Effect of Pin Shape and Rotational Speed on the Mechanical Behaviour and Microstructures of Friction Stir Spot Welding of Aa6061 Aluminum Alloy

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Abstract

Friction stir spot welding (FSSW) is a modern solid-state joining process able to weld similar and dissimilar overlap joints in different classes of materials and is widely being considered for automotive industry. In this work, the mechanical behavior (i.e. tensile shear tests, Microhardness), and microstructure of friction stir spot welded joints were studied for AA6061-T6 aluminum alloy sheets with thickness of 1.6 mm. Series of FSSW experiments were conducted using vertical CNC milling machine type "C-tek". FSSW is carried out at different pin profiles (cylindrical, taper, and triangular) and tool rotational typically speeds, i.e. 800, 1000, 1200 and 1400 rpm. Based on the welding experiments conducted in this study, the results show that sheets welded by triangular pin tool have highest tensile shear load, of 3.2 kN, followed by welds with cylindrical pin, while welds made using taper pin has the tensile shear load 2.1 kN at optimum speed of 1200 rpm. Also the pin shape and rotational speed had an obvious effect on microstructural parameters i.e. hook height and bond width.

Keywords: Aluminum Alloy A6061, Friction Stir Spot Welding, Micro hardness, Tensile Shear, Pin Profiles.

Introduction

FSSW is a new solid-state joining process able to weld similar and dissimilar overlap joints in different classes of materials with a reduction of energy consumption and capital costs of, approximately, 85% and 50% as compared resistance spot welding [1].

The FSSW process consists of three phases; plunging, stirring, and retraction, as depicted in figure (1). The tool geometries, i.e. shape and diameter of both tool pin and shoulder and welding parameters such as spindle rotational speed, axial feed rate, dwell time, and plunge depth exert significant effect on the

Microstructures and mechanical properties of the friction stir spot welded joints. For microstructures of FSSW, there are two microstructural parameter; bond width and hook light, figure (2) shows the cross-sectional view of FSSW. In FSSW, the bond formation is same around the pin hole, therefore microstructure on one side of the exit hole shows as a mirror image to that on the other side, a region of a certain width exists, on which the tower and upper sheets are fully bounded. The width of this region called “bond width”, the fully bonded ends on the outside boundary between the stir zone and thermos mechanically heat affected zone, after the fully bonded region a partially bonded region appears, on which the lower and upper sheets separated by discontinues, irregular interface line. The partially bonded region is usually consisted within the radius of the shoulder. On the beginning of partially bonded region, due to stirring and plunging action of the tool, the interface line separating lower and upper sheets turns upward a lite part forming a “hook” [2].

Different researchers were studied the effect of the pin shape and rotational speed of the FSSW process, e.g. **Sun et al. [3], Cox et al. [4],** and **Ikuta et al. [5]**. **Sun et al. [3]** investigated the influence of tool design and tool rotational speed variations on the torque, energy output, stir zone temperature and average grain size in the stir zones of magnesium alloy (AZ31) friction stir spot welds**. Cox et al. [4]** confirmed the FSSW to these parameters on the thin plate of an aluminum alloy 6061-T6 and their effects on the mechanical properties. Also they identified three distinct failure modes when the weld is placed under tensile loading; shear modes, mixed modes and nugget pullout mode. **Ikuta et al.[5]** investigated the influence of the tool shape, i.e. threaded, half threaded and no threaded on the mechanical properties and microstructural feature on the dissimilar aluminum alloy (Al 5754/Al 6111) lap joint friction stir spot welding.

Sergio et al. [6], Guler [7], and **Mahmoud et al. [8]** studied the effect of the rotational speed and dwell time on the welding process. **Sergio et al. [7]** selected the AA2024-T3 alloy (rolled sheets) for the FSSW procedure. “Design of

Experiment and Analyses of Variance techniques” were employed to evaluate sound joint with evaluated shear strength under static loading and the influence of the main process parameters on joint strength. **Guler [6]** established FSSW of 1-mm-thick AA5754 Al-alloy plates in the H-111 temper conditions. Mechanical properties of the joints were obtained with extensive hardness measurements and tensile shear tests. **Mahmoud et al. [8]** performed FSSW on annealed aluminum alloy AA5754 sheets. They presented the influence of these parameters on the weld structure included width of the bond region and microstructure of the weld region.

Karthikeyan et al [9] investigated the effect of three parameters, the rotational speed, plunge rate and dwell time. They used a rolled sheet of AA7075-T6 Al alloy to fabricate the FSSW joint. They attempted for getting the optimize process parameters to attain maximum lap shear strength and sensitivity analysis of the process parameters.

Another study focused on conducting FSSW on aluminum alloy 2014 in T4 and T6 conditions, with and without Alclad layers, using different values of rotational speed and plunging depth to study their influence on bond width and hook formation by **Babu et al. [10].** And the work of **Paider et al. [11]** who investigated the effect of the shoulder penetration depth and the rotational speed on the friction stir spot welding of 2024-T3 aluminum alloy on the surface appearance, macrostructure, temperature profile, maximum failure load, and failure fracture modes. On the other hand, **Song et al. [12]** divided the plunge speed into two speeds, including pin and shoulder plunge speeds. The effect of the pin and shoulder plunging speeds on hook geometries and mechanical properties of FSSW of Al 6061-T6 sheets were investigated.

It is clear that the literature is diverse that may attributed to several aspects such as tool design, variations of welding parameters, nature of welded alloy and variation of sheet thickness. The main objectives of the present work is to study the effects of the tool rotational speed and pin shape on the mechanical properties and microstructural parameters, i.e. bond width and hook height of AA6061-T6 aluminum alloy sheet joint by FSSW.

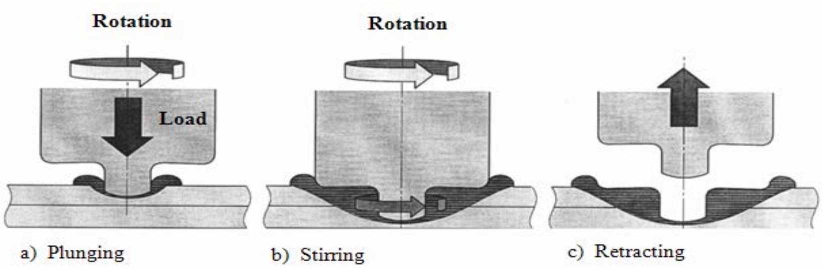

Figure (1) Friction stir spot welding (FSSW) process [1]

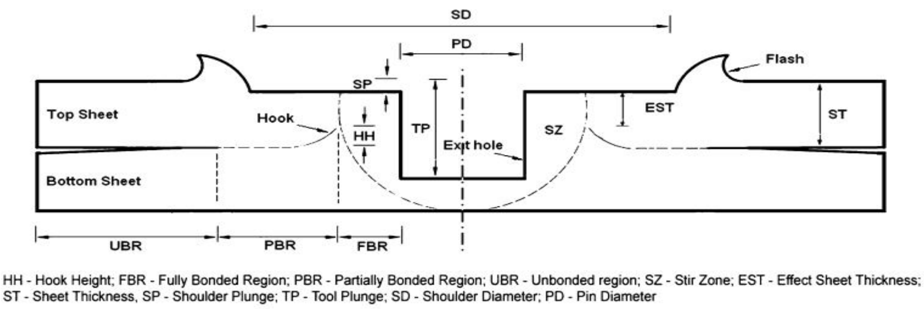

Figure 2: Schematic cross-sectional view of a friction stir spot weld [2].

Experimental Work

Base Material

AA 6061-T6 alloy sheets with thickness of 1.6 mm were used to produce FSSW lap joints.

The chemical compositions and mechanical properties of these Al alloys sheets are given in **table (1)** and **table (2).**

Welding equipment and conditions

Vertical CNC milling machine type "C-tek" equipped with special fixture for FSSW was used. All the welded specimens were welded in lap configuration according to the AWS C1.1: 2007.

As shown in figure (3) the specimen was produced using two 100×25 mm sheet with 25×25 mm overlap area. The overlap joint configuration was obtained by securing the welding samples plate in to the fixture prepared for this purpose.

The fixture was fastened into the milling machine bed and was adjusted to have a level surface, figure (4). After cleaning the lap surface and the surface of the upper plate, sheet welded at the center of the overlap area. In this study, FSSW was conducted on with four different tool rotational speeds: typically, 800, 1000, 1200, and 1400 rpm; and three different tool pin shape, as listed in table 3. All the tools had flat shoulder, while had different pin geometry cylindrical pin, taper pin and triangular pin, figure (5), figure (6), and figure (7). In all experiments, the tool penetration depth, the tool plunger rate and the dwell time were held constant at 0.3 mm and 15 mm/min and 11.2 sec, respectively.

Tensile Shear

Tensile shear test was carried out on samples taken in a perpendicular direction to the welding to determine the shear load. All tensile shear tests were carried out at room temperature and constant loading rate 0.5mm/min by computerized universal testing machine (United Hydraulic SHFM Series), which has a maximum capacity of 100kN, Figure(6) . Then, the average value of the tensile shear load for three specimens was taken to evaluate the tensile shear behavior of each welded joint.

Microstructure Testing

According to ASTM E3, the specimens were prepared through a series of successive steps starting from grinding with 220, 320, 400, 600, 800, 1000, 1200 and 2000 emery paper, the specimens were rotated at 90º when the grinding paper was replaced to insure that all scratches were removed, then the specimens were polished to a mirror finish with different grades of alumina suspension by universal grinding and polishing machine for metallographic specimen preparation. Washing the specimens with distilled water between stages was necessary to prevent carryover of abrasive and contamination of preparing surfaces. Finally the specimens were etched in special chemical solution; Flick's amacroetchnt [14], consisting of 90 ml distilled water, 15 ml HCl and 10 ml HF was used to reveal special features of the welded area especially at the weld zone and base metal interface.

Microhardness Testing

Microhardness testing of the welded joints was done by Vickers microhardness machine. Micro-hardness measurements were taken in horizontal axes using diamond pyramid indenter with a load of 100 g and loading within 10 sec according to ASTM-E384. The specimen surface was prepared in different grades of emery papers (according to ASTM-E3 explained in in microstructure test) to provide a suitable flat surface. Microhardness is recorded at the prepared surface in the points settled in the Figure (8) to evaluate the microstructural changes taken in both plates during FSSW welding processes

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Table 1: Standard and actual chemical composition of aluminum alloy AA6061-T6

Percentage Composition	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Nominal [13]	0.4-0.6	0.70 Max	0.15-0.4	0.15 Max	0.8-1.2	0.04-0.35	0.25 Max	0.15 Max	Balance
Actual	0.435	0.370	0.224	0.100	0.810	0.185	0.026	0.055	Balance

Table 2: Standard and actual mechanical properties of aluminum alloy AA6061-T6.

	σ_y	σ_u	EI %
Standard Value[13]	345	393	15%
Actual Value	356	405	16%

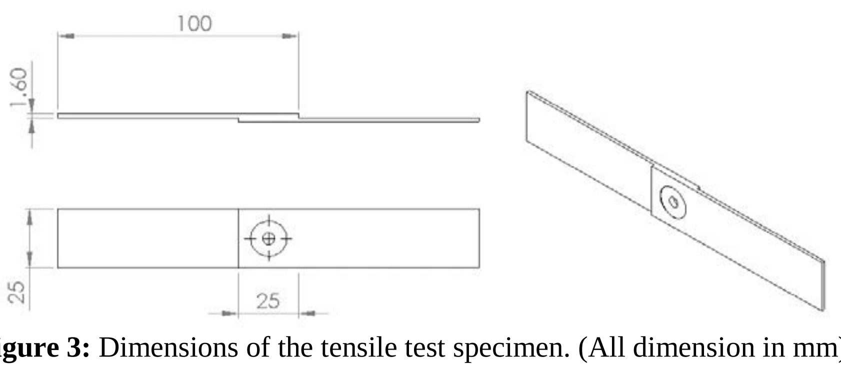

Figure 3: Dimensions of the tensile test specimen. (All dimension in mm).

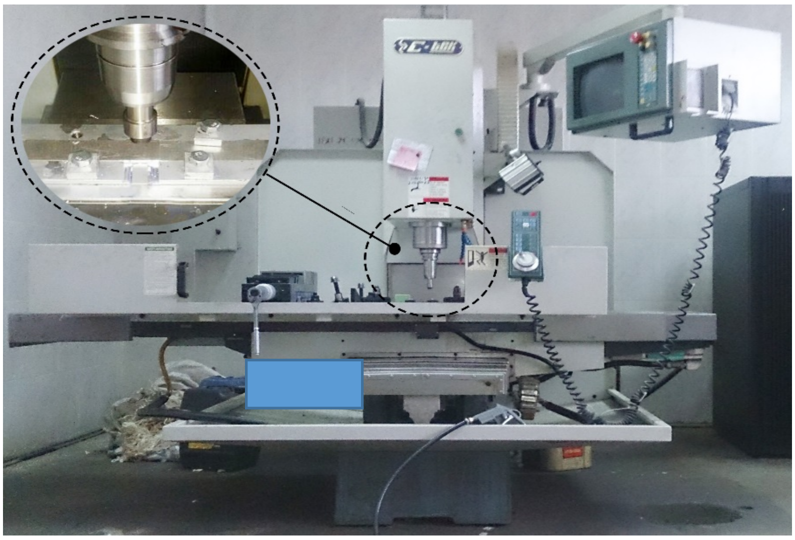

Figure 4: CNC milling machine used for welding process**.**

Table 3: Tools used in the FSSW experiments.

Tool No.	**Pin Shape and Dimensions**			
	Pin Shape	Pin Details	Pin Length	Shoulder Diameter
Tool 1	**Cylindrical**	5 mm diameter	2.5 mm	15 mm
Tool 2	**Taper**	5 mm dia. (at shoulder), 4 mm dia. (at pin's tip)	2.5 mm	15 mm
Tool 3	**Triangular** (equilateral)	3.78 mm base, 3 mm height, and 0.25 mm edge chamfer	2.5 mm	15 mm

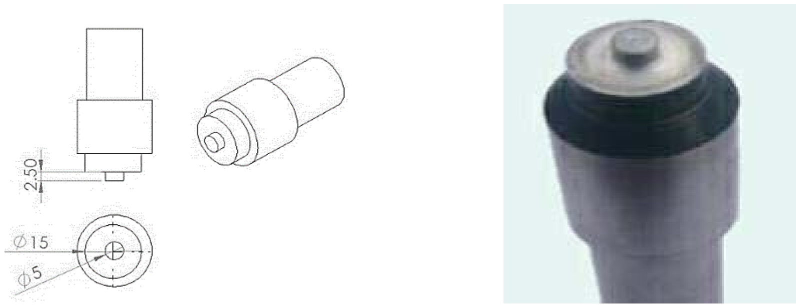

Figure 5: Cylindrical pin tool (All dimension in mm).

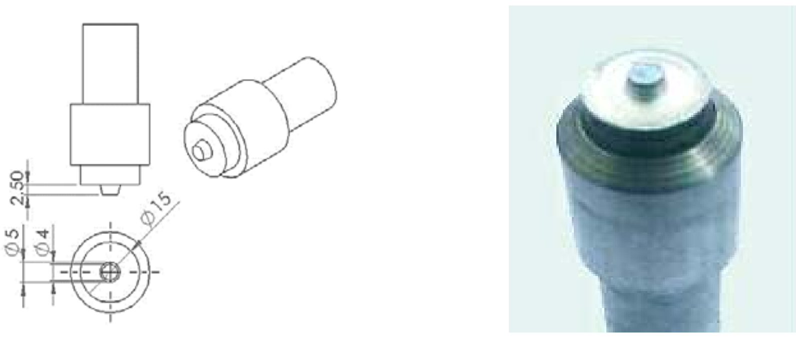

Figure 6: Tapered pin tool (All dimension in mm)

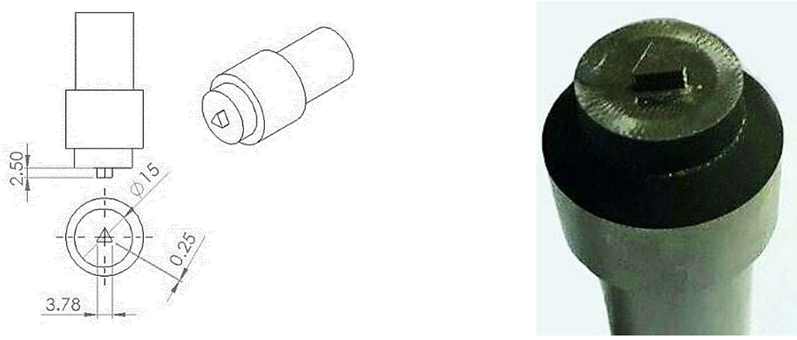

Figure 7: Triangle pin tool (All dimension in mm)

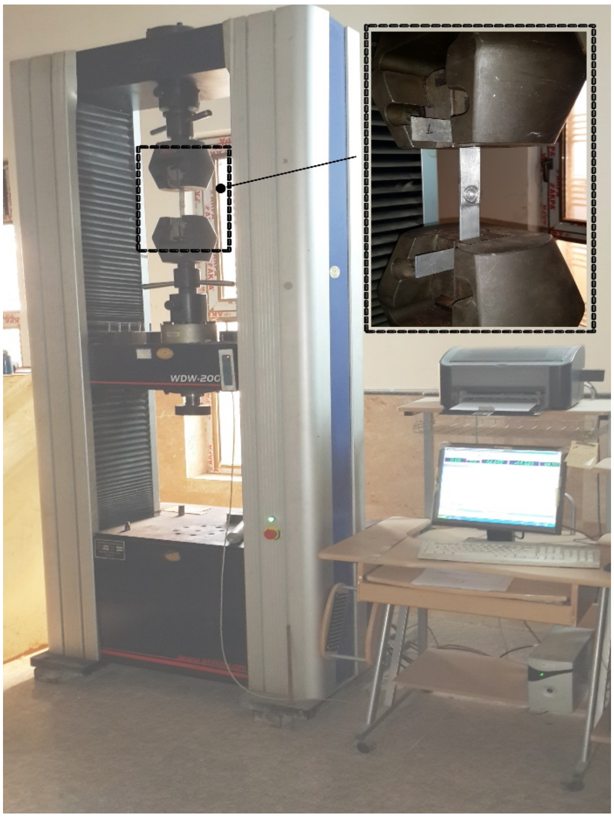

Figure 6: Computerized universal tensile testing machine (United Hydraulic SHFM Series).

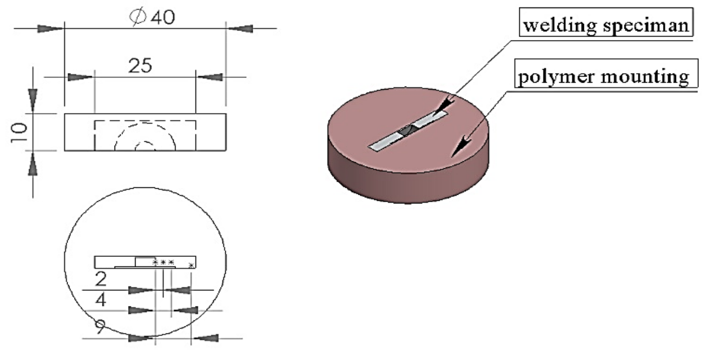

Figure 8: Positions of the micro hardness test. (All dimension in mm).

Result and Discussion

Tensile Shear Test

The variation of the ultimate tensile shear force with the tool rotational speed at different pin profile is represented in figure (9). The result revealed that at constant pin profile, i.e. triangular pin, increasing the tool rotational speed up to certain level causes increases the tensile shear force. Further, increase in rotational speed slightly decreases the tensile shear force. For example, increasing the tool rotational speed from 800 to 1200 rpm increase the tensile shear force from 2.17 KN to 3.2 KN, but additional increase in tool rotational speed to 1600 rpm reduces the tensile shear force to about 2.15 KN. This consistent with the other reports on friction stir spot welding of aluminum alloy, i.e. reference [8], which studied the influence of the tool rotational speed with the dwell time on the mechanical properties of FSSW Aluminum Alloy AA5754 joint and they conclude that at constant dwell time, increase rotational speed increases the tensile shear but further increase reduced the tensile shear load. The reason, for this behavior can be associated with increasing stir zone area due to the fact that frictional heating and material flow, are intensified by increasing tool rotational speed. Also, from the results, the behavior cylinder pin profile and taper profile similar to the triangular pin. Among the three weld tests, weld produced using triangular tool showed highest tensile shear load followed by those using made straight cylinder. Welds made using taper pin showed the lowest tensile shear load. This is consistent with reference [11], which achieved FSSW several different tools over broad range of welding process parameters.

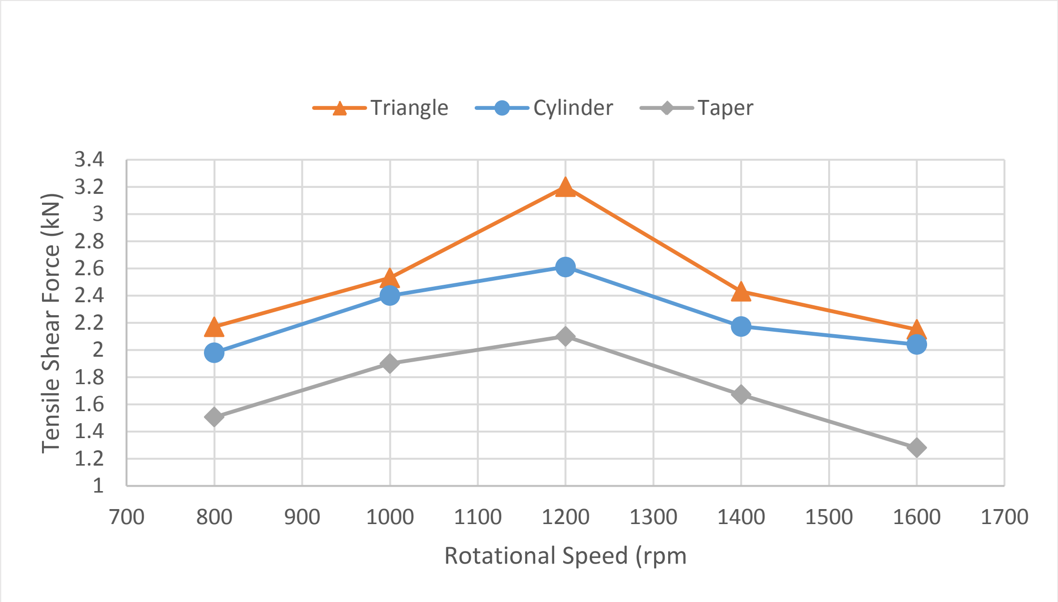

Figure 9: Tensile shear loads at different pin profile and rotational speed

Microhardness Test

In all specimens, the micro-hardness found to be nearly symmetric with respect to pinhole center. According to the figure (10) – figure (12), the higher micro-hardness found in the periphery of the weld pin profile. The increasing in the hardness caused by strain hardening from plastic deformation during FSSW process [7]. This is due to fine grains that

Produced from dynamic recrystallization during the welding process. Figure (10) shows the variation of the micro hardness with increasing in the tool rotational speed for the triangular pin profile. The 1200 rpm had the maximum micro hardness, otherwise the 800 rpm had the lowest micro hardness value. This agree well with result of the tensile shear, Figure (9). The plastic Deformation produces an increase in the tensile shear and the microhardness because the strength and the hardness increase together depending on dynamic recrystallization. On the other hand, Figure (11) and Figure (12) shows the changes of the micro hardness for the other pin profiles, i.e. cylindrical pin and tapered pin respectively. Both the parts of the figures showed a similar behavior of the triangular pin. This agree with references [15] and [16], which conducted that the triangular pin has finer grain size compared with cylindrical pin; therefore the weld with triangular pin has micro-hardness value higher than welds with cylindrical pin. From the current tests, welds using triangle pin has the shear stress more than welds with cylindrical pin, which also has highest tensile shear stress compared with welds with tapered pin so that the triangular pin profile has the highest micro hardness, then comes the micro hardness of the cylindrical pin profile. The tapered pin profile has the lowest micro hardness.

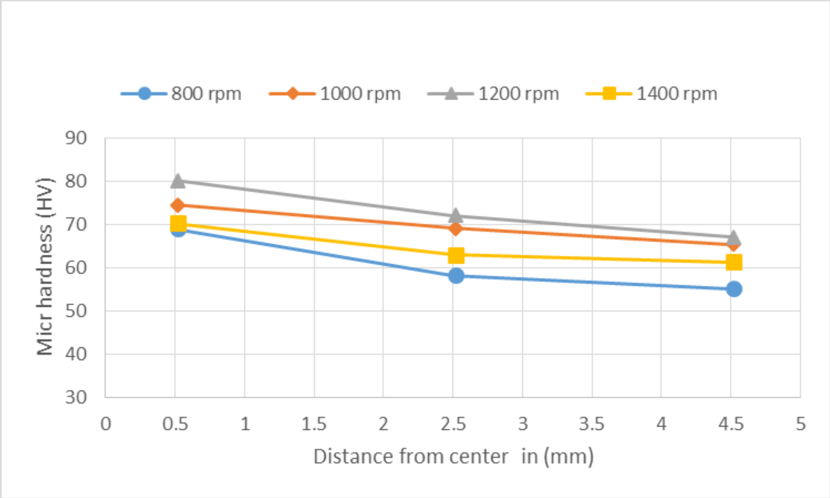

Figure 10: Microhardness profile of welds with triangular pin at different rotational speeds

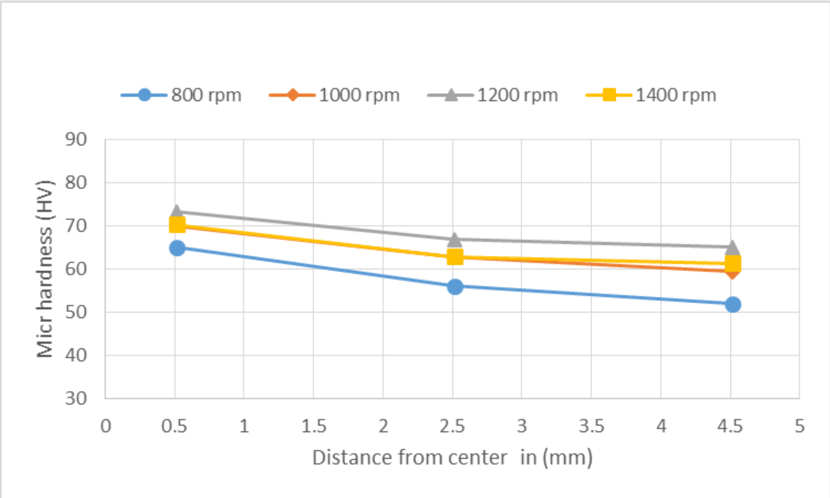

Figure 11: Microhardness profile of welds with cylindrical pin at different rotational speeds

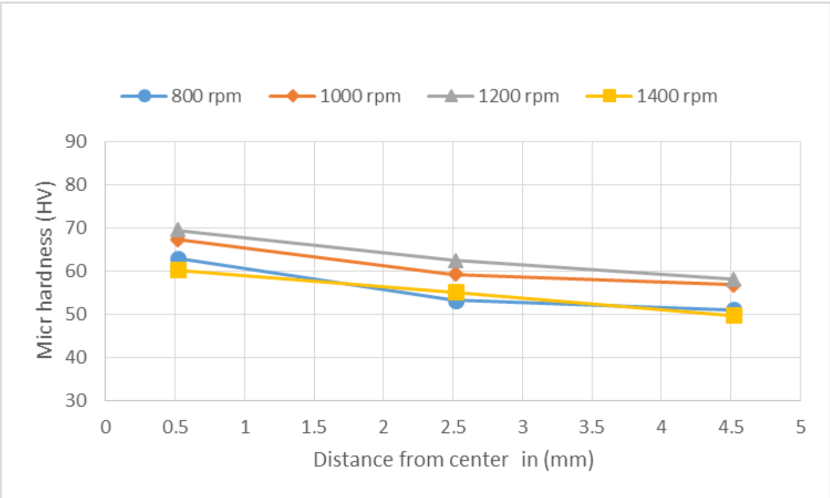

Figure 12: Microhardness profile of welds with tapered pin at different rotational speed,

Microstructure Test

Figure (13) shows the optical microstructure of the base metal which is 6061-T6 aluminum alloy. The base material contented large number of dissolved second phase particles. Three distinct microstructure regions show in FSSW specimens, i.e. stir zone (SZ), thermo-mechanical heat affected zone (TMAZ) and heat affected Zone.

From figure (14) SZ showed very fine recrystallized grains in all specimens. The TMAZ showed separately deformed and crystallized grains, while the heat affect zone showed no significant grains coarsening. For triangular pin profile, the bond width increases with the increase rotational speed to a certain level rotational speed.

Using very high rotational speed did not improve the bond width because very high rotational causes excessive heating. This is in agreement with reference [11] that studied the formulation of hook height and bond width of FSSW specimens of AA 2014 with Alclad. For example, rotational speed 800 rpm shows bond width and hook high equal to (0.952 mm) and (0.407 mm) respectively, figure (15). On the same context, for rotational speed 1200 rpm, figure (16) showed the bond width higher (around 1.511 mm and 0.382) than the welds using 800 rpm. The excessive heating appeared in 1400 rpm. On the other hand, for welds produced by using cylindrical pin profile, figure (17), there are no significant difference were observed with regards to the hook height compared with welds produced using triangular pin profile showed significant Higher band width compared with specimen with cylindrical pin. For welds produced using tapered pin profile tool, there is no hook height formulation, also the bond width in these welds was lower than welds produced cylindrical pin profile. The bond width and hook height in FSSW are influenced by nature and extent of the material flow around the pin. In reference [17] investigated the material flow in friction stir butt joint using cylindrical pin and tapered pin. According to them, joint using cylindrical pin shows an upward flow of the metal around the pin. On the other hand, welds produced by taper pin results a downward material flow, especially at higher angle of the pin. Downward material flow is beneficial in FSSW as it helps to minimize the hook height. Similar finding reported by reference [11] which concluded that the joint produced tapered pin shows lower hook height.

In current work results that triangular tool it better suited for friction stir spot welding. This agreement with reference [18] which studied the differences in material flow during friction stir spot welding using triangular and straight cylindrical tools. During friction stir spot welding using cylindrical pin profile, the pin cause plasticized metal to flow around its axis i.e. rotational flow. Triangular pin causes the rotational flow in addition to the material movement forth and back in the radial deformation occurs over a wider region and more intensely around the pin. Thus triangular tool can help to maximize the bond width in the FSSW.

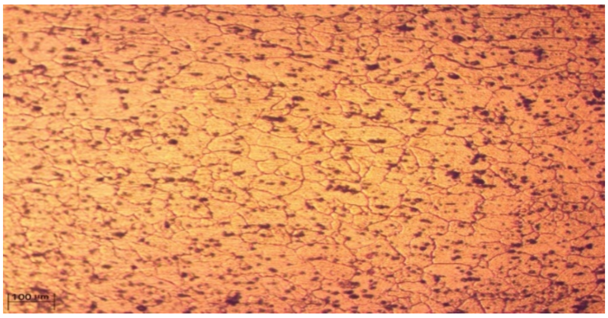

Figure 13: Microstructures of AA6061-T6 base material.

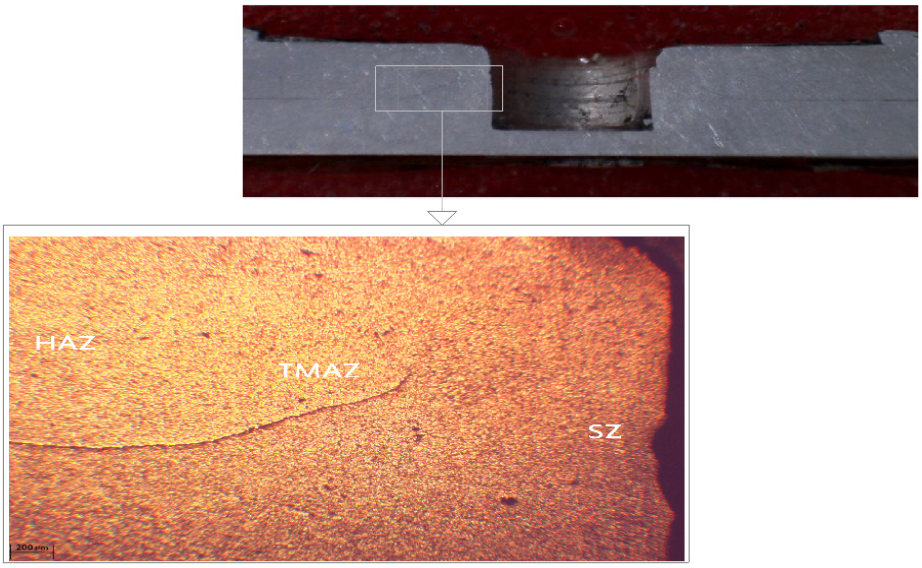

Figure 14: Macro- and microstructures of a friction stir spot weld made using triangular pin 1000-rpm tool rotational speed.

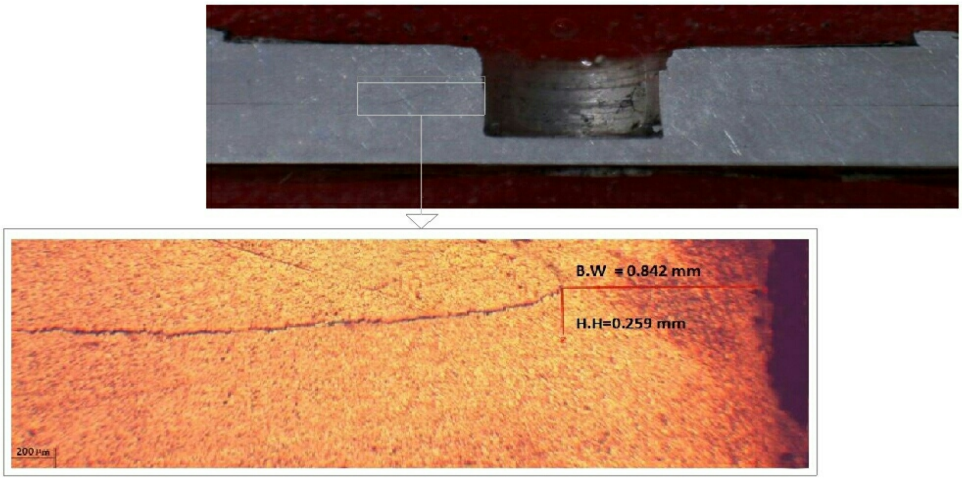

Figure 15: Macro- and microstructures of a friction stir spot weld made using triangular pin 800-rpm tool rotational speed.

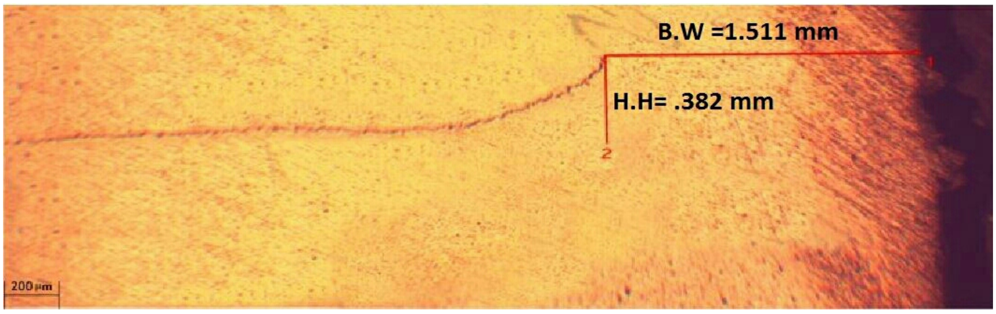

Figure16: microstructures of a friction stir spot weld made using triangular pin 1200-rpm tool rotational speed.

Figure (17) microstructures of a friction stir spot weld made using cylindrical pin 800-rpm tool rotational speed.

Conclusions

In this research, the effect of the tool rotational speed and pin shape on the mechanical properties and the microstructure of 1.6 mm thick AA6061-T6 aluminum alloy were investigated. The following conclusions were made:

1. AA6061-T6 aluminum alloy is weld able by using different pin shape and rotational speed, it gave different welding efficiency.
2. Increasing tool rotational speed increase the tensile shear load, but further increase of tool rotational speed slightly decrease the tensile shear load for specified pin shape. On the same context, at constant tool rotational speed, triangular pin give higher tensile shear load followed by cylindrical pin and tapered pin respectively.
3. The micro hardness decrease gradually from the nugget zone through the thermo-mechanical heat affected zone and then heat affected zone due to friction heating and amount of plastic deformation.
4. The mechanical behavior of friction stir spot welding of AA6061-T6 aluminum alloy sheets is mainly affected by its geometrical feature, i.e. hook height and bond width. A good basis for FSSW optimization is maximize bond width and minimize hook height.

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تأثير شكل راس اداة اللحام وسرعة الدوران على التصرف الميكانيكي والبنية المجهرية لسبيكة الألمنيوم AA6061 الملحومة بالخلط الاحتكاكي النقطي

محسن نوري حمزة
قسم الهندسة الميكانيكية
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الجامعة التكنلوجية

الخلاصة :

اللحام بالخلط الاحتكاكي النقطي من طرق لحام الحالة الصلبة الحديثة قادرة على لحام وصلات التراكب متشابهة والمتباينة في أصناف مختلفة من المواد التي تستخدم بشكل واسع في صناعة السيارات. في هذا العمل،تم دراسة الخصاص المكانيكية (حمل قص الشد، الصلادة الدقيقة) والبنية المجهرية لوصلات صفائح سبيكة الألمنيوم A6061-T6 الملحومة بالخلط الاحتكاكي النقطي ذات سمك(1.6) ملم. تم تنفيذ التجارب بواسطة ماكنة تفريز عامودية نوع C-tek. تم اجراء اللحام الاحتكاكي النقطي لثلاث اشكال مختلفة لراس عدة اللحام مثلث ودائري ومخروطي وعند اربعة سرع دورانية عملية (800 ، 1000، 1200 ، 1400 دورة بالدقيقة). استنادا إلى التجارب التي أجريت في هذه الدراسة، أظهرت النتائج أن صفائح الملحومة بواسطة راس اداة اللحام ذات مثلثة الشكل لديها أعلى حمل لشد القص (3.2kN) تليها الصفائح المحلحومة بواسطه راس اداة اللحام اسطوانية الشكل،في حين حققت اللحامات باستخدام لراس عدة اللحام مخروطية الشكل ادنى حمل لشد القص(2.1kN) عند السرعة المثلى (1200 دورة في الدقيقة). كذلك شكل راس اداة اللحام وسرعة الدوران لهما تأثير واضح على ارتفاع الخطاف وعرض الرباط.