Effect of pin length on Friction Stir Spot Welding (FSSW) of dissimilar Aluminum-Steel joints

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Abstract

Friction stir welding (FSW) has produced a great impact in several industries due to the advantages that this process presents. In particular, the automotive industry has developed a variant of the original process, called Friction Stir Spot Welding (FSSW), which has a strong interest related to the welding of aluminum alloys and dissimilar materials in thin sheets. Aluminum-steel welding is an actual challenge, being FSSW an alternative to produce these joints. However, the information available related to the influence of process parameters on the characteristics of aluminum-steel joints is scarce. The aim of this work was to study the effect of the pin length of the welding tool and its penetration depth, during friction stir spot welding (FSSW) of overlaps joints of AA6063 with galvanized low carbon steel. FSSW was done by changing the pins length between 0.65 and 1.5 mm, and also by modifying the tool penetration depth in the welded joints. On the welded spots macro and microstructural characterization was performed, Vickers microhardness profiles were determined and Peel and Cross Tension Tests were also done. The maximum loads increased when the tool penetration depth goes up and the pin length decreased. The fracture mode was, at first, interfacial while it changed to a circumferential mode when the tool penetration depth increased and the pins length was reduced.

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Keywords: Friction Stir Spot Welding (FSSW); Pin; Tool Penetration Depth; Aluminum; Steel; Peel Tests.

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1. Introduction

| Nomenclature | Definition                                      |
|--------------|------------------------------------------------|
| A            | Effective joint length                         |
| AA           | Aluminum Alloy                                 |
| BM           | Base Material                                  |
| Cs           | Cross Tension Sample                           |
| CT           | Cross Tension Test                             |
| E-1          | Thickness of the top sheet                     |
| E-2          | Thickness of the bottom sheet                  |
| EDX          | Energy Dispersive X Ray Spectroscopy           |
| Fl           | Fracture Load                                  |
| FSSW         | Friction Stir Spot Welding                     |
| FSW          | Friction Stir Welding                           |
| HAZ          | Heat affected zone                             |
| IH           | Distance between the lower point of the shoulder and the interface |
| IMC          | Intermetallic compounds                        |
| LCG-S        | Low Carbon Galvanized Steel                    |
| LM           | Light Microscopy                               |
| Ms           | Macrographic sample                            |
| Ps           | Peel Test Sample                               |
| P            | Distance between the surface left by the pin and the bottom sheet |
| PCBN         | Poly Crystalline Boron Nitride                 |
| PT           | Peel Test                                      |
| RSW          | Resistance Spot Welding                        |
| SLM          | Stereo Light Microscopy                        |
| SEM          | Scanning Electron Microscopy                   |
| SZ           | Stir zone                                      |
| TMAZ         | Thermomechanically affected zone               |
| TPD          | Tool Penetration Depth                         |
| TWI          | The Welding Institute                          |

In recent years the transport industry has shown great interest in reduce fuel consumption and in consequence toxic emissions. To achieve this aim during cars production, one way is to reduce vehicles weight. This may be done by replacing certain ferrous parts with high strength steels (HSS) such as Dual Phase, Hot Stamped or TRIP steels that present high mechanical properties allowing the reduction of parts thicknesses. However, further weight reduction of 30% or more is hardly achievable with exclusive dependence on the use of thinner steel sheets (HSS). Because of this, certain ferrous parts can be replaced with low weight nonferrous alloys such as aluminum alloys or magnesium alloys, with similar mechanical properties. Multimaterial vehicle structures are an efficient countermeasure against this problem, which requires the development of reliable and cost-effective dissimilar material joining technique. One of the desired pairs is aluminum alloy and steel, which is highly difficult to be welded together due to their differences in physical and mechanical properties as well as the formation of large amount of brittle intermetallic compounds (IMC) using traditional fusion welding techniques (Liu et al. (2014)), besides other problems, and low mechanical properties achieved (Qiu et al. (2009)). In this context, it is really important the study and development of different joining technologies that would make possible the bonding of dissimilar materials.

One of the most important joining processes, specially used in the automotive industry, is Resistance Spot Welding (RSW). However, this process presents certain difficulties and disadvantages when it is used to weld low melting points materials, such as aluminum or magnesium alloys. These problems include low working time of the
welding electrodes, high energy consumption, the use of consumables and the level of defects introduced to the joint. Looking for a way to avoid these problems, in 2003 Mazda Motor Corporation has developed a new solid state joining process called Friction Stir Spot Welding (FSSW). This process is a type of solid state joining that is derived from the one that The Welding Institute (TWI) developed in 1991, called Friction Stir Welding (FSW). Friction stir welding has a solid-state nature and therefore exhibits certain advantages over traditional fusion welding methods: avoid solidification related problems and due its low heat input can effectively inhibit intermetallic compound (IMC) layer formation, which makes it a promising solution for dissimilar material joining. Several studies have been carried out on FSW of aluminum alloy to steel sheets (Liu et al. (2014), Lazarevic et al. (2013), Haghshenas et al. (2014) and Coelho et. al (2012)).

In Fig. 1 is shown a variant of FSSW used for Al alloy-steel joints, where the welding tool never gets in contact with the lower steel sheet. Because of this, the welding tool can be fabricated with a common tool steel material, such as H13. If this type of welding process is properly applied, it is capable to produce dissimilar joints at low temperatures with low thermal cycles (Tran and Pan, (2010)).

Fig. 1. FSSW process for joining Aluminum with Galvanized steel (Tran and Pan, (2010)).

Several process parameters may play a critical role in determining joint integrity. These include, but are not limited to, tool geometry, tool rotational speed, holding time and tool penetration depth (Francesco and Svoboda (2013)). It has been previously suggested that these mentioned aspects have an important effect on weldability and joint properties, particularly the TPD and tool geometry (Mishra and Mahoney (2007)). Properly welded joints, defects free, will have high shear strength and will fail by “tear-out” of a large section of the joined interface. Conversely, poorly welded joints will fail in a brittle manner at the weld nugget (Tran et al. (2009)).

The application of coated steels (i.e. Zn coated) in the automotive body industries shows an increasing trend in the last two decades thanks to enhanced vehicle structure durability. It has been proposed that Zn acts as a “lubricant” during friction stir lap welding by diffusing into the aluminum sheet and suppressing the melting point of the stirred material so that larger areas can be bonded (Elrefaey et al. (2005)). In a further study, Miyagawa et al. (2008) noted that the FSW Al joints with Zn coated steel exhibited considerably higher fracture load as compared with those involving uncoated steel.

In addition to coating type, another critical factor in the joint strength in dissimilar aluminum/steel FSW joining is the depth of the probe tip into the steel surface. Elrefaey et al. (2005) reported that the performance of dissimilar aluminum/steel joint depends heavily on the penetration depth of the pin tool into the surface of the lower steel sheet. All these studies noted that when the tool slightly runs into the steel surface, the joint strength is greater than that when the probe tip does not reach the steel surface. However, this also requires tool materials which are much higher strength than steel, such as carbide or other ceramics like PCBN. Imposing some pin penetration into the steel will promote the joint strength of Al/St friction stir lap welds, however, it is possible to use much lower cost tool material and still promote bonding via diffusion without penetrating the tool into the lower sheet of steel (Haghshenas et al. (2014)).

In the last ten years, a lot of work has been done on FSW, trying to figure out the relationship between the main process parameters and the microstructure of the welded joint of aluminum alloys. In spite of this, FSSW of aluminum steel dissimilar joints is still a great challenge and requires more studies.
2. Experimental Procedure

2.1. FSSW welded joints

Friction Stir Spot welds were done on dissimilar lap joints made of AA6063-T6 and a LCG-S of 2 mm and 0.7 mm thick, respectively. In this paper, the aluminum sheet was always placed on top of the lap joint. Every single welded spot was done with a penetration rate of 19 mm/min and a dwell time of 1 s. Three different welding tools were fabricated, with three different pins length, all of them smoothly tapered. The L tool had a pin length of 1.5 mm and its diameter at the end was 3.5 mm; meanwhile the S and C tool had pins whose length were 1 and 0.65 mm and their diameter at the end were 3.7 and 3.8 mm, respectively. Every single tool was made of H13 tool steel with a concave shoulder of 11.7 mm.

Table 1. Welding parameters and samples identification.

| Sample | Sample Type | Welding Tool | TPD (mm) |
|--------|-------------|--------------|----------|
| 3-L    | Ps, Ms      | L            | 0.3      |
| 4-L    | Ps, Ms, Cs  | L            | 0.4      |
| 4.5-L  | Ps          | L            | 0.45     |
| 5-L    | Ps, Ms, Cs  | L            | 0.5      |
| 6-L    | Ps, Cs      | L            | 0.6      |
| 8-S    | Ps, Ms, Cs  | S            | 0.8      |
| 9-S    | Ps, Cs      | S            | 0.9      |
| 10-S   | Ps, Ms, Cs  | S            | 1        |
| 11-S   | Ps, Ms, Cs  | S            | 1.1      |
| 13-S   | Ps, Ms, Cs  | S            | 1.3      |
| 12-C   | Ps, Ms, Cs  | C            | 1.2      |
| 15-C   | Ps, Ms, Cs  | C            | 1.5      |
| 16-C   | Ps, Ms, Cs  | C            | 1.6      |
| 17-C   | Ps, Ms, Cs  | C            | 1.7      |
| 18-C   | Ps, Ms, Cs  | C            | 1.8      |

The TPD was varied from 0.3 to 1.8 mm. Table 1 lists the analysed welding conditions and the identification used for each sample. The samples names include the TPD and the welding tool used.

Fig. 2. (a) Clamping device; (b) Ps sample; (c) Cs sample.

Fig. 2(a) shows the clamping device used during the welding process. For each welding condition three types of samples were welded. One of them (Ps) was used for the Peel Tests as it can be appreciated in Fig. 2(b). The second
type of sample (Cs sample in Fig. 2(c)) was used for Cross Tension Tests. Finally, the third type of sample (Ms) was welded for macro/microstructural and dimensional analysis, as well as for the microhardness profile.

2.2. Macro and Microstructural Characterization

The specimens for metallographic examination were sectioned to the required sizes comprising the SZ, TMAZ, HAZ and BM zones (Mishra and Mahoney (2007)). After metallographic preparation the specimens were etched with the Keller’s reagent to reveal their macrostructures. Metallographic observations were done using LM. The interface structure and element distribution in the weld were analyzed by SEM equipped with an EDS analysis system. On the other hand, a dimensional analysis was performed in order to establish the main characteristics of the welded spots. In Fig. 3, it may be seen the dimensions measured on every welded spot. The TPD is the distance between the surface of the top sheet and the lower point of the surface left by the tools shoulder. The distance between the surface left by the pin and the free surface of the bottom sheet is called P, meanwhile the effective bonding length is called A. Finally, the distance between the lower point of the surface left by the shoulder and the joint interface is named IH.

2.3. Mechanical Properties

Microhardness profiles were done approximately 60 days after welding on the M sample at 200 µm from the interface, on the aluminum plate, with a load of 0.3 Kg and a dwell time of 10 s, according to ASTM E384 standard. The CT and PT tests were performed using an Instron TT10-DM universal testing machine at a constant cross-head speed of 1 mm/min. Load and displacement were recorded, obtaining the load-displacement curves. Two samples of each condition were tested. Finally, fracture surfaces were observed by LM.

3. Results and Discussion

3.1. Base Materials

In table 2 the chemical composition of the base materials used in this work is shown. It can be seen that the AA6063 is an Al-Mg-Si alloy with some amounts of Cu and Fe, heat treatable, used in a T6 condition.

Table 2. Chemical composition of the materials used.

| Material | Si  | Fe  | Cu  | Mn  | Mg  | Zn  | Al  | C  |
|----------|-----|-----|-----|-----|-----|-----|-----|----|
| AA6063   | 0.41| 0.85| 0.81| 0.11| 0.41| 0.52| Bal.| ---|
| LCS-G    | 0.02| Bal.| --- | 0.50| --- | --- | --- | 0.02|

The microhardness of the AA6063 was 90 HV. On the other hand, the galvanized steel presented low amounts of C and Mn, as common deep drawing steel, having a microhardness of 115 HV.

3.2. Macro and Microstructural Characterization

Figs. 4(a) to (f) show several friction stir spot welds achieved with different TPD and welding tools. An excellent appearance can be observed in the welded spots for all the welding conditions studied. Welding parameters, such as
the TPD, affect the heat generation and the material flow. Because of this effect, the material of the top surface is squeezed out and accumulated along the outer circumference of the shoulder indentation. It can be observed that the material which flows out of the spot increases with the TPD.

![Fig. 4. Surface appearance of the welded spots. (a) 3-L; (b) 6-L; (c) 8-S; (d) 11-S; (e) 11-C; (f) 14-C.](image)

Macrographic observations along the symmetry plane of the spot welds cross sections, obtained with different welding conditions, are shown in Figs. 5(a) to (c). The indentation profile reveals the general shape of the probe and the concave shoulder of the welding tool, showing no defects for all the conditions studied. It can be also seen that the welding tool never reaches the galvanized steel plate.

Due to high pressure and large plastic deformation, the upper and lower sheets are compressed together to form and effective joint in the vicinity of the probe (Tran et al. (2009)).

It can be appreciated in Figs. 5(a) to (c) that the TPD could be increased, when welding with shorter tools, in order to achieve the same remaining thickness P. It may be observed also, under the tools profile into the aluminum plate, dark zones which increase in density when welding with shorter pins (Fig. 5(c)). This is evidence that the steel sheet coating material (Zn) is displaced into the stir zone, since etching revealed fine bands of material directed upwards from the center of the sheet interface. These zones are related to the dispersion/diffusion of Zn particles thanks to the termomechanical action of the welding tool onto the joint interface in agreement with previous reports (Miyagawa (2008)).

![Fig. 5. Macrographic appearance of the welded joints. (a) 6-L; (b) 8-S; (c) 15-C.](image)

Previous works have shown that the most part of the heat input is produced in the contact zone between the top plate and the shoulder of the welding tool (Mishra and Mahoney (2007)). Therefore, as much as the shoulder gets close to the interface, higher will be its action on the interface, achieving a better metallurgical bonding. It is well known that the main dimensional characteristics of the welded spots are established by the process parameters and will define the resistant section of the spot (Francesco and Svoboda (2013)). In Fig. 6 it can be observed the evolution of IH with the remaining thickness P (which is inversely proportional to the TPD).

It can be appreciated in Fig. 6(a) that IH decreased when P diminsh (equivalent to TPD increasing). This effect has consistency with what it was shown in Figs. 5(a) to (c). It must be pointed out that, for the same value of P, IH decreases when welding with tools of shorter pins. Moreover, it can be observed a lineal tendency of IH with the TPD. In figure 6b it is shown variation of A with the remaining thickness P.
It may be clearly noted that A increases with the TPD showing the thermomechanical effect that the shoulder makes onto the interface. This effect goes along with previous reports of Mishra and Mahoney (2007). Moreover, Fig. 6(b) shows that when welding with tools with shorter pin, the indentation can be increased (without reaching the steel sheet), increasing the effective joint length. Furthermore, taking into account Figs. 6 (a) and (b), IH and A are the magnitudes that must be minimized and maximized, respectively, in order to improve the joint strength.

Related to interface, all of them were continuous and defects free, as it may be seen in Figs. 7(a) and (b), where can be observed that the aluminum sheet is forged onto the galvanized steel sheet with no evidences of plastic deformation in the steel sheet. According to Figs. 6(a) and (b), 7(a) and (b), it can be concluded that, for the same P value, welding with tools of shorter pin improves the forging and stirring of the aluminum onto the steel because of the increased thermomechanical effect of the shoulder onto the interface.

Fig. 7(a) shows that Zn particles were dispersed into the aluminum plate. It was also observed that reducing IH increases the Zn density below the tool profile into the aluminum plate. This effect is closely related to the improvement of the thermomechanical effect mentioned. Fig. 7(c) shows the EDS spectrum achieved next to the joint interface onto the aluminum plate. It can be noted that Zn particles are present in the aluminum plate because of the tools action. Moreover, Figs. 8(a) to (d) indicate that a significant amount of inter-diffusion of Al and Fe occurred between the sheets. This clearly suggests that the heat and pressure generated by the FSSW process are sufficient to promote diffusion bonding between the aluminum and steel sheets.

![Fig. 6. (a) IH vs. P. (b) A vs.P.](image)

![Fig. 7. Aluminum – LCG-S interface. (a) LM; (b) SEM; (c) EDS.](image)
It has been previously shown that when friction stir spot welds are made in Al/St lap joints, the presence of lower melting point coating on the steel appears to promote higher joint strengths and increased bonded areas (Elrefaey et al. (2005) and Miyawa et al. (2008)). A key feature of the coating is that the formation of an iron oxide is inhibited, and thus mutual inter-diffusion is promoted which may also facilitate the formation of IMC (i.e. AlFe and Fe$_2$Al$_5$) between the sheets (Haghshenas et al. 2014 and Elrefaey et al. (2005)).

3.3. Mechanical Properties

Microhardness profiles can be observed in Fig. 9. Each profile corresponds to the different welding tools used and it is representative of what happens for every single condition studied.

There are no significant differences between measured microhardness profiles. It can be seen that the microhardness decreases from the BM (90 HV) up to the HAZ, where the minimum microhardness is reached (45 HV). This is due in the HAZ of heat treatable aluminum alloys precipitation and partial dissolution may take place because of the temperature that this zone reaches. Inside the TMAZ, the plastic deformation is the responsible for the little increased in hardness values (Mishra and Mahoney (2007)). It can be seen that there are several local maximum (up to 100 HV) related to the Zn rich zones, in coincidence with what was shown in Figs. 5(a) to (c). Finally, in the SZ, the microhardness is higher than the minimum measured in the HAZ, but lower than the BM. In the SZ dynamic recrystallization may take place related to high levels of plastic deformation and the high temperatures achieved. This effect produces high reduction of the grains size which increases microhardness in that zone (Mishra and Mahoney (2007)).

Fig. 10(a) shows the results achieved in PT tests for different remaining thickness P and welding tools. It is clearly noted that the Fl increases when welding with tools of shorter pin. This would be related to the improvement of the theromomechanical effect onto the interface, previously mentioned. For each tool the Fl increases with the TPD until a limit is reached. This behavior shows the relationship that exists between the increase of A and the reduction of IH when the TPD goes up. When the ratio between A and IH is optimum, the fracture load is maximized (4700 N – Tool C). The reduction of the Fl after the maximum is reached is a consequence of the great
reduction of IH. The same behavior is appreciated for CT tests (Fig. 10(b)). However, the Fls achieved in CT tests are lower than those achieved in PT tests. In both cases, the Fls were maximized when welding with the C tool and were higher than the ones previously reported in the literature (Lazarevic et al. (2013), Tran et al. (2010) and Bozzi et al. (2010)). The C tool has the shorter pin and because of this, the shoulder is closer to the interface (IH is reduced). Figure 11 shows the influence of IH on the Fl for PT, showing that reducing the distance between the shoulder and the interface the fracture load is improved. This effect is appreciated for all the tools used in this work.

Three types of fracture modes have been observed in PT and in CT tests. For low levels of TPD, an interfacial fracture with low fracture loads was achieved, as it can be seen in Fig. 12(a). For the optimum value of indentation, the fracture mode is mixed (Fig. 12(b)). This fracture mode is related to the optimization of A and IH, achieving maximum fracture loads. Finally, for the highest levels of indentation, the fracture mode is circumferential (Fig. 12(c)) because of the great reduction of P. This fracture mode presented lower fracture loads.
4. Conclusions

FSSW on dissimilar aluminum-galvanized steels joints were produced with different TPD and welding tools. The aluminum sheet is forged onto the galvanized steel sheet with no evidences of gross plastic deformation in the steel sheet. It was appreciated that welding with tools of shorter pins improves the forging and stirring of the aluminum onto the steel because of the increase of thermomechanical effect of the shoulder onto the joint interface. Zn particles were dispersed into the aluminum plate and a significant amount of inter-diffusion of Al and Fe occurred between the welded sheets. The heat and pressure generated by the FSSW process are enough to promote diffusion bonding between aluminum and steel sheets. The effective bonding length (A) has increased when welding with tools of shorter pin and when the TPD is increased. In that sense, the reduction of IH, has shown the increase of the thermomechanical effect of the welding tool. The highest values of Fl in PT (4700 N) and CT (280 N) tests were achieved with the C tool. When IH is high (low TPD), the fracture is interfacial, with low fracture load. When IH is reduced, the fracture mode is mixed, corresponding to highest Fl. Finally, when IH is highly reduced, the fracture mode changed to circumferential with lower Fl. An optimum balance between A and IH improves the mechanical properties. The microhardness profiles showed a reduction of this property from the BM until the HAZ, where minimum values are reached. Microhardness values increased in the Zn rich zones and in the SZ.

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