Influence of Refill Friction Stir Spot Welding Technique on the Mechanical Properties and Microstructure of Aluminum AA5052 and AA6061-T3

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Abstract: This paper presents the effects of using the refill friction stir spot welding (RFSSW) technique on the mechanical properties and microstructure of aluminum AA5052 and AA6061-T3. Specimens were first prepared from AA5052 sheet of thickness 2 mm and AA6061-T3 of 1.6 mm, for chemical analysis and mechanical tests. Workpieces were then stir spot welded by RFSSW at four rotational speeds (2000, 2500, 3000 and 4000 rpm) using two tool pin diameters (5 and 7 mm) to carry out the tensile shear tests. Microhardness testing was conducted at the best conditions along the cross-section of the welded specimens, as well as microstructure examination. The results of the tensile shear tests manifested that, for AA5052 and AA6061-T3 at the tool rotational speeds 2000 rpm and 3000 rpm, respectively, using a tool pin of 7 mm the ultimate tensile shear force was slightly higher than at other speeds in both diameters of tool pin (5 and 7 mm). However, the microhardness results displayed a W-shape at the best conditions. Finally, the microstructure inspection revealed the morphology of the major zones of the weld joint.

Keywords: RFSSW, AA5052, AA6061-T3, Tensile shear force, Microhardness, Microstructure

1. Introduction
In the automotive industry, the trend is toward the use of lightweight alloys as a replacement for the conventional iron-based alloys. The usage of aluminum alloys for auto-body plates leads to an important shrinkage in the vehicle’s body weight, and enhanced progress, fuel economy and performance [1]. Oguz Tuncel et al. (2016) [2], studied the effects of the welding parameters, i.e. rotational speed, plunge depth, feed rate and dwell time, and the effect of the mechanical performances of friction stir spot welding for AA6082-T6 sheets. The plastic deformation of the refill friction stir spot welding specimens during tensile tests was studied by P. Lacki and A. Derlat Ka, (2015) [3], whereby 2 mm of AA6061-T6 sheets were welded at different spot weld arrangements. The tensile tests were performed via an optical deformation measurement system, to find the plastic deformation field on the sample surface. Mohsin N. Hamzah et al. (2017) [4], investigated the mechanical behavior of the friction stir spot welded (FSSW) joints in tensile shear tests and microhardness, and microstructure for AA6061-T6 sheets of 1.6 mm thickness. In their work, FSSW was carried out at different pin profiles (taper, cylindrical, and triangular) and tool rotational speeds, (800, 1000, 1200 and 1400 rpm).
Sergio T. Amancio-Filho et al. (2011) [5] studied the microstructure and mechanical behavior of 2024 aluminum alloy friction spot welds. They used the AA2024-T3 for the welding procedure. S. Venukumar et al. (2013) [6], determined the mechanical characteristics and microstructure of the welded pure aluminum, they used a technique that was developed to refill the probe hole using an additional filler plate called “refill friction stir spot welding” (RFSSW). Four rotational tool speed values were used (900, 1120, 1400 and 1800 rpm). Identification of the mechanical characteristics and microstructure of traditional and RFSS welds in AA 6061-T6 employing filler plate were investigated by S. Venukumar et al. (2013) [7]. FSSW with refilling by ‘friction forming process’ (FSSW-FFP) was modified adequately by use of a filler plate. Both of these new refilling techniques and the traditional (FSSW) procedure were utilized for welding AA6061-T6 lap shear samples, and the comparison of the outputs was conducted.

The effect of welding parameters on the microstructure and mechanical properties of the friction stir spot welding for AA5052 was studied by Zhang et al. (2011) [8]. Their research focused on two types of FSSW, namely normal FSSW and walking FSSW, applied to join AA5052-H112 plates, and then the influence of the rotational speed and dwell time on the microstructure and mechanical properties was discussed. An examination of friction spot welding in AA6181-T4 was conducted by Parra et al. (2011) [9], they investigated the application of refill friction spot welding for spot joining AA6181-T4. Different welding times and rotational speeds were used with the objective of finding those best suited to the production of high-quality joints in terms of mechanical performance and microstructure. Changing the mechanical properties during friction stir spot welding was examined by Abhijit et al. (2014) [10]. Finally, Kadhim K. Resan et al. (2018) [11], explored the effects of temperature on the fatigue strength and life of friction stir welding joints for aluminum alloy.

The aim of this work is to investigate the influence of the refill friction stir spot welding (RFSSW) technique on the mechanical properties and microstructure of AA5052 and AA6061-T3.

2. Materials and Methods

Sheets of aluminum alloy with thicknesses of 2 mm) for AA5052 and 1.6 mm for AA6061-T6 were used in this work. The base material was chemically analyzed per the Central Organization for Standardization and Quality Control by spectrometer apparatus, the results are given in Table 1 and Table 2 according to [12]. The mechanical properties were defined by tensile testing of the sample according to the ASTM standard [13]. To ensure compliance, the tensile test was carried out in the University of Technology –Mechanical Engineering Department, to specify the mechanical properties by Tinius Olsen H50KT apparatus. The mechanical properties of aluminum alloys AA5052 and AA6061-T6 are given in Table 3. The tensile specimen geometry was fabricated by a CNC milling machine according to standard [14], as shown in the Figure 1.

| Percentage Composition | Si% | Fe% | Cu% | Mn% | Mg% | Cr% | Zn% | Ti% | Al% |
|------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Standard [12]          | Max | Max | Max | Max | 2.2-2.8 | 0.15-0.35 | Max | 0.10 | Remainder |
|                        | 0.25 | 0.40 | 0.10 | 0.10 | | | | | |
Table 2: Standard and actual chemical compositions of AA6061-T6 aluminum alloy

| Percentage Composition | Si% | Fe% | Cu% | Mn% | Mg% | Cr% | Zn% | Ti% | Al% |
|------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Standard [12]          | 0.4-0.8 | <0.7 | 0.15-0.4 | <0.15 | 0.8-1.2 | <0.25 | <0.15 | 0.04-0.35 | Remainder |
| Actual                 | 0.717 | 0.433 | 0.164 | 0.104 | 0.871 | 0.0242 | 0.0579 | 0.187 | Remainder |

Table 3: Standard and actual mechanical properties of AA5052 and AA6061-T6

| Al Alloys | Yield Stress (MPa) | Ultimate Stress (MPa) |
|-----------|--------------------|-----------------------|
| AA5052    |                    |                       |
| Standard [13] | 90                  | 195                   |
| Actual    | 156                | 206                   |
| AA6061-T6 |                    |                       |
| Standard [13] | 276                 | 310                   |
| Actual    | 310                | 345                   |

The workpiece dimensions are 30 mm, 30 mm and 100 mm for width, overlapping length, and length, respectively, as shown in Figure 2. Four different rotational speeds for the spinning tool, namely 2000, 2500, 3000 and 4000 rpm, were selected, and each test was repeated, being completed three times at each rotational speed for all welding processes. The RFSSW tools were fabricated from tool steel X12M. The tools’ geometry and specifications are shown in Table 4 and Figure 3. The macrostructures of the welded specimens are illustrated in Figure 4, for refill friction stir spot welding (RFSSW).

Figure 1: The tensile specimen geometry according to standard (E 8M–00b) [14]
Table 4: Specifications of (RFSSW) tools used in welding experiments

| Tool No. | Type of process | Pin Shape and Dimensions |
|----------|-----------------|--------------------------|
| Tool 1   | RFSSW           | Cylindrical | 5 mm diameter | 6 mm | 18 mm |
| Tool 2   | RFSSW           | Cylindrical | 7 mm diameter | 6 mm |       |
| Tool 3   | Flat with curve 3 degrees (Pinless) | Flat with curve 3 degrees (Pinless) | Flat with curve 3 degrees (Pinless) | Flat with curve 3 degrees (Pinless) | Flat with curve 3 degrees (Pinless) |

Extrusion and refilling are the main steps of the RFSSW technique. The initial stage depends on inserting a spinning tool by force through a workpiece of aluminum sheet. The friction generates heat at the contact area between the tool and workpiece, and this softens, deforms and displaces the sheet material and makes in the lower plate a bushing projection that leaves at the rear a probe hole in the upper plate, as depicted in Figure 5. Refilling is the second step of RFSSW technique, and operates by taking back the pin that was extruded in the first step and plunging it by the pinless tool, as shown in Figure 6.
A mold was fabricated from a rectangular solid bar steel (30 mm x 20 mm) of 200 mm in length. In the middle length, a hole was drilled to be a punching mold, two molds were fabricated for each tool diameter (5 mm and 7 mm). At 15 mm from each side of the specimen, a stud of diameter 6 mm was fixed, to be a guide for keeping the lap joint distance at a constant 30 mm for all welding specimens, as shown in Figure 7. The mold was designed to be changeable and similar when using the tools (5 mm and 7 mm). Since too many of specimens are required to be welded in this mold, so the simplification in welding process (set up and release of the specimen) was taken into account. A holder was fabricated from steel plate with thickness 1 mm, and deformed to mimic a spring action with two open slots for quick release of the specimen. Also, a butterfly nut was used instead of a hexagonal common nut, so that it could be tied by hand. After the extrusion step of RFSSW, the extruded pin was collected by a simple collector that was placed below the mold to deliver the extruded pin, which will be used again as a filler material in the refill processes, as shown in Figure 8.
3. Results and Discussions

3.1 Tensile shear force

The ultimate tensile shear test was conducted on AA5052 and AA6061-T6 at four speeds and two tools with different pin diameters (5 mm and 7 mm). This test was achieved for RFSSW. The obtained results of the ultimate tensile shear test are presented in Figure 9 and Figure 10, for AA5052 and AA6061-T6 at tool pin diameters (5 mm and 7 mm), respectively.

Generally, ultimate shear force values of RFSSW, for AA5052 at tool pin diameter 7 mm were higher than for tool pin diameter 5 mm. The same was observed for AA6061-T6, because the area of 7 mm welding joint gives more ability to carry the load than 5 mm. From the results, it is noted that for AA5052, the ultimate value of shear force (4450 N) was obtained at a speed of 2000 rpm and tool pin diameter 7 mm, while for AA6061-T6, the ultimate value of shear force was 4635 N at a speed of 3000 rpm and 7 mm tool pin diameter. The aim of these comparisons, between the tool pin diameters (5 and 7 mm) is to identify the optimum welding conditions for each alloy, according to the ultimate tensile shear force, micro hardness and microstructure tests. In Figures 9 and 10, it is clear that the alloys with low yield strength, such as AA5052 aluminum alloy, presented greater weld strength at low pin rotational speed, while the material with higher yield strength, such as AA6061-T6 aluminum alloy, required higher rotational speed to provide the joint with a higher strength aluminum alloy. These effects mean that the yield strength of the joined sheet plates represents an influential character in choosing the pin’s rotational speed. In other words, the pin’s rotational speed, which presents greater weld strength, was inversely proportionate to the sheet plate yield strength.
3.2 Microhardness

The results of the microhardness test along the welded specimen cross section via the RFSSW method at the best welding conditions are shown in Figure 11 and Figure 12, for AA5052 and AA6061-T6, respectively. The examination of microhardness for all specimens revealed this to be approximately in a symmetrical form with respect to the tool pin center as distribution of Vickers hardness. The general shape of the hardness test results depicted a W-shape, and this variant was produced by the formation of the main zones at the weld joint.

It is clear from Figures 11 and 12, for the microhardness shape along the upper sheet of the refill friction stir spot welding samples, that the Vickers hardness value reached the lowest value in HAZ, and increased progressively in SZ and TMAZ in the direction of the center of the joint. But it can also be seen that the microhardness values in all welding zones were reduced, compared to the microhardness values at the base material zone. This may be ascribed to the higher heat input caused by the welding process at the refill step, which produced the dissolution of fine precipitates in the localities that were presented to unusual plastic flow, particularly in the SZ, and further produced softening in the additional regions that were subjected to the influence of thermal cycle due to coarsening of precipitates and grains [15].
3.3 Microstructure

Figures 13 and 14 display the morphology of the main zones at the right and left side of the refilled friction stir spot welded joint at the best conditions, for AA5052 and AA6061-T6. These figures also exhibit the base material microstructure, heat affected zone (HAZ), thermo mechanical affected zone (TMAZ), stir zone (SZ) and nugget zone (NZ) as well as the hook shape that formed during the welding. As is demonstrated in Figures 13 and 14 for the cross section of the RFSSW specimen for selected alloys, it can be seen that there is no keyhole at the center of the spot joint, which is the main benefit of the refill friction stir spot welding technique to reduce the concentration stress. Also, some of the material at the top surface is squeezed out and has collected along the outer circumference of the tool shoulder boundary; this is called flash. The extruded pin filler was squeezed and formed the lower sheet; this process produced many hooks along the parting line between them. This practice ensures that there are oxide-free surfaces meeting with each other, followed with high pressure and high temperature, which indicates that the conditions are acceptable to manage the welding. In general, the density of the hooks as this appeared in the microstructure inspection was different for each alloy. It is clear in Figure 13 that for AA5052, the hook was larger than those produced in AA6061 welded specimens (which are shown in Figure 14). The reason for the disappearance of the hook formation may be due to the high strength of AA6061-T6 alloy, and perhaps indicates that it needs more heat generated, which depends on the welding parameters.
Figure 1: Microstructure of AA5052 at tool rotational speed 2000 rpm and pin tool diameter 7 mm for RFSSW (scale 5X and 20X)

Figure 13: Microstructure of AA5052 at tool rotational speed 2000 rpm and pin tool diameter 7 mm for RFSSW (scale 5X and 20X)

Figure 14: Microstructure of AA6061-T6 at tool rotational speed 3000 rpm and pin tool diameter 7 mm for RFSSW (scale 10X and 20X)

4. CONCLUSIONS
The ultimate shear force values of RFSSW, for AA5052 at tool pin diameter 7 mm were higher than for tool pin diameter 5 mm. Similar results were observed for AA6061-T6. So, the increase in the pin tool’s diameter conveys greater ability to carry the load. The best welding conditions, from the ultimate shear force results, were considered for microhardness and microstructure tests. Generally, the microhardness tests of the welded joint at the best conditions by RFSSW technique manifested a W-shape. The microstructural examinations of the refilled friction stir spot welded joint at these
conditions revealed the morphology of the main zones as well as the hook formation. Finally, the ultimate value of shear force for AA5052 (4450 N) was obtained at speed 2000 rpm and tool pin diameter 7 mm. Meanwhile for AA6061-T6, the ultimate value of shear force was (4635 N) at speed 3000 rpm and 7 mm for tool pin diameter.

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