a tool in high rotational speed is pressed against the materials to be joined. The friction between the surfaces generates heat and intense plastic deformation, resulting in a metallurgical bond between the sheets. In this paper, an exploratory study was conducted in order to compare mechanical behavior of similar Al-alloy (1200H14) and dissimilar Al-alloy to steel joints (AISI 1020), which were obtained from FSSW process applied in a machining center using Computerized Numerical Control (CNC). Two welding tools were manufactured with difference in shoulder diameter as well as pin diameter and length. The welding operations were performed by applying distinct parameters: rotational speed (from 1000 to 4000 rpm), plunge rate (from 10 to 100 mm/min) and tool dive. The performance of the welded joints was evaluated in terms of tensile strength tests and microstructure characterization. Acquired results shows that FSSW process is practicable in non-specialized equipment, yet sensible to operational parameters. The results showed that in order to obtain mechanically sound dissimilar joints it was necessary apply tool plunge values larger than pin length. Furthermore, the results indicate that shoulder and pin height directly influenced in the effective contact area, impacting on tensile strength of the joints. As a result of the adopted methodology, it was possible to identify optimum operational parameters that conduct to elevated tensile strength of joints.*

Keywords: *FSSW, aluminium, steel, dissimilar, microstructure, mechanical properties*

1. INTRODUCTION

Many important innovations in the aerospace and automotive industries are motivated by efforts to reduce mass of mechanical components thus increasing energy efficiency of end products. In this context, a promising alternative is the use of lightweight materials, such as polymers, Al or Mg alloys partially replacing steel parts. In the case of lightweight metals, the major adversity to dissimilar joining of Al alloys to steel is that at high temperatures, particularly in the presence of a liquid phase, brittle intermetallic compounds are formed at the faying interface which results in poor joint characteristics. In addition, solidification from the liquid phase may lead to cracking, pore formation, residual stresses and distortion (European Aluminium Association, 2016). For these reasons, solid state welding processes, in which much lower temperatures are observed in comparison to conventional fusion-based welding techniques, have drawn considerable attention from both industry and researchers.

The Friction Stir Spot Welding (FSSW) process is a variant of Friction Stir Welding (FSW), in which there is no transversal tool movement, aiming to replace single-point joining processes like Resistance Spot Welding (RSW) and riveting. These conventional processes have been widely used for Al alloys sheet assemblies. However, they have disadvantages such as consumption of tool during joining, distortions caused by heating and poor weld strength in RSW; porosity by laser spot welding; and increased cost and weight in riveting processes (Yang, *et al* 2014). Therefore, incorporation of lightweight metals, requires from manufactures the development of innovative bonding techniques that allows the confection of efficient and safe dissimilar bonds without tensile strength loss. (Sun, *et al*, 2012).

In Fig. 1 the FSSW process is illustrated, considering the production of an overlap joint. The welding cycle begins with a rotating tool with a protruded pin plunging into the upper sheet of the lap joint, as in Fig. 1(a) – only half segment of the tool is shown, which is in reality axisymmetric. The tool is pressed downwards to the joint and kept for a predetermined holding time, which causes heat generation by friction, softens the base material leads to intense plastic deformation, Fig. 1(b). Much more heat is generated underneath the tool shoulder after contacting the top surface of the upper sheet. The tool shoulder also serves the purpose of confining the plastic flow that tends to be expelled from the interface during the process. The softened material is pushed and stirred to form the metallurgical bond around the rotating pin. The tool is retracted at the end, leaving the characteristic hole in the middle of the weld, as shown in Figure

1(c) (Feng, *et al* 2004). Process parameters usually include: tool geometry, rotational velocity of the tool, plunge rate, tool penetration depth, downward load and tool holding time (Fanelli, *et al* 2012).

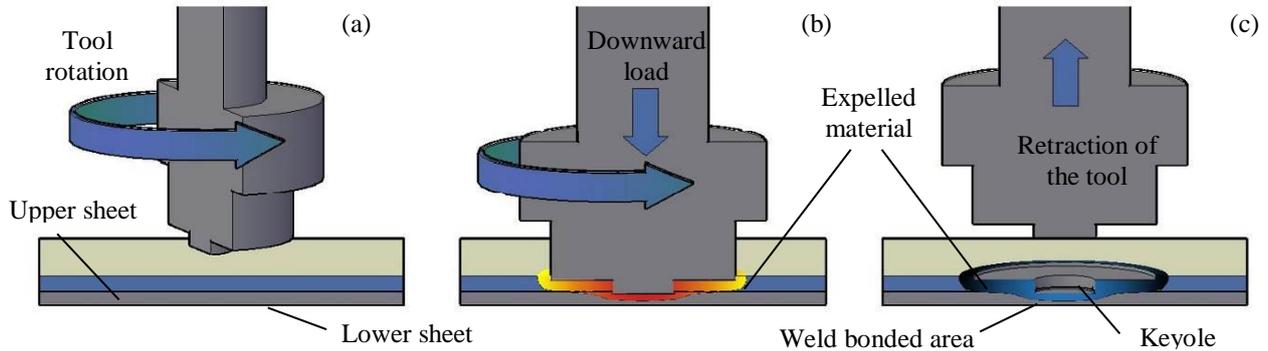


Figure 1: Illustration of the FSSW process: (a) plunging, (b) stirring, (c) retracting

In this paper a study of the FSSW process applied to produce similar overlap joints of 1200H14 Al-alloy sheets and also dissimilar overlap joints of 1200H14 Al-alloy to AISI 1020 carbon steel is presented. To this end, two tools with distinct geometry were used to manufacture the joints. Different combinations of process parameters were applied in an attempt to obtain a correlation between the experimental conditions and the resulting microstructure and mechanical properties. The work was conducted in a machining center with Computerized Numerical Control (CNC), widely used in industry, which could motivate future developments of FSSW process even in the absence of specialized FSSW machinery.

2. EXPERIMENTAL PROCEDURE

2.1 Materials

Thin sheets of the materials (plain carbon steel 1020 and aluminium alloy 1200H14) used in this study were acquired with the dimensions: 25 x 100 x 1 mm. The overlap area of the welded joints in all cases was 25 x 25 mm².

2.2 Development of welding tools

The tools used to manufacture the joints were developed using steel AISI H13. The main dimensions of the tools are: shoulder diameter, pin diameter and pin length. The first tool had a shoulder \varnothing 10mm, pin \varnothing 4mm and pin length of 1.3mm length. The second tool had shoulder \varnothing 18mm, pin \varnothing 6mm and pin length of 1.5mm. The H13 steel was first machined according to these dimensions, quenched and tempered to 50 HRC and ground with 1200 SiC grinding paper for reducing surface roughness. The tools developed are presented in Fig. 2. The body of both tools was kept at 12.7 mm in order to allow fixation to the spindle of the CNC machining cutter.

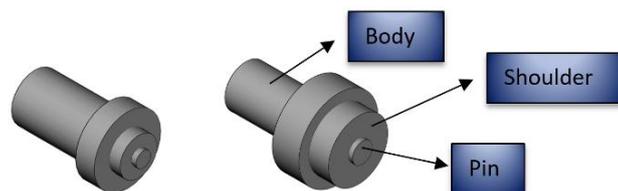


Figure 2: (a) Isometric view of tool 1 (b) Isometric view of tool 2

2.3 FSSW procedures

The welding operations were performed on a TRAVIS 800 CNC machining center. For tensile strength and microstructure analysis, four tests were performed for each parameter configuration. Three samples were submitted to tensile testing and the fourth specimen from each experimental condition was cut and prepared for metallographic examination. The tensile strength of the joints was evaluated using an EMIC universal test machine with maximum capacity of 10t. Metallographic preparation involved grinding in SiC paper followed by polishing in a 3 μ m diamond suspension. Etching of the samples was performed by using Keller's reagent and the images were registered in a Carl Zeiss Axio A1 optical microscope.

3. RESULTS AND DISCUSSION

3.1 Tool selection

The welding procedures were executed by employing a combination of parameters, which were: rotational speed, plunge rate, tool dive and tool geometry. The parameters values used in this work were initially selected from a compilation of the literature: Ibrahim *et al.* (2014), Zhang *et al.* (2014), Aghdam *et al.* (2014), and then adapted to the experimental conditions of this study. The first parameter evaluated was tool geometry. A comparison of the tensile strength (given in N) and sample cross section obtained with tools 1 and 2 for predetermined values of rotation and plunge rate is presented in Fig. 3.

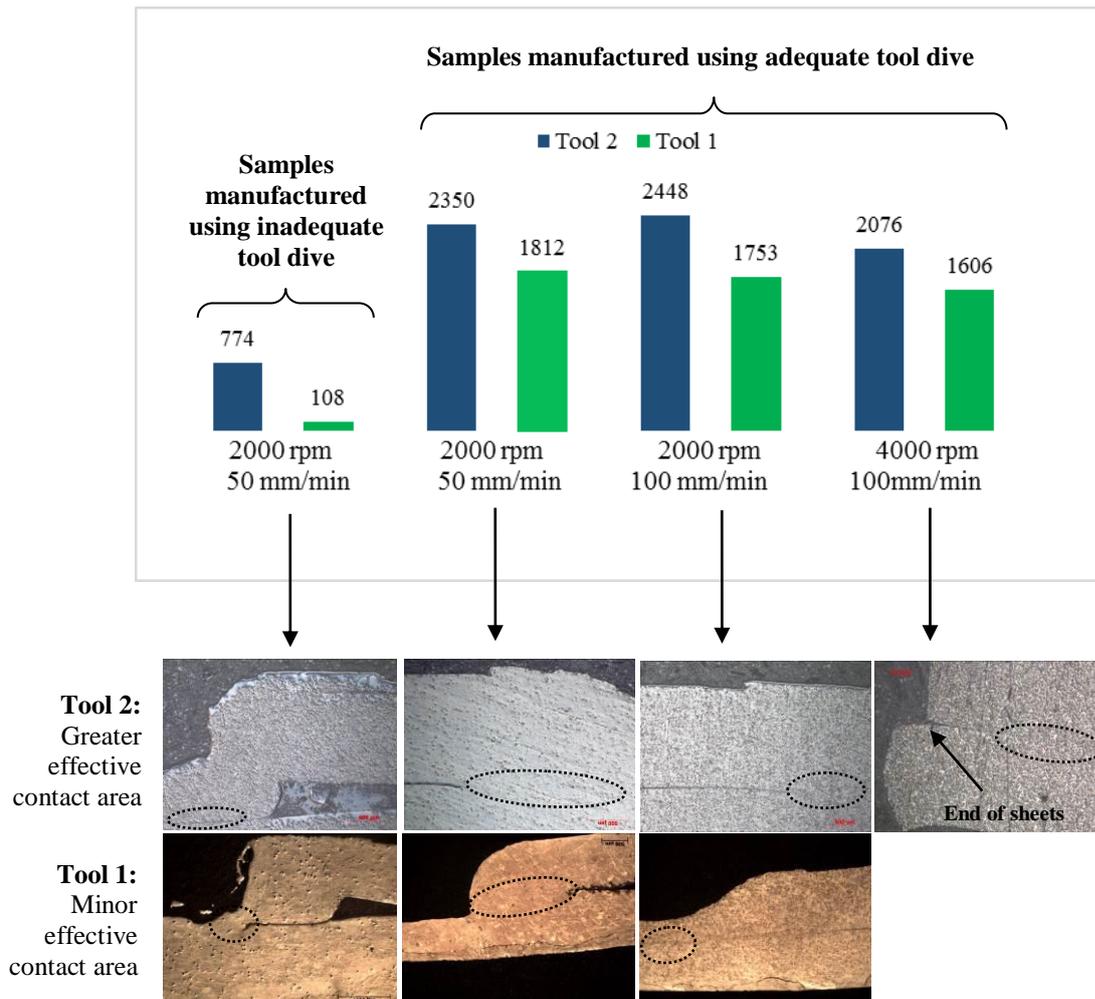


Figure 3: Parameters comparison of similar bond of Al alloy

Jambhale *et al.*, (2015) affirm that the shoulder of the tool is responsible for compression stress on the softened material. Hence, increasing tool shoulder diameter, while fixing a set of welding parameters, would restrict material expulsion from the welded joint. Therefore, as can be seen by Fig. 3, the effective contact area for all samples manufactured by tool-1 was smaller than that of samples manufactured by tool-2. The results presented here, therefore, supports the statement by Jambhale *et al.*, (2015), since the effective contact area is directly related with tool shoulder function.

The results presented in Fig. 3 also seem to indicate that plunge rate at 2000 rpm does not significantly impact tensile strength of the joints and that increasing tool rotation speed to 4000 rpm has a negative influence on the load bearing capacity of the welds (for both tool geometries). These results are in contradiction to the observations by Although Zhao-hua, *et al.*, (2011) who observed that mechanical properties of FSSW joints were reduced by increasing tool rotation speed. Jambhale, *et al.*, (2015), however, point out that only very little is reported in the literature about varying the rotation speed in FSSW and the effect of the rotation speed on the microstructure evolution in the weld is not fully understood, which suggests that further testing would be necessary in order to clarify the issue.

3.2 Processing parameters

After initial testing directed towards proper tool selection, a more systematic approach was endeavoured in order to assess the influence of process parameters on the mechanical strength of both similar and dissimilar FSSW joints. The main experimental combinations are presented in Tab. 1, along with the resulting tensile strength and aspect of the fractured specimens obtained after tensile testing.

Table 1. FSSW process parameters

Sample	Overlapped joint	Tool	Tool rotation [rpm]	Feed speed [mm/min]	Pin height [mm]	Max. Force [N]	Fracture
A	Al/Al	2	1000	50	1,5	1322	
B	Al/Al	2	2000	100	1,5	2448	
C	Al/Al	1	2000	100	1,3	1752	
D	Steel/Al	2	2000	50	-	-	
E	Steel/Al	2	4000	100	1,7	1752	
F	Steel/Al	2	4000	50	1,7	1557	

Visual inspection of the as-welded specimens can reveal important process information. A compilation of selected experimental conditions is presented in Fig. 5 (samples are labeled according to the identification given in Tab. 1). In samples A and D it was possible to notice adhesion of the Al-alloy to the welding tool. This reflected on the surface appearance of the welded region, which exhibits circular grooves indicating material detachment. In contrast, no such surface features were presents *e.g.* in samples C and F which yielded moreover higher mechanical strength (Tab. 1). The difference in strength between samples A and C (both similar welds) is a clear reflection of the influence of tool rotation on the mechanical properties of FSSW joints, in agreement with the preliminary test results presented in Fig. 3. It might be possible to draw an analogy between the effects of increasing rotation speed in FSSW and in machining Al-alloys. According to Songmene, *et al.* (2011), machinability of Al-alloys is improved at relatively high tool speeds, avoiding the formation of built-up edges which is a major cause of tool degradation during metal cutting operations (Thamban, 2013). The same was noted for Al-alloy to steel joints, where sample D submitted to 2000 rpm indicated adhesion between upper sheet (Al) and tool, while sample F show no or little sign of aluminium adhesion.

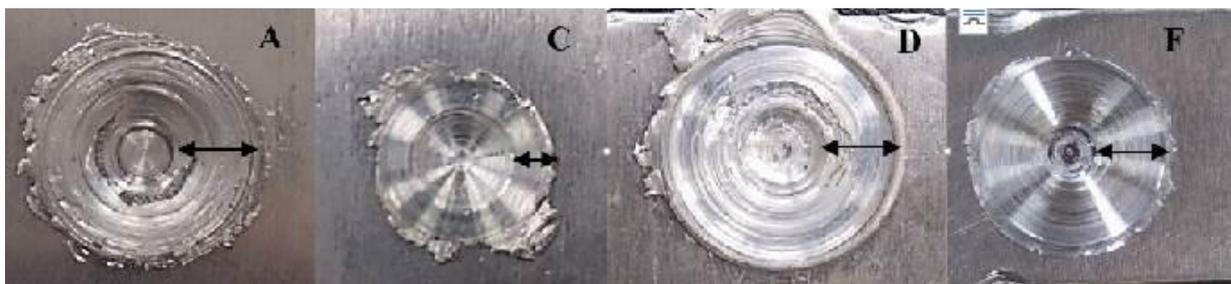


Figure 5: Visual inspection of welded regions of select samples.

The production of dissimilar Al-alloy to steel joints proved to be a difficult task because of large discrepancies in physical properties (hardness, thermal conductivity, density) and it was not possible to obtain dissimilar welds with the same mechanical strength as similar joints (Tab. 1). It is also worth mentioning that, in the case of similar joining, it was possible to achieve welding conditions which led to fracture of the base material during tensile testing (samples A and C), whereas for the dissimilar joints fracture occurred always at the edges of the welded zone.

It is important to notice that the optimal parameters for similar Al-alloy welding were not the same as for dissimilar welding. The dissimilar joint offered much more resistance to bonding, requiring more heat input that was provided by increasing the rotational speed of the tool. Jambhale *et al.* (2015) state that increasing pin height has a positive effect on the tensile shear strength of FSSW welded joints. This is in agreement with the present study, which shows that increasing tool dive deeper than pin length is beneficial to shear strength in dissimilar bonds of Al alloy to steel as can be referred to in Tab. 1. Increasing tool dive on the overlapped sheets means imposition of higher pressure, which leads to more resistance offered by the overlapped joint to the movement of the tool, meaning that more friction or, heat, was given to bond the sheets. Therefore, this makes necessary the need to increase rotational speed, to avoid adhesive interface formation between the tool and the upper sheet, that is susceptible in relatively low rotational velocities, as observed for the similar joint, explaining the difference between optimum tool rotations for similar to dissimilar joints. The plunge rate can also have an effect on the heat input, leading to differences in mechanical strength as can be visualized in Fig. 6. Considering same parameters, plunge rate of 100mm/min over 50/mm/min gave 14% more in terms of mechanical strength.

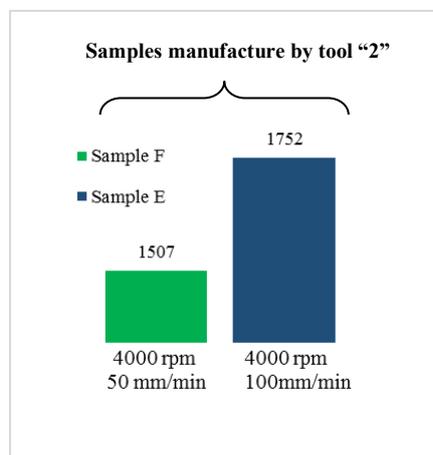


Figure 6. Parameters comparison for dissimilar bond of Al alloy to steel

The force-displacement curves from the best similar and dissimilar welded joints are compared in Fig. 7. The differences in the linear portion of the diagrams indicates that deformation modes are different from each condition. Naturally, in the case of the similar joints, for low displacements the diagram reflects simply elastic deformation of the Al-alloy. In the case of the dissimilar welds this seems not to be the case and the curves could indicate formation of secondary phases in the welded zone.

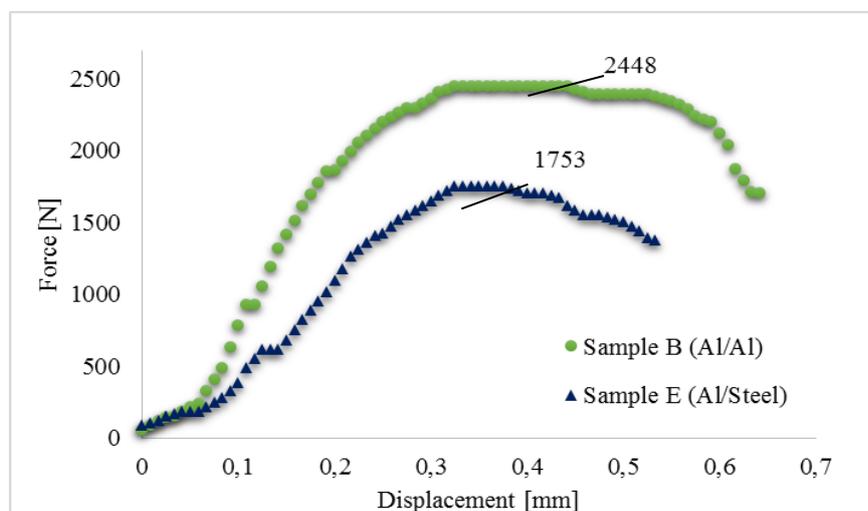


Figure 7. Results comparison for similar and dissimilar welds

3.3 Microstructure

3.3.1 Similar welding

In Fig. 7 the bond region of welded joints A, G, H and B is shown. The corresponding welding parameters are presented in Tab. 2.

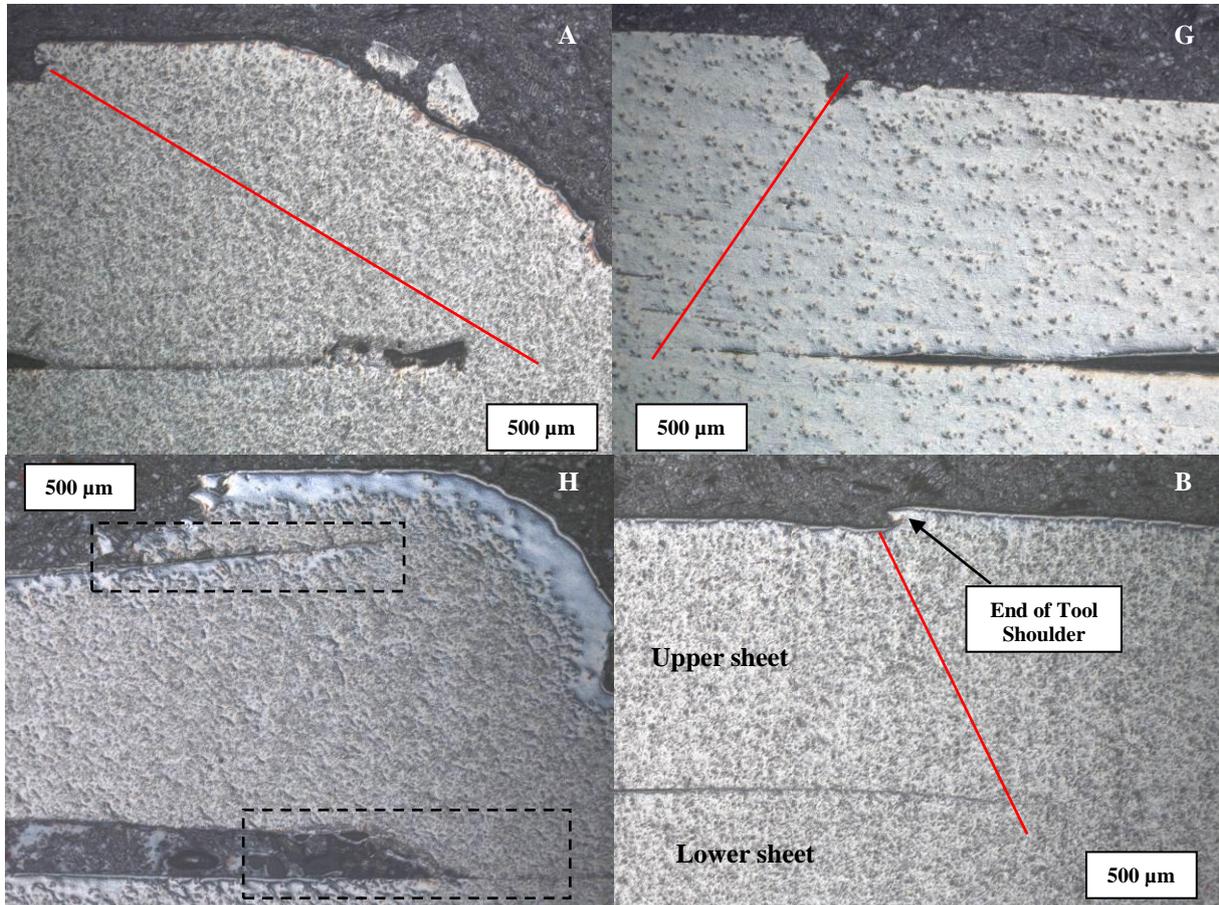


Figura 7: Microstrutura de Amostras A, G, H e B: Comparação de área efetiva de contato

Table 2. Al/Al samples of second tool

Sample	Tool rotation [rpm]	Feed speed [mm/min]	Tool dive [mm]	Max. Force [N]	Set of parameters	Fracture
A	1000	50	1,5	1322	Inadequate	
G	2000	50	1,5	2350	Inadequate	
H	2000	50	1,0	773	Inadequate	
B	2000	100	1,5	2448	Adequate	

As inferred from results of the previous section, tool shoulder plays an important role in the effective contact area between the sheets. Samples A and H exhibited low effective contact area due to inadequate parameters used in their manufacture, as shown in table 2 and Figure 7. Samples G and B produced better results, based on its effective contact area that was compared with tool shoulder, an immutable parameter for these 4 samples. Sample B was manufactured using a plunge rate of 100mm/min. It can be seen that the effective contact area of this larger than that of sample G, manufactured using plunge rate of 50mm/min, therefore, the load supported on the tensile shear strength test was greater than that of sample G. These results and comparison of parameters, allowed to set the best fit of parameters for Al alloys samples, that were, tool “2”, tool rotation of 2000 rpm, plunge rate of 100mm/min and tool dive the same as pin height.

3.3.2 Dissimilar welding

Al-alloy to steel joints microstructure analysis allowed an understanding of bonding difference between the similar and dissimilar joint. Figure 8 shows the interface between upper and lower sheet that is clearly seen, of sample E. There was bonding alongside tool shoulder, but unlike similar joint, plastic deformation occurred on upper Al alloy sheet, resulting in bonding through mechanical mixing. Right underneath the pin, 2mm wide, some of the steel, floated into the aluminium sheet, in a defined pattern, as it is indicated by the yellow arrows.

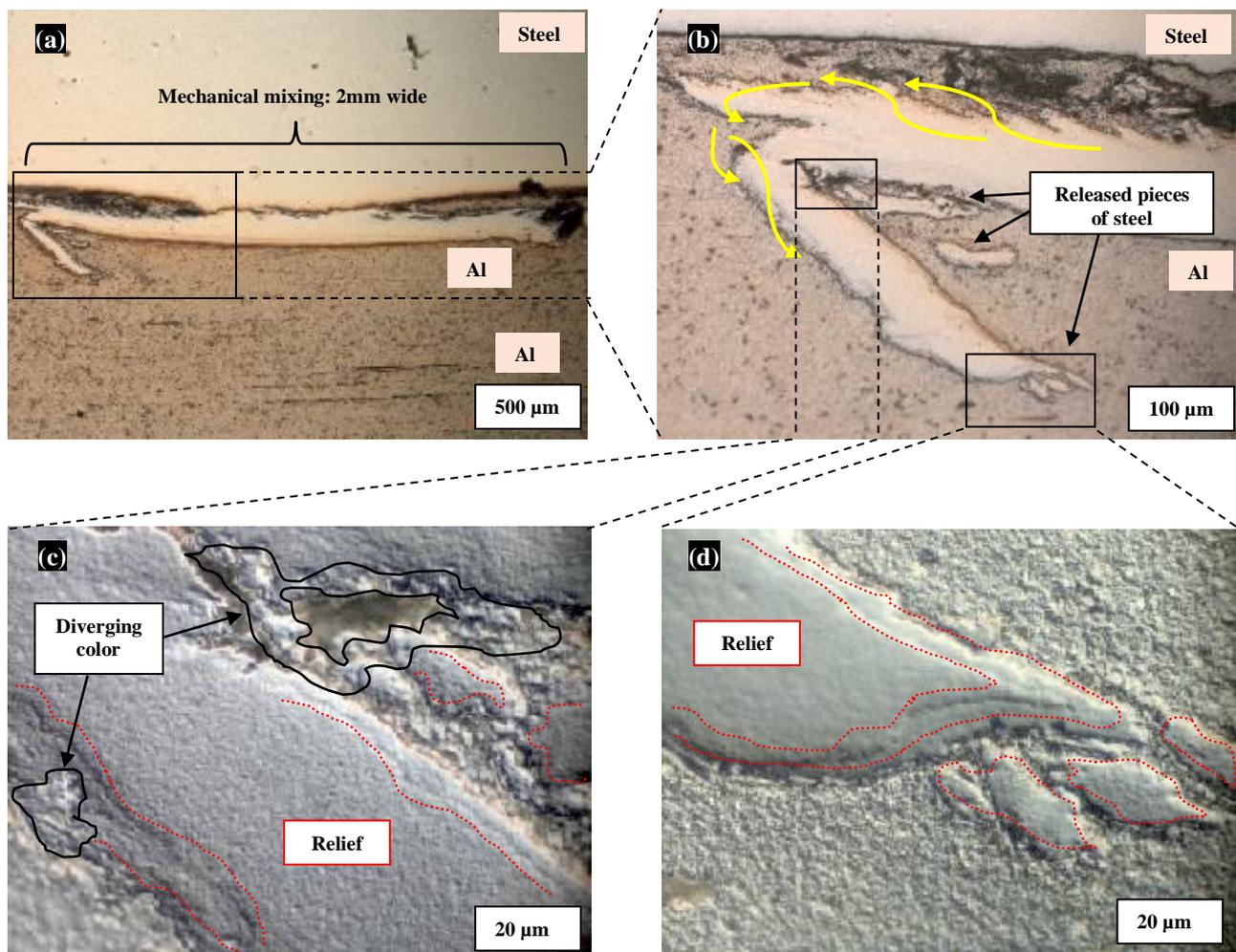


Figure 8. Microstructure formation in dissimilar welded joint

It can be seen in Figure 8(c) and (d) that polishing was not complete relief free, which indicates the presence of intermetallic compounds. The diverging contrast present in Figure 8(c) could indicate the presence of secondary phases, possibly intermetallic Fe-Al compounds which might also account for the differences noted in during tensile testing. Confirmation of this hypothesis would, however, require further analysis of the interface region using more advanced microscopy techniques.

4. CONCLUSIONS

It can be inferred from this study that FSSW technique can be used to joint Al alloy to steel using a non-conventional FSSW machinery. From analysis and results discussion can be said that optimum welding parameters for both similar and dissimilar joints requires large tool shoulder diameter, explaining tool “2” best performance over tool “1”, resulting in larger effective contact area; high rotational speed (2000rpm for similar and 4000rpm for dissimilar joint), in order to avoid adhesion of Aluminium on shoulder and pin of the tool; high plunge rate (100mm/min for both similar and dissimilar joint), that from results, increases tensile strength. Tool dive was studied and results indicate that for dissimilar joints, it must be greater than pin height.

5. ACKNOWLEDGMENT

This work was financially supported by Pontificia Universidade Católica de Minas Gerais through undergraduate research scholarship PROBIC/FAPEMIG under contract n° 9885. The authors wish to acknowledge the support by PUC-MG Contagem Laboratory technician’s assistance and Engineer Ewerton Dutra and from I. J. Silveira.

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