Effect of Different Tool Geometries in Friction Stir Welding of AA 2024-T3 using Design of Experiments

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Abstract:

In this work, Aluminum alloy (AA2024-T3) was welded by friction stir (FSW) method using different pin profile design types; straight cylinder, threaded cylinder, tapered cylinder hexagonal, square, and threaded taper. For each type, a flat and concave shoulder was used, as well as, the welding process was single and double. The results of mechanical tests are analyzed using design of experiments method (DOE). The best and weaken mechanical properties (tensile strength, bending force and hardness) are observed when the welding is achieved by hexagonal and straight cylinder pin profile respectively. A concave shoulder gave higher mechanical properties as compared with flat shoulder. The change in welding process type presented a sensible effect. Nugget zone hardness is higher than that of base metal for all specimens. The optimum hardness result is recorded by hexagonal pin with concave shoulder profile.

Keywords: Friction stir welding, tool geometry, DOE.

1. Introduction:

FSW is a solid-state process, which means that the base materials to be joined do not melt during the joining process. This is a door opener to completely new areas in the field of welding technology. Alloys from 2xxx and 7xxx series, which have traditionally been non-weld able can now be joined with FSW with speed and quality [1]. The maximum temperature reached during the process is 0.8 of the melting temperature of the work pieces. The welds are created by the combined action of frictional heating and mechanical deformation due to a rotating tool. The detrimental effects of arc welding such as distortion and residual stresses are due to the rapid heating beyond the melting temperature and cooling of the joints. These detrimental effects are minimized in FSW, as the heat generated is not

Severe enough [2]. FSW can be used to join aluminum sheets and plates without filler wire or shielding gas. Material thicknesses ranging from 0.5 to 65 mm can be welded from one side at full penetration without porosity or internal voids. In terms of materials, the focus has traditionally been on non-ferrous alloys, but recent advances have challenged this assumption, enabling FSW to be applied to a broad range of materials [3]. It can be performed in all positions (horizontal, Vertical, overhead and orbital), and it can produce or repair joints utilizing equipment based on traditional machine tool technologies [4]. The joining does not involve any use of filler metal and therefore any aluminum alloy can be joined without concern about the compatibility of composition, which is an issue in fusion welding [5]. A simple FSW process is shown in figure (1), in which, the tool is pressed on the sample with two main speeds; rotating and Linear speed along the weld line [6].

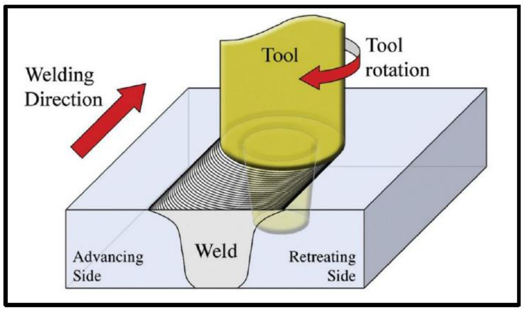


Figure 1: Schematic of the friction stir welding process [6].

R. Palanivel et al, 2010 [7] studied the influence of tool pin shape of dissimilar aluminum alloys AA6351- AA5083H111 in friction stir welding process. Tools with five pin profiles were used; square, threaded cylindrical, tapered square, tapered octagon, and straight cylindrical to fabricate the joints. The square pin profile gave better tensile strength among the five. Indira Rani M and R N Marpu 2012 [8] investigated the effect of variation of tool geometry on friction stir welded aluminum alloys;

AA6351 and AA6061 separately. Three types of tool profiles (tapered, threaded cylindrical and square) with flat and groove (concave) shoulder have been used. It can be concluded that the shape of the tool pin and shoulder play a very important role in obtaining better mechanical properties for the weld joints. This is evident from the results obtained for the square pin profile because flat faces produce a pulsating stirring action in the flowing material.

2. Experimental work:

2.1 Tool preparation:

The tools material were used is of oil hardening tool steel (ASTM A681 O1 type), [9]. The chemical composition of this material is presented in table (1):

Table 1: Measured and standard chemical composition of A681 O1 tool steel type

Element	Measured wt%	Standard [9] wt %
C	0.894	0.85-1
Si	0.268	0.1-0.5
Mn	1.11	1-1.4
W	0.4	0.4-0.6
Cr	0.5	0.4-0.7
V	0.15	0.3
Cu	0.16	Cu + Ni = 0.75 Max.
Ni	0.06	

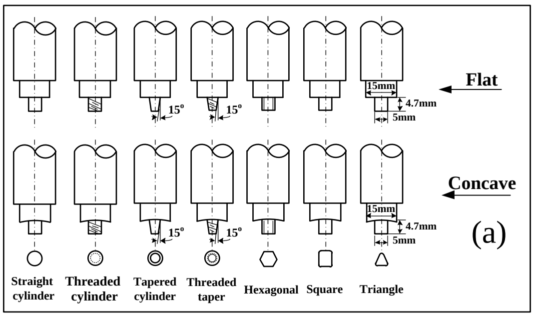
In order to improve the tool properties, a hardening and tempering procedure are used [10], as shown in table (2).

Table 2: Hardening and tempering procedure of tool steel [10]

Rate of heating	slowly
Preheat temperature	650 ^{o}C
Hardening temperature	790-815 ^{o}C
Time	10-30 min
Temperate temperature	175-260 ^{o}C

The dimensions of tool are (5, 4.7 and 15 mm) for pin diameter, pin height and shoulder diameter respectively.

In order to examine the effect of shoulder surface on the strength of weldment, two type of shoulder surface are used; flat and concave surface profile. For each type of surface, six pin profiles are manufactured. Figure (2) shows the design of all tool types with a sample photograph of hexagonal tool.



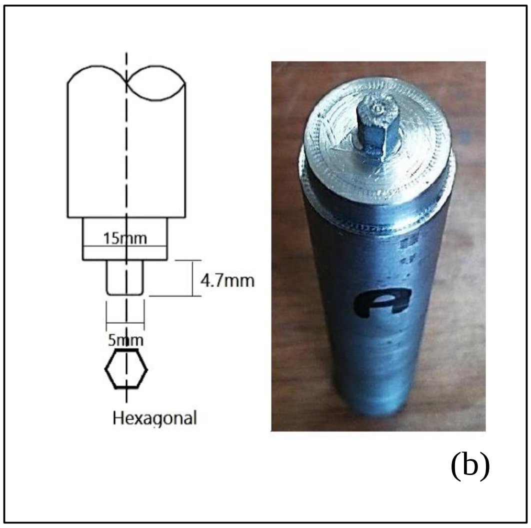


Figure 2: (a) Schematic of tools with flat and concave shoulder (b) Hexagonal.

2.2 Material properties:

An Aluminum alloy of type (AA2024-T3) is chosen to fabricate the welded specimens. This type of Aluminum alloy is difficult to weld by fusion welding due its sensitivity to thermal cracking. Chemical composition is analyzed, table (3).

Table 3: Chemical composition of AA2024-T3 alloy

Element	Measured wt %	Standard wt % (ASTM B209) [11]
Si	0.061	0.50
Fe	0.181	0.5
Cu	4.05	3.8 min. - 4.9 max.
Mn	0.596	0.3 min. - 0.9 max.
Mg	1.40	1.2 min. - 1.8 max.
Cr	0.004	0.1
Zn	0.076	0.25
Ti	0.027	0.15
Ga	0.0005	-
V	0.008	-
Ni	0.002	-
Other	0.024	0.2
AL	Rem.	Rem.

On the other hand, a simple tensile and hardness test are achieved. The standard tensile test specimen is manufactured according to ASTM B557-02a [12]. The results of mechanical properties has been illustrate in table (4):

Table 4: Mechanical properties of AA2024-T3 alloy

Tensile test specimen 	Nominal (ASTM B209) [11]	Actual
Yield stress (MPa)	289 Min	302
Tensile stress (MPa)	434 Min	446
Elongation (%)	12 Min	13.2
Hardness (HV)	137	145

The specimens to be welded were cut into two pieces with dimensions (150*75 mm) with (5mm) of plate thickness, figure (3). All specimens have been manufactured such that the frictional stir weld line will be perpendicular to the rolling direction.

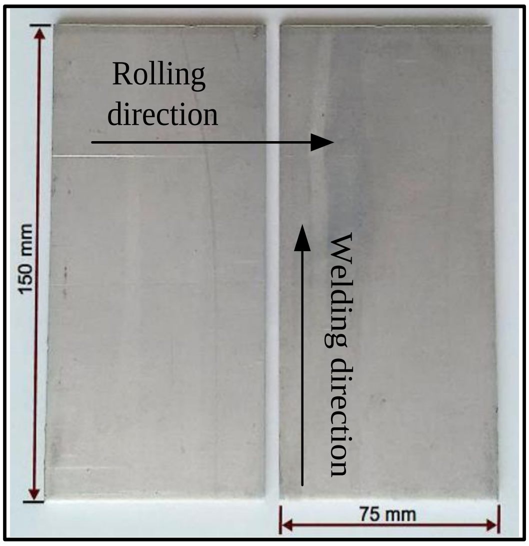
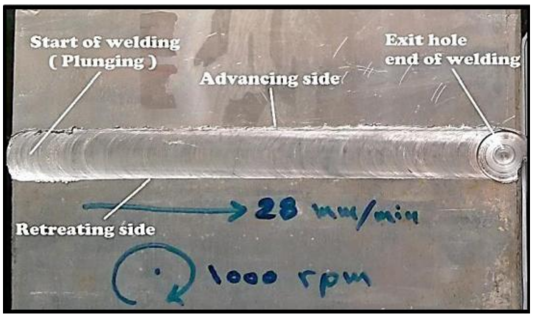


Figure 3: Sheet preparation for welding

2.3 Welding procedure:

A vertical milling machine is used to produce the welded specimens with square butt joint configuration, figure (4).

(a) welding process



(b) welding sample

Figure 4: Welding process and a simple welding sample

The welding procedure is achieved according to machine parameters mentioned in table (5):

Table 5: Welding parameters

Tilt angle	Rotation speed	Linear velocity	Dwell time
3^{o}	1000 RPM	28 mm/min.	50 sec

2.4 Mechanical tests:

2.4.1 Tensile test:

The tensile test of weldment specimens are made perpendicular to the weld line. It includes the nugget zone (NZ), thermo-mechanical zone (TMZ), heat affected zone (HAZ) and the base metal (BM) along the gauge length. The standard dimensions are considered according to AWS D17.3/D17.3:2010 [13], figure (5).

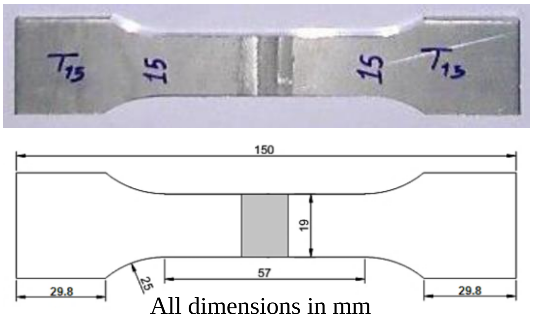


Figure 5: Photograph and schematic of standard tensile test welded specimen

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2.4.2 Bending test:

In order to determine the strength and ductility of welded joints, a standard bending test is achieved according to the fixture guidance AWS B4.0:2007 [14], figure (6). Flat specimens were tested in three- point transverse bending with dimensions (150 *38*5mm). The results were recorded after all specimens are cracked.

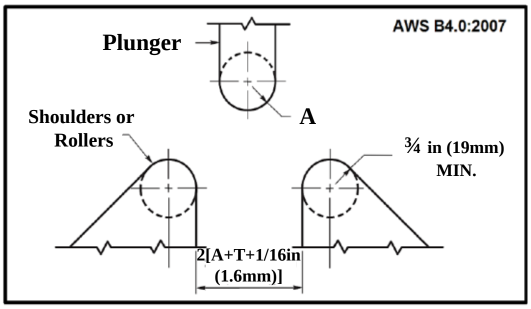

Figure 6: Bending test fixture [14]

2.4.3 Micro hardness test:

A Vicker hardness test was used according to ASTM E92-82 [15]. The recoded data were done with a step of (2mm) from the center line of weld metal at each side. This test includes the NZ, TMZ, HAZ and BM.

3. Results and discussion:

This work includes the change in tool geometry and process type. Table (6) presents all cases of the welded specimens.

Table 6: The welded specimen cases

Single side welding process	Concave shoulder	Specimen No.	1	2	3	4	5	6
		Tool pin profile	Straight cylinder	Threaded cylinder	Tapered cylinder	Threaded taper	Hexagonal	square
	Flat shoulder	Specimen No.	7	8	9	10	11	12
		Tool pin profile	Straight	Threaded	Tapered	Threaded	Hexagonal	square

(Cont. table-6)

Double side welding process	Concave shoulder	Specimen No.	13	14	15	16	17	18
		Tool pin profile	Straight cylinder	Threaded cylinder	Tapered cylinder	Threaded taper	Hexagonal	square
	Flat shoulder	Specimen No.	19	20	21	22	23	24
		Tool pin profile	Straight cylinder	Threaded	Tapered cylinder	Threaded taper	Hexagonal	square

The results of experimental data include the tensile, bending and hardness tests. Those results have been plotted in figures (7, 8, and 9) respectively. The maximum tensile, bending force and hardness are observed in specimen (5) that has been welded with a single side process by a hexagonal pin profile with concave shoulder.

On the other hand, the weakness in the tensile strength is observed in specimen (19). Specimen (7) gave a minimum bending force and hardness. Where, for specimen (5), the surrounded surface area is higher than those of specimen (7 and 19). Hence, large surface area gives a large friction in

The contact surface between pin and specimen which result in a higher heat transfer to the specimen. If the temperature at the pin reaches the melting point of specimen, a good weld quality can be obtained where a good mixing between the welded specimens is occurred.

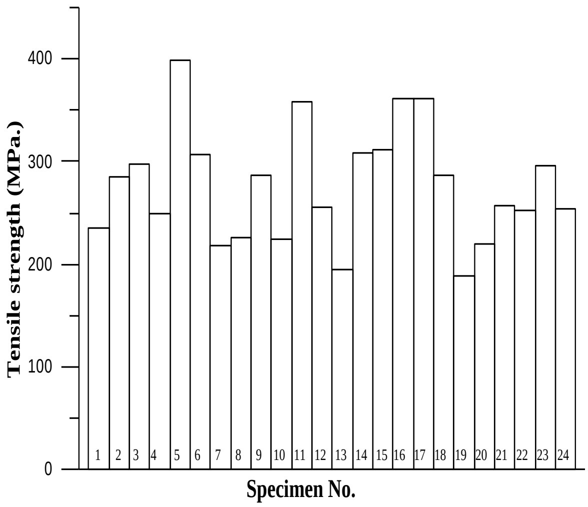

Figure 7: Tensile strength of the welded specimens

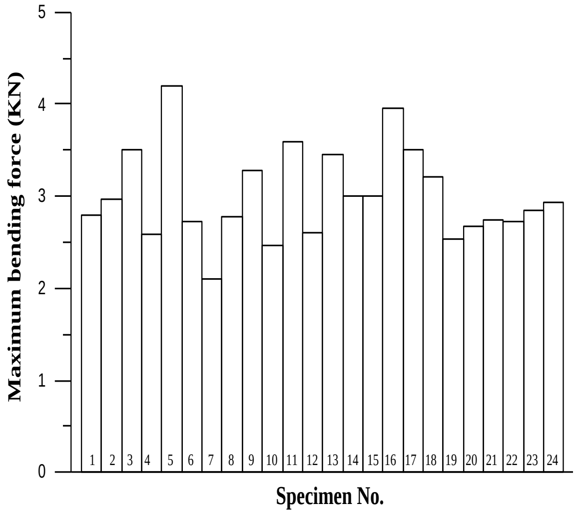

Figure 8: Maximum bending force of the welded specimens

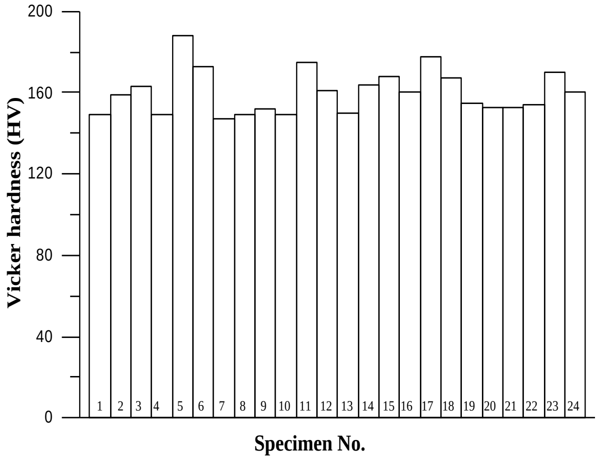

Figure 9: Vicker hardness of the welded specimens

The friction stir welding is a process accompanied by generating high temperature. The elevated temperature leads to grain refinement and other thermal changes in the weld zone, therefor; the hardness results are changed through the weld zone, figure (10). In general, Due to heat generated during the FSW, the hardness of all welded specimens in nugget zone is higher than those of base material (145 HV).
The weld metal hardness is higher than the HAZ and base metal. The difference between hardness for the corresponding points at each side (advancing and retarding side) can be interpreted as: the same direction of rotation velocity vector and the forward motion in the advancing side gave a higher heating than those of the retarding side.

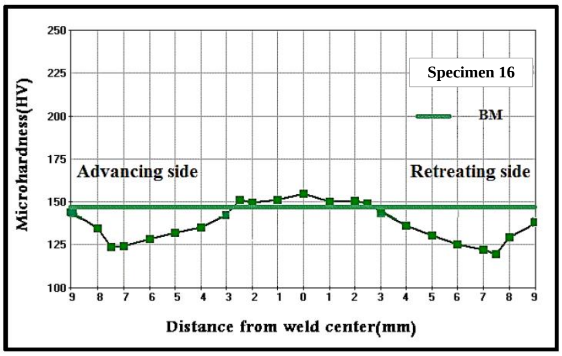

Figure 10: Hardness distribution of specimen (16)

The variation in the mechanical properties can be consoled as follows:

In the straight cylindrical pin profile tool, the plastic metal flow around the pin is in the form of circular paths due to the circular shape of the pin. The heat is generated by friction between the metal and the pin, on the other hand, between the metal and the shoulder. As the surface of friction area is smooth, the expectation of generated heat will be less than that generate by others tool shapes.

The modification on straight cylindrical tool is a screw. Two cases of welding may exist in this tool geometry, if the rotation of tool is in the same or opposite direction of thread. When the rotational direction is in the same thread direction that will lead to distortion in metal flow and raise it to top thus emerging in the form of flash, this lost quantity of the metal will make the weld weak. While in the second case the opposite rotational direction will strengthen the weld by good stirring, more heat generation, and compaction downward to backing plate. This case is used in this study.

It observed that the welding efficiency increased when use the threaded type, the same observation presented in [16].The higher improvement in tensile strength is (37%) in threaded cylinder, double side as comparing with those of straight cylinder, single side.
The tapered cylindrical pin profile was smoother during weld process due to its tapering shape. As a result of change in diameter along this pin of tool, the flow of plastic metal around the pin was different from the previous tool pins. The results of this tool are higher than the previous results of the straight cylindrical tool (~ 26%) and almost greater than threaded cylindrical tool (~ 12%) [17].

Threaded taper tool has the same functions of tapered cylindrical tool with taking advantage of screw threaded. In addition to the tapering shape of pin, screw thread was done along the pin of this tool. Threaded shape is affected quantity of the heat generation and flow of plastic metal.
The high quality of welding which accompanies the hexagonal pin profile tool is due to good stir process with an appropriate amount of heat generation. When stir process starts, the flow of plastic metal takes zigzag path as a result of a hexagon in contact with the plastic metal. This makes an ideal mixing process and the suitability of the heat generated and thus high efficiency in welding.

3.1 Analysis the experiments by fractional design:

A MINITAB program is used to analyze the results of experiments data by a fractional factorial design with general full factorial method. It's required to study the effect of the tool pin profile, shoulder surface and welding process type on the mechanical properties of weldments. The following tables (7, 8, and 9) represent the codes of those parameters used in the design of experiments.

Table 7: Tool pin profile codes

Tool pin profile	Code
Straight cylinder	SC
Threaded cylinder	THC
Tapered cylinder	TC
Threaded taper	THT
Hexagonal	H
square	SQ

Table 8: Shoulder surface codes

shoulder surface	code
Flat shoulder	Flat
Concave shoulder	Concave

Table 9: Welding process type codes

Welding process type	code
Single side welding process	SS
Double side welding process	DS

The results of mechanical properties (tensile strength, maximum bending force and hardness) is studied by the main effect plots, figures (11, 12 and 13) respectively.

In general, the hexagonal profile gave the maximum mechanical properties, where, the straight cylinder gave the minimum tensile strength and hardness. Also, the medium downgrade is obvious when the shoulder surface is changed from concave to flat, that means, a good mechanical properties is found when the concave shoulder used. A sensible increment and reduction in the tensile strength and hardness respectively is observed in the single side process as comparing to that in the double side figure (11 and 13) [18]. While, the reduction appears purposely in the bending force, figure (12).

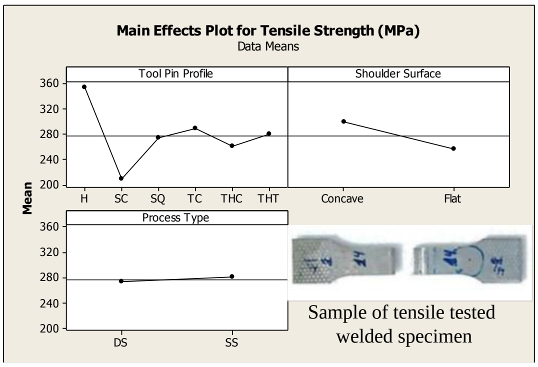

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Figure 11: Main effect of tool pin profile, shoulder surface and welding process type on the tensile strength

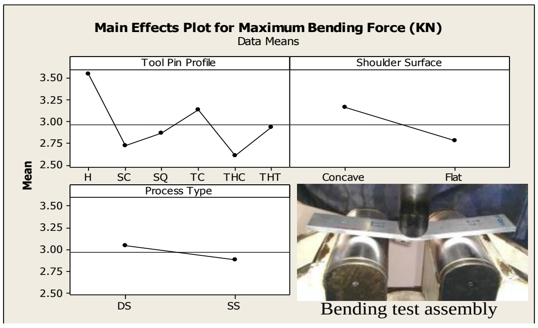

Figure 12: Main effect of tool pin profile, shoulder surface and welding process type on the maximum bending force

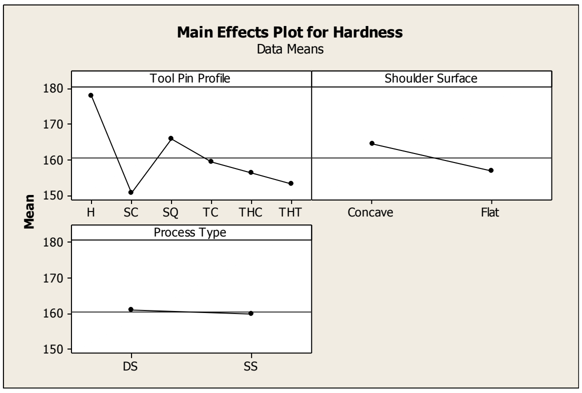

Figure 13: Main effect of tool pin profile, shoulder surface and welding process type on the hardness

3.2 Microstructure examination results:

The microstructure results of welded metal are different from that of base metal. During welding, a hot working process with a large deformation is induced into the work piece through pin and shoulder.

The microstructure of welded specimen5 (which represents the optimum mechanical properties) is presented here, figure (14, 15 and 16). Figure (14) explain the nugget zone or weld metal which is fully re-crystallized at the weld center. The microstructure of (NZ) consists of equiaxed grain in smaller size as comparing with the base material, figure (16-B).

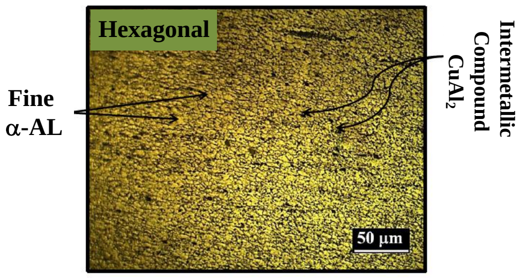

Figure 14: Microstructure of FSW welded joint specimen (5) in (NZ)

The other region is thermo-mechanical affected zone (TMAZ), figure (15) which has no re-crystallized. This region consists of two different microstructure regions. The first, fine grain region on the upper left side resulted from the action of prop rotation. The second region is an elongated microstructure remaining from base metal.

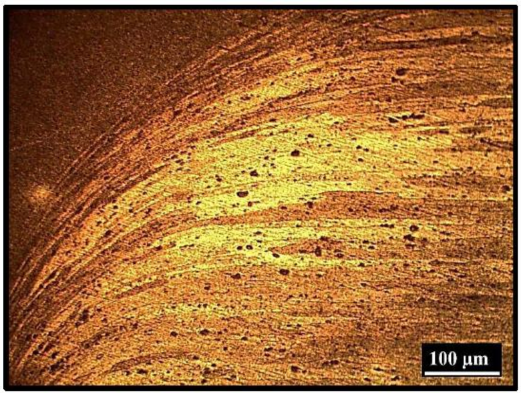

Figure 15: Microstructure of FSW welded joint specimen (5) in transition region

The microstructure of (HAZ) and (BM) is shown in figure (16).

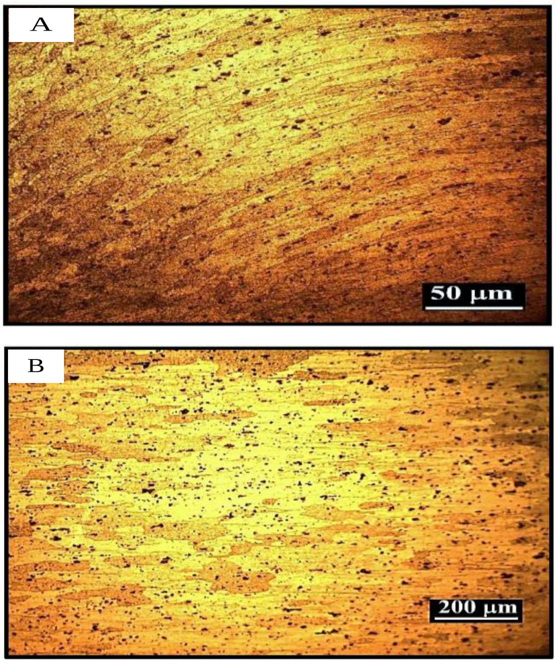

Figure 16: Microstructure of FSW welded joint specimen (5) in the regions of (a) HAZ (b) BM

4. Conclusions:

1. The optimum mechanical properties are observed when the specimen is weld by hexagonal pin profile concave shoulder with single side welding process.
2. The minimal tensile strength is found when the specimen is weld by straight cylinder as compared with the other profiles.
3. The minimum bending force and hardness is presented in the specimen welded by flat shoulder straight cylinder with single side welding process.
4. The hardness values of nugget zone are higher than that of base metal for all specimens. The optimum result is recorded by hexagonal pin with concave shoulder profile.
5. Design of Experiments illustrate that the hexagonal profile gave the maximum mechanical properties, where, the straight cylinder gave the minimum tensile strength and hardness.
6. From Design of Experiments, a good mechanical property is found when the concave shoulder used and a sensible increment and reduction in the tensile strength and hardness respectively is observed in the single side process as comparing to that in the double side.
7. The re-crystallization is fully in the NZ and not exists in the TMAZ.

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تأثير الاشكال المختلفة للعُدة في لحام المزج الاحتكاكي لسبيكة المنيوم AA2024-T3 بإستخدام طريقة تصميم التجارب

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الخلاصة:

في هذا البحث، تم لحام سبيكة الالمنيوم (AA2024-T3) بطريقة المزج الاحتكاكي باستخدام انواع مختلفة التصميم لشكل النتوء؛ اسطوانة مستوية, اسطوانة مسننة، اسطوانة مغزلية، سداسي، مربع ومغزل مسنن. استُخدم لكل نوع كتف مسطح ومقعر، بالاضافة الى ذلك، كانت عملية اللحام منفردة ومزدوجة. تم تحليل نتائج الاختبارات الميكانيكية بأستخدام طريقة تصميم التجارب. افضل واضعف الخواص الميكانيكية (مقاومة الشد، قوة الانحناء والصلادة) لوحظت عندما يُنجز اللحام بأستخدام النتوء ذو الشكل السداسي والاسطواني المستوي على التوالي. اعطى الكتف المقعر اعلى الخواص الميكانيكية مقارنة مع الكتف المسطح. اعطى التغيير في نوع عملية اللحام تأثير محسوس. صلادة منطقة خط اللحام اعلى من المعدن الاساس لكافة العينات. سُجلت امثل نتيجة صلادة بإستخدام النتوء السداسي ذو الكتف المقعر.