Effect of Process Parameters on Microstructure and Mechanical Behaviors of Friction Stir Linear Welded Aluminum to Magnesium

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Abstract

The microstructure and lap-shear behaviors of friction stir linear welded wrought Al alloy AA6022-T4 to cast Mg alloy AM60B joints were examined. A process window was developed to initially identify the potential process conditions. Multitudes of welds were produced by varying the tool rotation rate and tool traverse speed. Welds produced at 1500 revolutions per minute (rpm) tool rotation rate and either 50 mm/min or 75 mm/min tool traverse speed displayed the highest quasi-static failure load of ~3.3 kN per 30 mm wide lap-shear specimens. Analysis of cross sections of untested coupons indicated that the welds made at these optimum welding parameters had negligible microvoids and displayed a favorable weld geometry for the cold lap and hook features at the faying surface, compared to welds produced using other process parameters. Cross sections of the tested coupons indicated that the dominant crack initiated on the advancing side and progressed through the weld nugget, which consists of intermetallic

compounds (IMC). This study demonstrates the feasibility of welding wrought Al and cast Mg alloy via friction stir linear welding with promising lap-shear strength results.

Keywords: friction stir welding; dissimilar materials; Intermetallic compounds; lap-shear failure load; failure mechanism

1. Introduction

Automotive industries around the globe are increasingly investigating the use of lightweight materials to maximize vehicle mass savings, thereby improving the fuel efficiency of passenger cars, trucks and other automobiles. Lightweight alloys of Mg and Al have found ever-increasing use in replacing the existing relatively heavy steel-based alloys. Utility of Mg alloys in the automotive industry is, however, hindered by the fact that greater use of these alloys requires joining to Al alloys or steel, and existing fusion welding techniques, most notably resistance spot welding, cannot be used to do so effectively [1–3]. The alternative that has emerged as a viable technique is friction stir welding (FSW).

Friction stir welding, as a solid-state joining technique, has demonstrated promising capability and high efficiency in joining lightweight materials such as Al alloys and Mg alloys. For the most part, however, the FSW process has been studied in joining similar alloys, Al to Al [4–7] or Mg to Mg [8–12]. At times, owing to design constraints, two or more different alloys may be used in combination. Therefore, to exploit the optimum physical and mechanical properties of Mg alloys, there is an ever-growing interest in being able to join these alloys to Al alloys.

The challenge of joining these dissimilar alloys lies in the formation of brittle intermetallic compounds (IMC) in the weld zone. Most of the previous research conducted in solid-state welding of dissimilar alloys have reported on the formation of IMC and the effect on weld strength [13–20]. Constitutional liquation has been observed to occur during the welding of Mg and Al alloys, and the IMC ($\text{Al}_{12}\text{Mg}_{17}$, Al_3Mg_2) were produced at the weld interface [13,15,19–26]. During FSW of Al to Mg, the temperature attained in the stir zone is far below the melting point of either material. However, liquation is likely to occur in the stir zone, where temperatures can reach up to 450 °C, which is the eutectic temperature for the Al-rich IMC and higher than that of Mg-rich IMC according to Al-Mg binary phase diagram. Upon cooling, the liquid formed in the stir zone solidifies into Al_3Mg_2 at the Al-rich side of the weld and $\text{Al}_{12}\text{Mg}_{17}$ at the Mg-rich side of the weld [24–27]. The formation of IMC has been shown to reduce the weld strength in both friction stir spot and friction stir linear welds (FSLW) of dissimilar alloys [13,15,22,24,26,27].

As in conventional FSW of similar alloys, the weld process conditions and tool design have been observed to significantly influence the weld strength of dissimilar material welds. Yamamoto et al. [15] observed that the tensile strength of friction stir butt welded AA5083 and AZ31B decreased as the thickness of IMC formed at the bonding interface of the two sheets increased. The thickness of IMC was influenced by the frictional heat input from the welding process; a higher heat input resulted in thicker IMC, thereby reducing the weld strength. A high tool rotation rate and low tool traverse speed introduced high frictional heat, favoring the formation of thicker IMC. However, low frictional heat with a low tool rotation rate and high tool traverse speed introduced weak bonding due to insufficient frictional heat. Firouzdor et al. [27] studied the effect of joint configuration and material stack-up position on weld strength

during FSLW of AA6061 and AZ31. The butt weld configuration yielded higher weld strength compared to that of welds made in lap-shear configuration. The weld strength in butt-welded Al to Mg increased when Mg was placed on the advancing side of the weld and Al on the retreating side. The position of Mg on the advancing side of the weld favored adequate frictional heat input, which was just sufficient to plastically deform the material and at the same time suppress the formation of IMC at the interface. In friction stir spot welding of Al to Mg, Rao et al. [28] observed that the lap-shear strength of the weld joints was greatly affected by tool rotation rate and tool shoulder plunge depth. With an increase in tool rotation rate for the same tool plunge depth, the weld bond width decreased due to localized material flow and reduced material mixing in the stir zone. This decrease in weld bond width resulted in a lower lap-shear failure load. On the other hand, a shallow tool shoulder plunge depth produced welds with lower lap-shear strength due to insufficient material mixture.

Though FSW has been studied extensively on similar alloys, there have been very limited studies on FSW of dissimilar alloys. The available research in open literature on FSW of Al to Mg is primarily based on the butt weld configuration [14–16,22,23,26,29] and only few studies exist on lap welded configuration [24,25,27]. Even though most of these studies have indicated the formation of IMC and the effect on the weld strength, these studies have not fully investigated the influence of welding process conditions, such as tool rotation rate and tool traverse speed on weld strength. As such, this study investigates the influence of welding parameters on weld strength and identifies the optimum welding condition to join these particular Al and Mg alloys in a lap configuration. A comprehensive discussion is presented to address the weld integrity and microstructure on strength of FSLW produced at the optimum welding condition.

2. Materials and Experiment

Sheets of wrought Al alloy AA6022-T4, having a thickness of 1.5 mm, was FSLW to cast plates of Mg alloy AM60B, with a thickness of 3.1 mm. The FSW tool used in this study, shown in Fig. 1(a), was made of standard tool steel (H13) and constituted a concave tool shoulder and a triangular pin. The geometrical features and dimensions of the FSW tool are listed in Table 1. The Al sheet was placed on top of the Mg sheet with an overlay of 30 mm and the sheets were clamped together using an in-house designed clamping fixture, as shown in Fig. 1(b). The weld tool was made to traverse from one end of the stacked sheets to the other end as shown in Fig. 2(a) and the bold arrows represents the tool traverse direction and tool rotation direction. The welds were produced in such a manner that the advancing side (AS) of the welds was on the free end of the coupon and retreating side (RS) was on the loading side of the coupon. Three test coupons were water jet cut from each FSLW sample; the final dimensions of these test coupons are as shown in Fig. 2(b).

One of the research objectives of this study was to identify the ideal welding parameters for optimal lap-shear weld strength. Multitudes of preliminary welds were made to identify the feasible welding process conditions and thus, a process window was developed, as shown in Fig. 3. To identify the feasible and unfeasible welds, only a visual surface inspection was performed without cross-sectional observation. In case of preliminary welds showing visible sign of channel defect, pores or excess surface flash, the welds were considered unfeasible. On the contrary, welds produced without any of above mentioned signs were considered feasible. A tool shoulder plunge depth of 0.2 mm and a 3° tool tilt angle was maintained for all welding conditions. Lap-shear testing was conducted at room temperature using an Instron screw-drive machine (Model

1123) with a constant crosshead speed of 2 mm/min. In addition, video imaging during the lap-shear test of each specimen was recorded.

Selected tested and untested coupons were cross-sectioned perpendicular to the weld direction and cold mounted in epoxy. These cross-sections were further mechanically ground and finely polished with 0.05 μm aluminum oxide surface finish. To reveal the grain structure and IMC, the AA6022 side of the joint was first etched with 20% NaOH solution (caustic etching) and then the AM60B side was etched using an acetic glycol solution (20 ml acetic acid, 1 ml HNO_3 , 20 ml H_2O , and 60 ml ethylene glycol). The macro and microstructures of the welds and failure modes were analyzed using optical microscopy. To analyze the IMC and its composition, specimens were examined under a Jeol 7000F scanning electron microscope (SEM) with energy-dispersive x-ray spectroscopy (EDX) capabilities.

3. Results and Discussion

Two major factors influence the weld strength in FSLW joints of dissimilar materials in a lap configuration: macro features such as the hook geometry and the effective sheet thickness, and micro features such as the IMC in the stir zone. During FSLW, the faying surface on the AS forms into a hook-like feature, which points upwards towards the top sheet and the RS forms a cold lap feature and may extend across the weld nugget towards the AS [30]. To understand the different orientations of AS and RS faying surfaces, a schematic is shown in Fig. 4. Configuration A has the RS on the loading side of the coupon, while in configuration B, the AS is on the loading side of the specimen. Previous studies on FSLW of similar alloys indicated a higher lap-shear strength when the RS was subjected to loading compared to the AS loading [7,30,31]. Yuan et al. [30] observed a high weld strength in FSLW of Mg AZ31 alloy when the

RS cold lap feature terminated far away from the AS hook, and weld strength decreased when the RS cold lap feature terminated very close to the AS hook. In this study, all test coupons were produced in accordance to configuration A, where the RS of the welds was under loading during lap-shear testing.

All welds in this study failed by interfacial shear failure through the weld nugget, indicating that the effective upper sheet thickness was not linked to the weld strength. Therefore, any possible influence will not be discussed. It has to be noted that, all the discussions in this paper are based on the observations made in multiple welds produced under different welding conditions. However, only a representative weld cross-section produced under each weld condition will be presented for discussion purposes. Also for brevity's sake, only the microstructure of the welds with the optimum weld performance will be discussed in-detail.

3.1. Lap-Shear Strength

Monotonic mechanical properties of the FSLW test coupons were determined using lap-shear testing. A set of five specimens were lap-shear tested for each welding condition. The average maximum lap-shear peak load and standard deviation are presented in Fig. 5. For welds produced at 1000 rpm, a maximum peak load of 3.2 kN was obtained for FSLW produced under 30 mm/min. The maximum lap-shear strength of the FSLW coupons decreases with the increase in the tool traverse speed, as seen in Fig. 5(a). For welds produced at 1500 rpm, the tool traverse speed shows negligible effect, with an average maximum peak load of ~3.3 kN, as seen in Fig. 5(b). For welds produced at 2000 rpm, the maximum lap-shear load increases with the increase in tool traverse speed from 30 mm/min to 50 mm/min and nominally decreases on further increase to 75 mm/min, as seen in Fig. 5(c).

3.2. Macro Features of the FSLW

Representative cross-sections of the untested coupons produced at 1000 rpm and at various tool traverse speeds is present in Fig. 6. For ease of comparison of the hooking and cold lap features, the outermost portions of the welded specimens were trimmed for all presented cross sections. It is generally accepted that a higher tool rotation rate [9,20,32–36] and lower tool traverse speed [7,10,12] introduces more frictional heat and results in greater plastic deformation of materials in the stir zone. As shown in Fig. 6(a), the RS cold lap feature for the weld produced at 1000 rpm and 30 mm/min terminates in the stir zone and does not continue across the weld nugget towards the AS hook. As the traverse speed increases, the amount of frictional heat generated decreases, resulting in insufficient material mixing and a small stir zone size. This is clearly observed in Fig. 6(b) for the weld produced at 50 mm/min, for which the RS cold lap feature terminates very close to the AS hook, subsequently decreasing the stir zone size, which results in reduced weld strength. With further increase in the tool traverse speed to 75 mm/min, the RS cold lap feature extended all the way through the weld nugget and fused with the AS hook, as seen in Fig. 6(c). This is a strong indication that at high tool traverse speeds, the amount of frictional heat generated is much lower, which results in insufficient material mixing and poor weld strength. The formation of microvoids at 30 mm/min tool traverse speed, on the other hand, is likely related to flash generation at the relatively higher heat input compared to 75 mm/min tool rotation rate [37].

Figure 7 shows representative cross-sections of the untested welds produced at 1500 rpm and various traverse speeds. In general, the welds produced at 1500 rpm showed superior and consistent weld strength for all three tool traverse speeds employed in this study. For welds produced at 30 mm/min (Fig. 7(a)), the RS cold lap feature terminated away from the AS hook in

the stir zone. With the increase in traverse speed, the cold lap feature on RS was more suppressed and terminated in the weld nugget away from the AS hook. Microvoids are prominent in the weld made at 30 mm/min, as observed in Fig. 7(a), and become negligible at 50 mm/min (Fig. 7(b)) and 75 mm/min (Fig. 7(c)). The AS hook in FSLW produced at 1500 rpm always terminated away from the weld nugget and curved outwards from the weld nugget. This geometrical feature may have also contributed to the superior weld strength.

Figure 8 presents representative cross-sections of the untested welds produced at 2000 rpm and various tool traverse speeds. The cross-section of the untested welds produced at 30 mm/min shows large cavities on the AS of the weld, as seen in Fig. 8(a). The low failure load for welds made at 30 mm/min is related to the formation of cavity along with geometry of the AS hook, which is curved towards the weld nugget. A high tool rotation rate and slow tool traverse speed results in excessive heat input resulting in formation of cavities as the deformed materials are excreted on the surface as flash [15,37,38]. Since all welds in this study failed through shear overload, the AS hook pointing inwards into the weld nugget facilitates the least resistance for crack propagation through the weld nugget. At 50 mm/min, the weld strength was observed to increase significantly. Cross-section of the untested weld in Fig. 8(b) indicates a structurally sound weld bond in the stir zone without any channel/cavity defects and the cold lap feature and hook geometry favor good weld strength. The cross-section of a weld produced at 75 mm/min, on the other hand, revealed large cavities on both AS and RS indicating abnormal stirring, as seen in Fig. 8(c). It has to be noted that, an increase in tool traverse speed would result in lower frictional heat which is supposed to produce welds with less or without voids. The large cavities in the weld made at 75 mm/min are likely formed because of insufficient material mixing which

might be introduced by abnormal stirring at a combination of high tool rotation rate and traverse speed [37].

Welds produced at 1500 rpm showed very consistent lap-shear strength, as opposed to the welds produced at 1000 rpm and 2000 rpm. As such, 1500 rpm was identified as the ideal tool rotation rate for the Mg and Al alloys used in this study. Between the two possibly optimal tool traverse speeds, 50 mm/min and 75 mm/min, the latter was chosen, as the overall welding time would be much shorter, a great advantage in a manufacturing environment. To further understand the effect of weld microstructure on lap-shear behavior, microstructural analysis was conducted on welds made at 1500 rpm and 75 mm/min.

3.3. Microstructure Analysis

The representative microstructure of an untested FSLW coupon produced at 1500 rpm and 75 mm/min is presented in Fig. 9. The hook and cold lap features, as well as the weld nugget in the stir zone, which contains IMC, can be observed in the cross section shown in Fig. 9(c). Two kinds of IMC were identified in the weld nugget based on EDX analysis: $\text{Al}_{12}\text{Mg}_{17}$ and Al_3Mg_2 . The detailed composition and structure of these IMC will be discussed later in this section. Magnified view of the cold lap feature on the RS of the weld reveals the formation of IMC close to the cold lap feature, as seen in Fig. 9(a). On the AS of the weld, adjacent to the AS hook, a dark region was observed on the Al sheet, as seen in Figs. 9(b) and 9(c). Chemical analysis of this area, using EDX, indicates a region rich in oxygen. Firouzdor et al. [24] reported similar observations in FSW of Al to Mg and indicated the possibility of the metal oxide present on the surfaces of Mg and Al sheets being mixed in during the welding process. During FSLW, the stirring action of the tool pin extrudes the material from the bottom Mg sheet into a hook

shape on the AS, as seen in Fig. 9(c). In the weld nugget, the IMC were observed to constitute two different layers: a light-colored layer closer to the top Al sheet and a darker-colored layer closer to the Mg sheet, as seen in Fig. 9(c). A sandwich-like structure of light- and dark-colored layers (IMC) close to Mg and Al sheet can be clearly seen in Figs. 9(d) and 9(e), respectively. EDX analysis of these layers indicates that the dark-colored region is primarily constituted of $\text{Al}_{12}\text{Mg}_{17}$ and the light-colored region is primarily constituted of Al_3Mg_2 .

The interlocking of distinct IMC, which resulted in superior weld strength reported in other FSW joints of Al to Mg [15,24,27], was not observed in the current study, as evident from Figs. 9(d) and 9(e). Rather, a mixed IMC phase in the weld nugget was observed. This mixed or dispersed phase of IMC acts as a bonding agent that holds the top Al sheet and bottom Mg sheet together. During FSLW, the tool pin completely penetrates the top Al sheet, while partially penetrating the bottom Mg sheet. The frictional heat generated during the welding process softens the top Al sheet and the bottom Mg sheet in the stir zone. This, along with the stirring action of the tool pin, pushes and mixes the plastically deformed Mg and Al sheet materials. Upon cooling, the Mg-rich IMC ($\text{Al}_{12}\text{Mg}_{17}$) is formed close to bottom Mg sheet and Al-rich IMC (Al_3Mg_2) is formed close to top Al sheet [15,21,24,26,28].

Figure 10 shows the representative formation of IMC along the faying surfaces in an untested FSLW specimen produced at 1500 rpm and 75 mm/min. Figure 10(a) presents the full cross-section of this typical FSLW with back rectangular boxes (Z1, Z2, Z3 and Z4) indicating different zones analyzed under SEM and EDX. Figures 10(b) and 10(c) show the distinctive thin layer observed along the faying surface on the RS of the weld in zones Z1 and Z2, respectively. Figures 10(d) and 10(e) display the distinctive thin layer observed on the AS of the weld in zones Z3 and Z4, respectively. EDX analysis of these thin layers indicates that they are composed of

sandwich layer of Al_3Mg_2 and $\text{Al}_{12}\text{Mg}_{17}$. Such thin layers of IMC were not observed on the faying surface beyond the width of the weld tool shoulder on AS and RS of the weld. Previous studies have indicated that if the two faying surfaces are held close to each other and under high temperature, diffusion can readily lead to the formation of the IMC [16,22]. During FSLW, the downward forging pressure applied by the tool shoulder, combined with the forces applied by the clamping fixture, results in diffusion of atoms along the faying surfaces at high temperatures, thus leading to forming of IMC as observed in this current study.

While, the formation of IMC in FSW of Al-to-Mg has been discussed in detail elsewhere [21,24,26,39], only the structural and chemical information of the IMC are discussed in this study. A magnified view of the weld nugget shows different zones of IMC, as seen in Fig. 11(a). The stirring action of the tool pin causes the softened Al and Mg to mix with each other, which upon cooling forms into Al_3Mg_2 and $\text{Al}_{12}\text{Mg}_{17}$, respectively. The clear distinction between the two phases of Mg-rich IMC was observed near the Mg sheet as shown in Fig. 11(b), where the space between the dotted line indicates bands of lamellar phase ($\text{Al}_{12}\text{Mg}_{17} + \text{Mg}$), which eventually transforms to primary $\text{Al}_{12}\text{Mg}_{17}$ as it progress towards the top Al sheet. As the Mg-rich mixture is introduced to the Al-rich mixture in the core of the weld nugget, more Al atoms diffuse into the mixture transforming into Al_3Mg_2 . This transformation appears to exhibit a smooth gradient, as no visible cracks are observed in Fig. 11(c). A higher magnified view of the individual IMC under SEM reveals the distinctive structure of the different phases of the IMC. The island and lamellar phases, as seen in Fig. 11(d), show the structure of the Mg-rich IMC $\text{Al}_{12}\text{Mg}_{17}$. Similar observations have been reported in other studies of FSW of Al-to-Mg alloys [13,21,24,39]. EDX analysis of the region R1, the island phase, and region R2, the lamellar phase, in Fig. 11(d) indicates that region R1 is constituted of primary $\text{Al}_{12}\text{Mg}_{17}$ and region R2 is

eutectic $\text{Al}_{12}\text{Mg}_{17} + \text{Mg}$. Similarly, the structure of the Al-rich IMC Al_3Mg_2 is shown in Fig. 11(e). Based on the EDX analysis, region R3 is mainly constituted of primary Al_3Mg_2 . The exact chemical compositions of the regions (R1, R2 and R3) obtained using EDX are shown in Table 2.

Figure 12(a) shows a macro image of the same weld nugget as in Fig. 11, for which the rectangular box indicates the region of EDX mapping. A small portion of the IMC in the weld nugget on the RS of the weld was color mapped to show the clear distinction of IMC. The SEM image of the IMC shown in Fig. 12(b) also exhibits the difference in texture of the IMC. The colored EDX map in Fig. 12(c) highlights the different chemical composition; the green indicates the native Al alloy, the red indicates the native Mg alloy and the mixture of red and green indicates the IMC or possible solid solution. A sandwich-type structure of IMC can be observed between the top Al sheet and the bottom Mg sheet on the RS. Within the structure, a thin layer of Mg-rich IMC was formed adjacent to the Al sheet, followed by thick layers of Al-rich and then Mg-rich IMC towards the bottom Mg sheet. Contradictory to what has been generally acknowledged as well as the current IMC formation on the AS side that Al-rich IMC and Mg-rich IMC are most frequently observed close to the Al sheet and Mg sheet respectively, the formation of Mg-rich IMC adjacent to the Al sheet on the RS was due to transportation and deposition of lower Mg sheet into the stir zone from the RS during FSW with current triangular pin tool.

3.4. Failure Mechanism

Figure 13(a) presents the lap-shear test data of a representative FSWL coupon. To understand the failure mechanisms in FSLW of dissimilar alloys, lap-shear testing of multiple coupons was video recorded. Since the failure mechanism of all tested coupons exhibited

interfacial shear failure through the weld nugget, only a representative test coupon is presented. Image stills captured during lap-shear testing are presented in Fig. 13(b). The bold white arrows on the opposite ends of the weld coupons indicate the loading direction during testing. Two kinds of cracks were observed: the dominant crack (DC), which caused the failure, and the secondary crack (SC), which did not cause the ultimate failure. In stage 1, during initial loading of the joint, a secondary crack propagated through the faying surface on the RS and terminated very close to the weld nugget. In stage 2, with the gradual increase in load, a dominant crack propagated through the faying surface on the AS and terminated at the base of the AS hook. As such, it is clearly seen that the entire load (~ 2800 N) at this stage is carried by the weld nugget. In stage 3, as the load continued to increase the dominant crack propagated along the curved AS hook and through the weld nugget comprising the IMC. Once the DC propagated through the IMC, the weld failed, as shown in Fig. 13(b). In addition, it was observed that the ‘shepherd handle’ shaped RS cold lap feature clinched the two faying surface even after the failure of the weld, as seen in stage 4 (Fig. 13(b)).

Figure 14 shows the cross-section of the above video-recorded FSLW test coupon. It can be clearly seen that the DC propagated through the IMC and a portion of IMC was still adhered to the top Al sheet. This observed fracture seem reasonable since the IMC are obviously brittle in nature and facilitate easy crack propagation [15,28,39]. Hence, once the crack begins to propagate through the IMC, the weld nugget fails due to shear overload. Thus, it appears that the weld nugget displayed in Figs. 13 and 14, comprising primarily of IMC, has a load-bearing capacity of ~ 3340 N. On further increasing the load, the brittle IMC fail due to interfacial shear failure.

4. Conclusions

This study establishes that wrought Al and cast Mg alloys can be joined successfully by friction stir linear welding, with the proper choice of welding parameters. Based on the extensive results of this study, the following conclusions were reached:

- 1) Both tool rotation rate and tool traverse speed greatly influence the weld integrity and lap-shear strength of FSLW. Low tool rotation rate and high tool traverse speed lead to insufficient frictional heat, thus resulting in improper material mixing. On the other hand, high tool rotation rate and very low tool traverse speed result in high frictional heat, which leads to the formation of excess flash and cavities. Both of these conditions resulted in inferior performance of FSLW under lap-shear testing.
- 2) FSLW produced at 1500 rpm tool rotation rate and 50 mm/min or 75 mm/min tool traverse speed exhibited higher weld strength compared to other welding parameter combinations. An average lap-shear failure load of ~3.3 kN was achieved for 30 mm wide specimens.
- 3) Formation of IMC $\text{Al}_{12}\text{Mg}_{17}$ and Al_2Mg_3 at the interface of the overlapped sheets is known to be unavoidable. However, this study demonstrates that the FSLW welding parameters can be successfully optimized so that the IMC is effectively dispersed in the stir zone by the current triangular pin tool. The formation of mixed and dispersed IMC in the stir zone, along with favorable geometrical weld features such as the hook and cold lap feature, result in FSLW joints that exhibit promising lap-shear strength between wrought Al and cast Mg alloys.

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Figure Captions

Fig. 1. (a) FSW tool profile; (b) the clamping fixture.

Fig. 2. Representation of (a) the FSLW methodology, samples and geometrical dimensions of the welding condition; (b) geometrical dimensions of the FSLW test coupons.

Fig. 3. Plot showing the process window developed based on the welds produced initially.

Fig. 4. Schematic of retreating side (RS) and advancing side (AS) loading in FSLW in lap-shear configuration.

Fig. 5. Lap-shear test data for welds produced at different tool rotation rates (a) 1000 rpm; (b) 1500 rpm; (c) 2000 rpm.

Fig. 6. Cross sections of the untested welds produced at 1000 rpm and (a) 30 mm/min; (b) 50 mm/min; (c) 75 mm/min.

Fig. 7. Cross sections of the untested welds produced at 1500 rpm and (a) 30 mm/min; (b) 50 mm/min; (c) 75 mm/min.

Fig. 8. Cross sections of the untested welds produced at 2000 rpm and (a) 30 mm/min; (b) 50 mm/min; (c) 75 mm/min.

Fig. 9. Cross section and microstructures of an untested and etched weld produced at 1500 rpm and 75 mm/min: (a) microstructure of cold lap feature on the RS; (b) microstructure of hook region on the AS; (c) cross section of the weld showing the various geometrical features; (d) microstructure of bottom of the weld nugget; (e) microstructure of the interface between the Al sheet and the IMC in the nugget.

Fig. 10. Macrograph and SEM images of the IMC on the faying surface in an untested weld produced at 1500 rpm and 75 mm/min: (a) the full cross-section indicating regions of interest; (b) SEM of region Z1 on the RS; (c) SEM of region Z2 on the RS; (d) SEM of region Z3 on the AS; and (e) SEM of region Z4 on the AS of the weld.

Fig. 11. Macrograph and SEM images of the IMC for the untested weld in Fig. 9: (a) magnified view of the weld nugget indicating the various IMC regions; (b) SEM of the region rich in $\text{Al}_{12}\text{Mg}_{17}$; (c) SEM showing transition of Mg-rich $\text{Al}_{12}\text{Mg}_{17}$ to Al-rich Al_3Mg_2 ; (d) magnified view of the Mg-rich IMC; (e) magnified view of the Al-rich IMC.

Fig. 12. EDX chemical mapping of the weld nugget in Fig. 9 and 11 (a) macrograph of the weld nugget; (b) SEM image of the IMC; (c) colored layer map of the IMC region indicating the local composition variations.

Fig. 13. (a) Lap-shear test plot of a representative FLSW test coupon with square boxes indicating the various stages of interest during fracture; (b) screen shots from the video recorded during testing, showing different stages of fracture and crack growth.

Fig. 14. Cross section of the representative FSLW test coupon that was video recorded.

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Tables

Table 1: The FSLW tool material and geometric features.

Tool material	H13 Tool steel	
Tool profile	Shoulder shape	Concave
	Shoulder diameter	12 mm
	Pin shape	Triangular
	Pin diameter	Tri. = 5.4 mm (eq.)
	Pin length	2.4 mm

Table 2: Composition (wt. %), measured using EDX, at various locations in the weld stir zone.

Region	Phase	Mg (wt. %)	Al (wt. %)	O (wt. %)	Total
R1	Primary $\text{Al}_{12}\text{Mg}_{17}$	59.7	38.8	1.5	100.0
R2	$\text{Al}_{12}\text{Mg}_{17}$ + Mg eutectic	64.1	33.2	2.7	100.0
R3	Primary Al_3Mg_2	39.9	57.2	2.9	100.0