The Effect of Tool Geometry on Strength of Friction Stir Welding

تأثير الشكل الهندسي للعدة على متانة لحام الخلط الاحتكاكي

Dr. Moneer H. Al-Saadi — Prof. — Monerht@yahoo.com — University of Kerbala

Dr. Sabah Khammass Hussein — Asis. Prof. — Sabah.kh1974@yahoo.com — Technical college-Baghdad

Mursal Luaibi Saad — Mursal673@gmail.com — Technical college-Baghdad

Abstract

In this research, attempt has been made to understand the effect of tool shape on the strength of aluminum alloy (AA2024-T3). Seven different tool pin profiles (straight cylindrical, threaded cylindrical, tapered cylindrical, threaded taper, triangular, hexagonal and square) with two different shoulder surfaces (flat and concave) that have been used to fabricate the joint.

The effect of tool geometry on the strength of welded joints was investigated using different mechanical tests including (tensile, bending and microhardness tests). Also, a non-destructive tests including (visual and liquid penetration tests) were achieved. Microstructural characteristics during friction stir weldingprocess were studied and the welding joints were investigated using optical microscope.

The best mechanical properties obtained in this research were observed in the hexagonal pin profile with concave shoulder where the maximum welding efficiencies were (89.4%) and (85.71%) in terms of ultimate tensile strength and bending force respectively. The weakness tensile strength and bending force were found in the straight cylinder pin profile with flat shoulder as compared with the other tool shapes. The hardness values are higher in the weld zone compared to that in base metal. The maximum value of hardness is observed in the nugget zone of welded sample with hexagonal pin and concave shoulder profile. A fine equiaxed grains size is formed along the parent metal grain structure.

Keywords: Friction stir welding, tool geometry, tensile strength.

الخلاصة

في هذا البحث تم دراسة تأثير شكل العدة على مقاومة سبيكة المنيوم(AA2024-T3). تم استخدام سبعة اشكال لنتوء العدة لأجراء اللحام(الأسطوانة المستقيمة، الأسطوانة المسننة، اسطوانة مائلة، سن مائل، مثلث، سداسي ومربع) مع نوعين مختلفين لسطح الكتف (المسطح والمقوس). لدراسة تأثير شكل العدة على الملحومات استُخدِمَت اختبارات ميكانيكية مختلفة (الشد، الانحناء والصلادة الدقيقة). كذلك استُخدِمَت اختبارات لا اتلافيه (الفحص البصري والصبغة السائلة). دُرِسَت خصائص البنية المجهرية للملحومات باستخدام المجهر الدقيق.
احسن الخواص الميكانيكية وجدت في لحام النتوء ذو الشكل السداسي والكتف المقوس حيث اقصى كفاءة للحام هي(89.4% و 85.71%) لأقصى مقاومة شد وقوة انحناء على التوالي. اضعف مقاومة شد وقوة انحناء وجدت في لحام النتوء ذو الشكل الاسطوانة المستقيمة مقارنة مع بقية الأشكال. قيم الصلادة كانت عالية في منطقة اللحام مقارنة مع المعدن الأساس. اقصى قيمة للصلادة لوحظت في مركز خط اللحام للنتوء السداسي ذو الكتف المقوس. تشكلت الحبيبات البلورية الناعمة المتساوية المحاور بامتداد البنية البلورية للمعدن الأساس.

(1) Introduction.

Friction Stir Welding (FSW) is one of the solid state processes where the plates to be joined are fixed on a backing plate to resist the vertical, longitudinal and horizontal forces. A tool with a specific design made from a hard, wear resistant material relative to the material being joined, is rotated at a fast rate and slowly plunged into the abutting or overlapping edges of the plates to be welded**[1]**.

In friction stir welding the joining of plates takes place below the melting point of the materials. 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].**

1.1 The FSW Process Phases.

The frictional stir weld consists of the following processes:-

• **Plunge**: In the plunge, the tool penetrates slowly into the material with a predefined rotation speed until the shoulder has a full contact with the material. The required forces are the biggest in this phase.

• **Dwell**: In this phase the material is being heated up. There is no traverse motion and the dwelling phase ends when the material has reached a satisfying plasticity. In thin material this phase can be very short or can even be neglected.

• **Weld**: After reaching an adequate temperature, the tool moves in the direction of the weld seam at certain tilt angle and traverse speed.

• **Retract**: After reaching the end-point the tool is pulled away from the material while it is still rotating. This leaves a keyhole in the material **[3]**.

A simple FSW process is shown in figure(1)

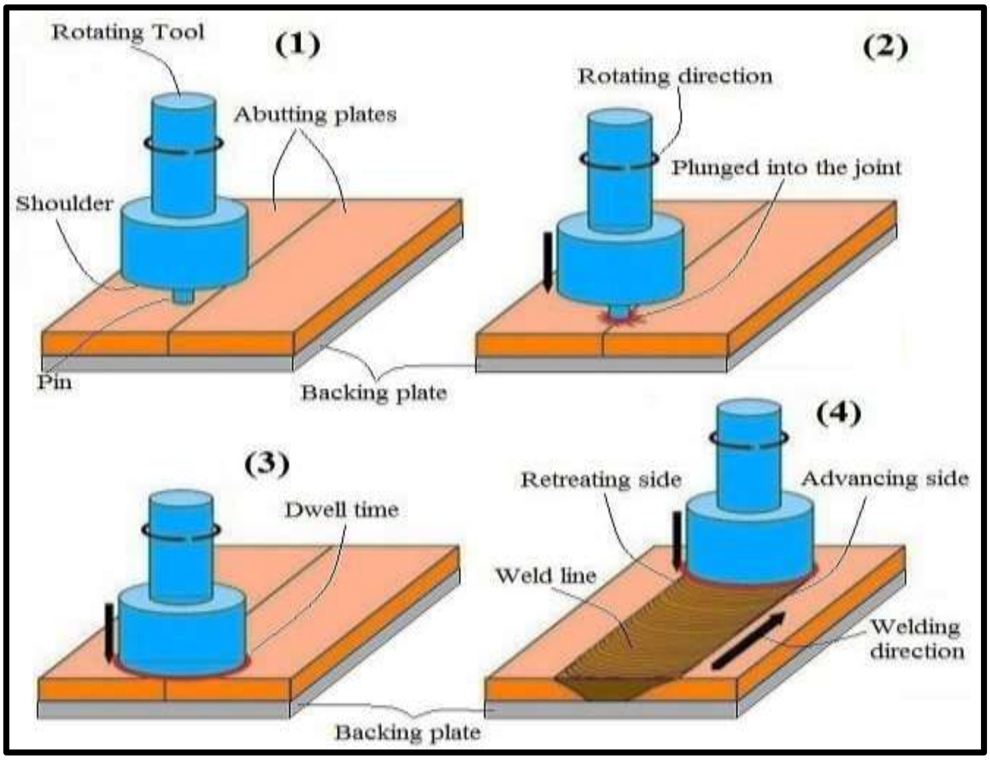


Figure 1: Friction stir welding steps**[4]**.

1.2 Friction Stir Welding Tools.

The tool is a primary member in (FSW) where the welding is not possible without this nonconsumable tool. It causes thermo-mechanical deformation and the necessary frictional heating. During plunging step, the rotation tool is pressed into the workpiece.

The friction stir welding tool includes pin or probe and shoulder. When the pin is in contact with the workpiece, it produces deformational and frictional heating that makes workpiece material soft. The contact between workpiece and shoulder raises the heat in workpiece, increases the zone of softened material and prevents the deformed material from escape**[5].**

1.3 Tool Geometry.

Tool geometry is the most influential aspect of process development. The tool geometry plays a critical role in material flow and in turn governs the traverse rate at which FSW can be conducted **[6].**

The most of the heat has been generated by the shoulder while both the tool pin and the shoulder affect the material flow**.** Friction stir welds are characterized by well-defined weld nugget and flow contours, almost spherical in shape, these contours are dependent on the tool design and welding parameters and process conditions used **[7].**

(2) Experimental Work.

2.1 Select the Proper Tool Material.

The tools material that were used in this work were oil hardening tool steel (ASTM A681 O1 type). The hardness value of this type was (207 HB) before heat treatment process. Chemical compositions are listed in Table(1) below.

2.2 Design and Manufacturing of Tools.

In this work, the dimensions of probe are:-

Rotation diameter = 5mm

Height = 4.7mm

The shoulder diameter is chosen three times pin diameter (shoulder diameter = 15mm). In order to obtain an optimum strength in weldments, two groups of pin and shoulder profile are used. The first group(A) represents a flat shoulder profile with seven pin profile. The second group(B) represents a concave shoulder profile with same seven pin profiles as follows, and as shown in Figure(2):

- Straight cylindrical
- Threaded cylindrical
- Tapered cylindrical
- Threaded taper
- Hexagonal
- Square
- Triangular.

Figure 2: Photograph of FSW tools.

The hardening and tempering were achieved for each tool after manufacturing process for improve their properties. After the heat treatment of each tool was done, a hardness test was achieved and the mean value of tool hardness is found (≅62 HRC), comparing with its value (17 HRC) before the hardening process.

Table (1) Chemical composition of ASTM A681 O1 tool steel type.

	C	Si	Mn	W	Cr	V	Cu	Ni
Measured	**0.894**	**0.268**	**1.11**	**0.4**	**0.5**	**0.15**	**0.16**	**0.06**
Standard [8]	**0.85–1**	**0.1–0.5**	**1–1.4**	**0.4–0.6**	**0.4–0.7**	**0.3**	**Cu+Ni = 0.75 max.**	

Schematic details of both groups (A and B) of tools are shown in figures (3) below.

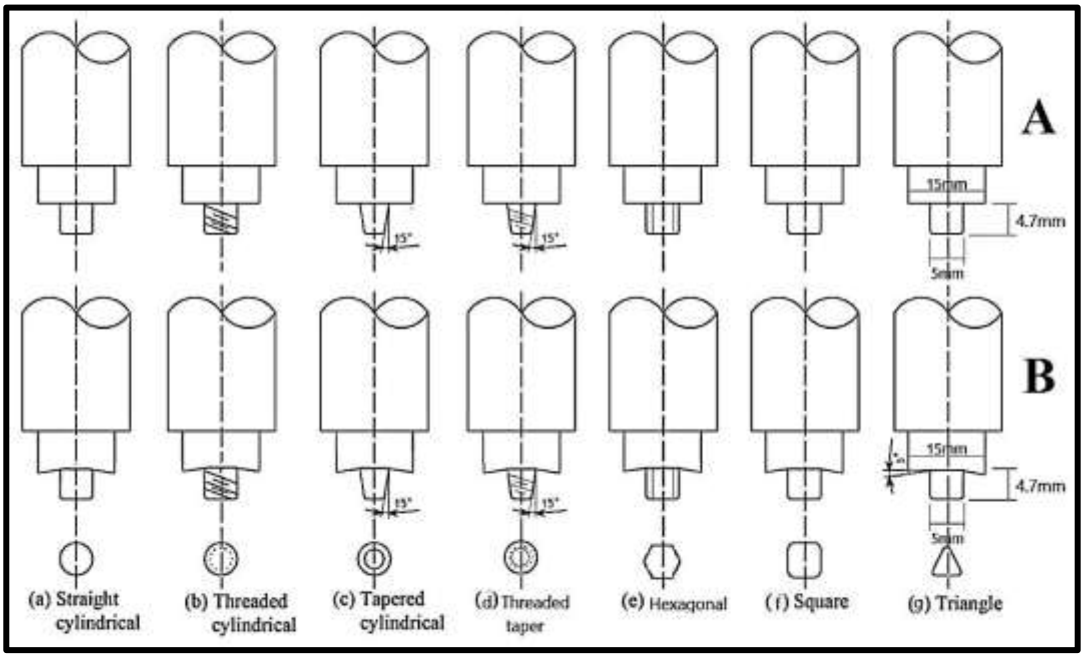


Figure 3 : Schematic of the tools with flat(A) and concave(B) shoulder surface.

2.3 Welding process.

2.3.1 Prepare the Plate:-

The material of specimens that was used in this work is of Aluminum alloy type (AA2024-T3 alloy). Chemical composition and mechanical properties of this material are listed in Tables(2) and (3) respectively.

Table (2) Chemical composition of AA2024-T3 alloy.

	Standard % (ASTM B209) [9]		Measured %
Si	0.50		0.061
Fe	0.50		0.181
Cu	3.8 min. 4.9 max.		4.05
Mn	0.3 min. 0.9 max.		0.596
Mg	1.2 min. 1.8 max.		1.40
Cr	0.10		0.004
Zn	0.25		0.076
Ti	0.15		0.027
Ga	-		0.0005
V	-		0.008
Ni	-		0.002
Other elements	each	0.05	
	total	0.15	0.024
Aluminum	Rem.		Rem.

Table (3) Mechanical properties of AA2024-T3 alloy.

	Yield stress (MPa)	Tensile stress (MPa)	Elongation (%)	Hardness (HV)
Nominal (ASTM B209) [9]	289 Min	434 Min	12 Min	137
Actual	302	446	13.2	145

The specimens to be welded were cut into small rectangular pieces with dimensions (150mm×75mm) from 5mm plate thickness by Pressure Cutting Machine, Figure(4).

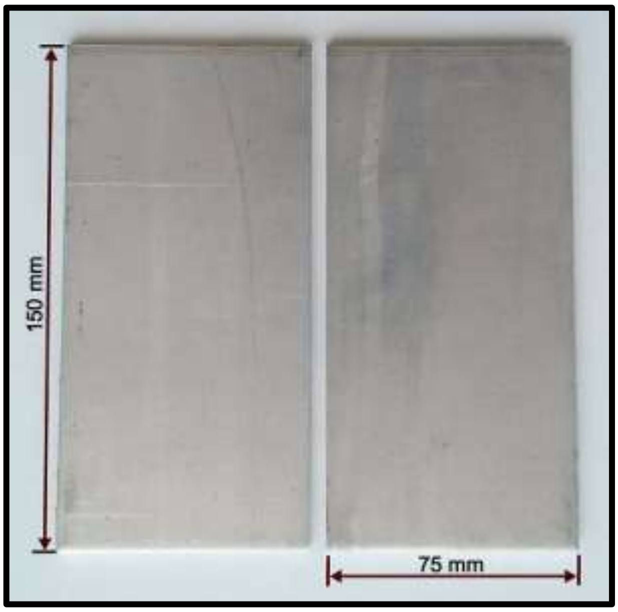


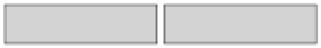
Figure 4: Sheets preparation for welding.

The rolling direction was considered during cutting process (perpendicular to welding line). The pieces edges were grinded to insure that there was no gap between the two pieces.

2.3.2 Process Features.

The welding machine used in this work was a milling machine. Details of the features of the welding process are listed in Table (4).

Table (4) Summary of the FSW patterns.

Weld feature	The details
Joint configuration	Butt joint 
Material welded	AA2024-T3 to AA2024-T3
Plate thickness	5mm
Length of welds	140-150mm
Number of welds made	Two for each tool shape
Welding method	1- One side 2- Both sides with remixing process
Rotation speed	1000 rpm
Welding speed	28 mm/min
Tool tilt angle	3°

2.4 Welding Tests.

In this work, two types of tests were done to investigate the welding properties.

- ❖ Nondestructive tests which include :-
  - Visual test.
  - Liquid penetrant test.
- ❖ Destructive tests which include :-
  - Tensile test.
  - Bending test.
  - Micro hardness test.

A simple tensile test specimen is cut perpendicular to the weld line. It includes the (NZ, TMAZ, HAZ and the base metal) represented along the gage length.

Tensile specimens were prepared from the weldments according to the AWS D17.3/D17.3M:2010 **[10].**

Standard dimensions of tension test specimens are shown in Figure(5).

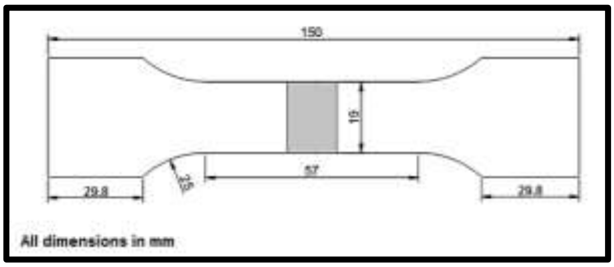


Figure 5 : Standard dimensions of tensile test specimen for FSW **[10].**

The tensile test data is recorded for each specimen which includes the force and elongation that were calculated from tensile test machine. All specimens were machined in a similar manner to the same dimensions. Figure(6) shows the tensile test specimens of welds.

Figure 6 : Tensile test specimens of FSW.

Bending test is used to determine the ductility and strength of welded joints. Bending specimens were machined from the weldments according to the AWS(B4.0:2007) **[11]** in dimensions (150*38*5) mm. The specimens were tested in three-point transverse bending, which was used in this study.
The Vickers hardness test was used in this study. The testing was performed according to (ASTM E92-82) **[12].**

(3) Results :-

3.1 Nondestructive Tests Results:

3.1.1 Visual Tests Results:

Visual tests are the first of tests that are used before, during and after the welding process. In this test a lot of the defects can be discovered with eye then evaluated directly if it were acceptable or not. Consequently, the quality of welded joints in several shapes of tool geometries will be evaluated also.
Visual test of weldment is applied in three stages:
1- Prior welding process.
2- During the welding process.
3- After the welding process.

3.1.1.1 Prior Welding Process: This stage of visual inspection includes more functions such as checking the weld joint preparation, edges finishing, and other features that might affect the quality of the weld. Generally, the following matters have been checked.

- Machine parameters and the adjusting process.
- Welding procedures.
- Joint preparation, dimensions, and pre-cleaning.
- Good finish of two pieces (plate) edges that will be welded and fixed together (butt joint) without a gap between them, this gap if it exists affects weld quality and causes defects in welding line.
- Fixture setting, alignment, and the two pieces clamping to prevent any movement during welding process.

3.1.1.2 During Welding: The second stage of visual inspection begins with the start of the welding process and perform the checking:

- Surface of weld line if defects exist which are due to tool offset and shoulder heel, figure (7).
- Excess flash of metal due to excessive plunging tool depth, figure (8).
- Smoothness of weld face, figure (9).

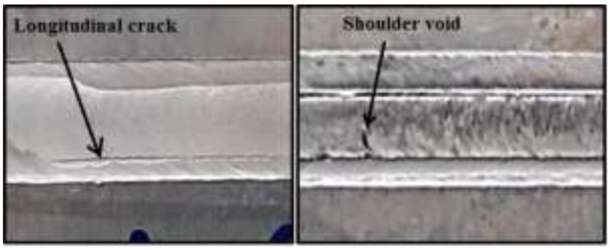


Figure 7 : Longitudinal crack and shoulder void.

Figure 8 : Flash formation.

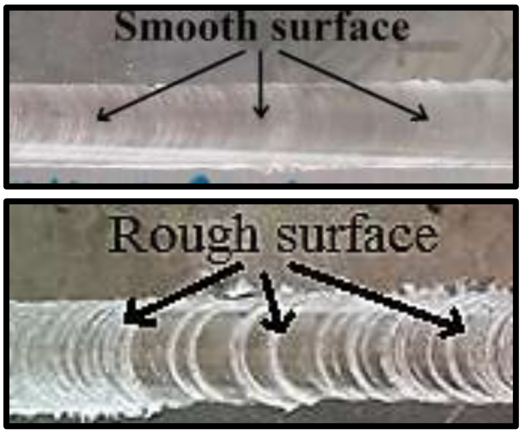


Figure 9 : Smoothness of weld face.

3.1.1.3 After Welding: Matters that were inspected through this stage of visual inspection include weld line dimensions (plunging and width), figure(10), angular distortion of the joint, figure(11), misalignment of weld, figure(12), back surface cracks, and lack of penetration(LOP).

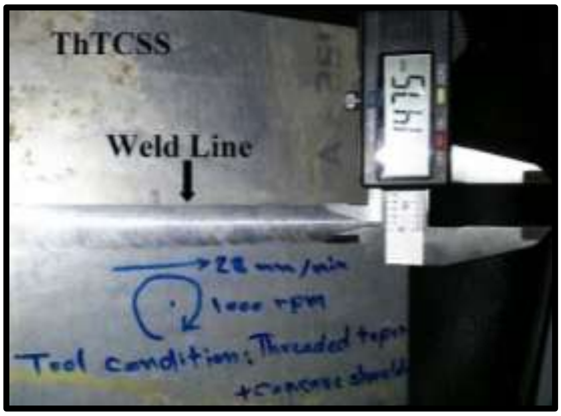


Figure (10): Measurement of weld line dimensions.

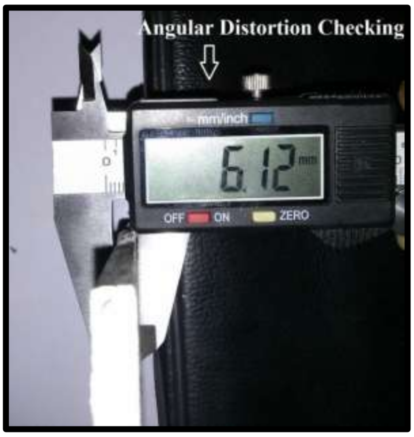


Figure (11): Check of the angular distortion of specimens.

Figure (12): Misalignment of weld.

3.1.2 Liquid Penetrant Test Results:

During this type of inspection, defects that had accurate sizes could be detected easily. These defects were found by using the Liquid Penetrant Inspection, they were surface cracks that cannot be detected by visual inspection due to the critical nature of surface cracks for the (FSW) on face and root of weld. The result of liquid penetrant test and visual test are compared with the requirements of friction stir welding specification **[10].**

3.2 Destructive Testing Results:

These tests were performed on the weldments that passed through nondestructive tests and met the acceptance criteria. The results were recorded for each tool for its four cases (single side welding: flat and concave tool shoulder and welding of both sides with remixing process: flat and concave tool shoulder).

3.2.1 Tensile Test Results:

Tensile test was done until the failure take place, figure (13).

Figure 13: Tensile tests specimens after testing.

The results were divided according to the tool profile and process type. The tensile strength values were compared with the parent metal value(446MPa). Figure(15) shows the tensile strength for all types of tool profile. As it has been observed , the hexagonal type gives approximately a higher tensile strength as compared with the other types. On the other hand , the minimal tensile strength is observed in the straight cylinder profile.

3.2.2 Bending Test Results:

The results of bending test were recorded after all the specimens cracked, figure(14). The maximum values of bending force were compared with the parent metal value (4.9KN). All tensile and bending specimens were broken during the test in the welding area, this gives reassurance and reduces the expected error percentage. The results of tensile and bending tests will be displayed together below for each of the tools.

Figure 14: Bending test.

Higher bending forces are found in the hexagonal pin profile especially in the single sided process. The minimal bending force is found in the straight cylinder especially in the double side with remixing process, figure(16).

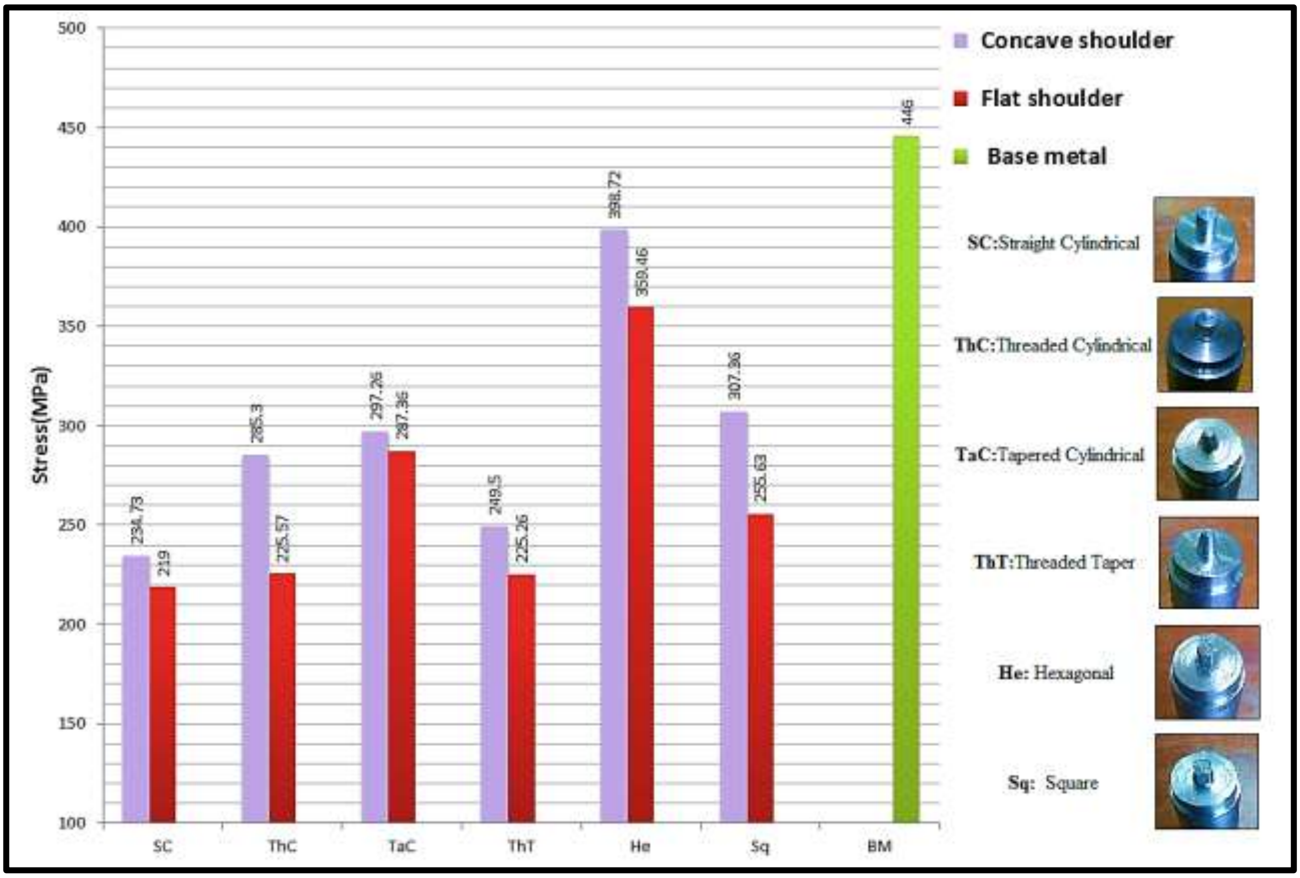


Figure 15: Variation of ultimate tensile strength for all types of tool.

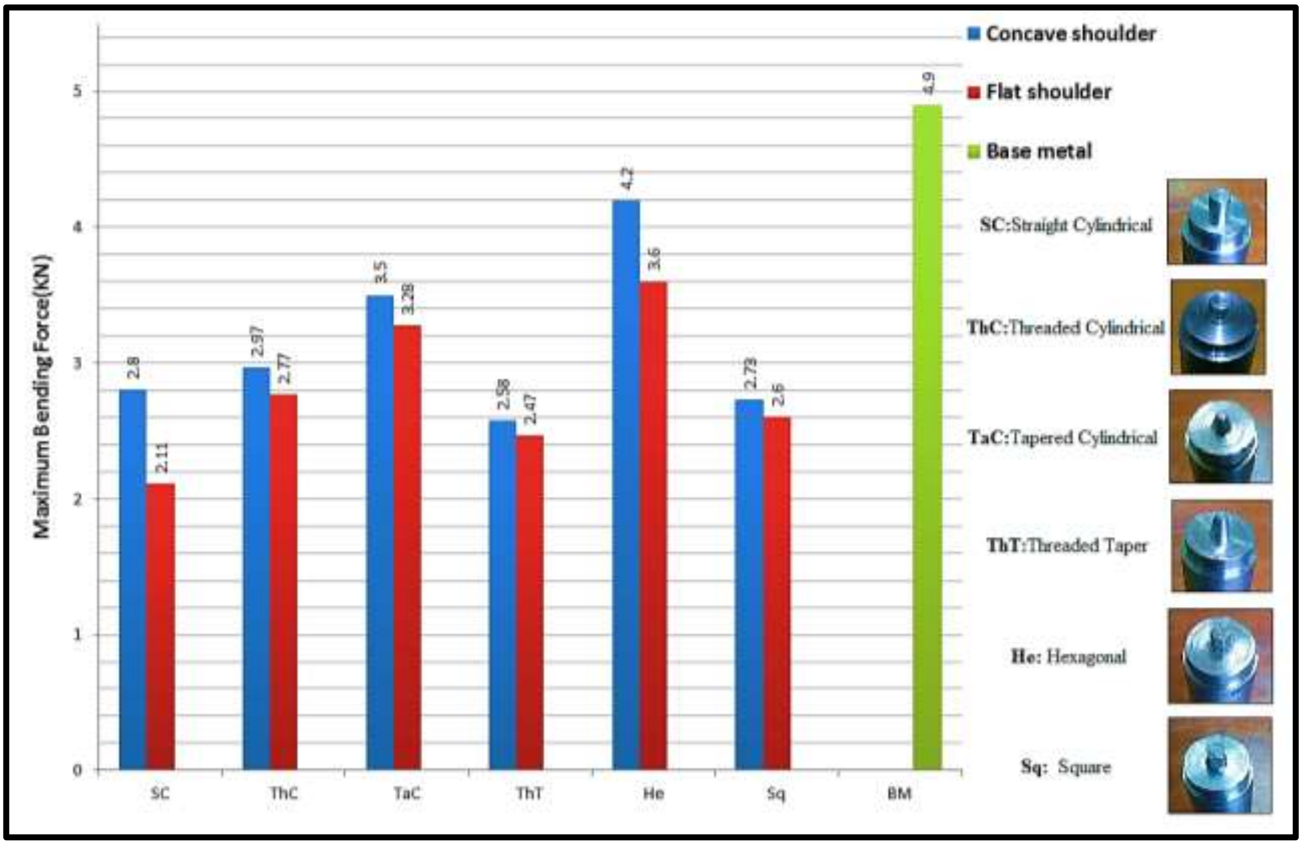


Figure 16: Variation of maximum bending force for all types of tool.

Triangle Pin Profile: The Triangle(Tr) shape of tools was failed to made welding where the stir action isn't adequate to create joint between the two sheets that to be welded.

3.2.3 Microhardness Results:

The microhardness results of all specimens show almost similar behavior of test data from HAZ toward the center of weld figure(17).

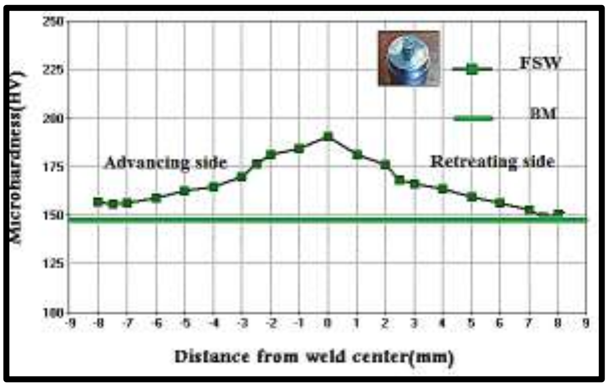


Figure 17: Hardness distribution along (FSW) zone of hexagonal tool with concave shoulder.

The microhardness results prove that the hardness on one side of weld center differs from the other side.

This phenomenon can be interpreted as follows: On the advancing side of the rotating tool where the rotational velocity vector and the forward motion vector are in the same direction and due to this there is higher heating on one side of the weld center and hence higher the hardness.

The microhardness results show that value of the hardness in nugget zone of all specimens is high compared with base metal hardness, figure(18) . The maximum value of hardness(188 HV) was observed in tool with hexagonal pin, concave shoulder profile. On the other hand the minimum value of hardness(146.5 HV) was observed in tool with straight cylindrical pin, flat shoulder.

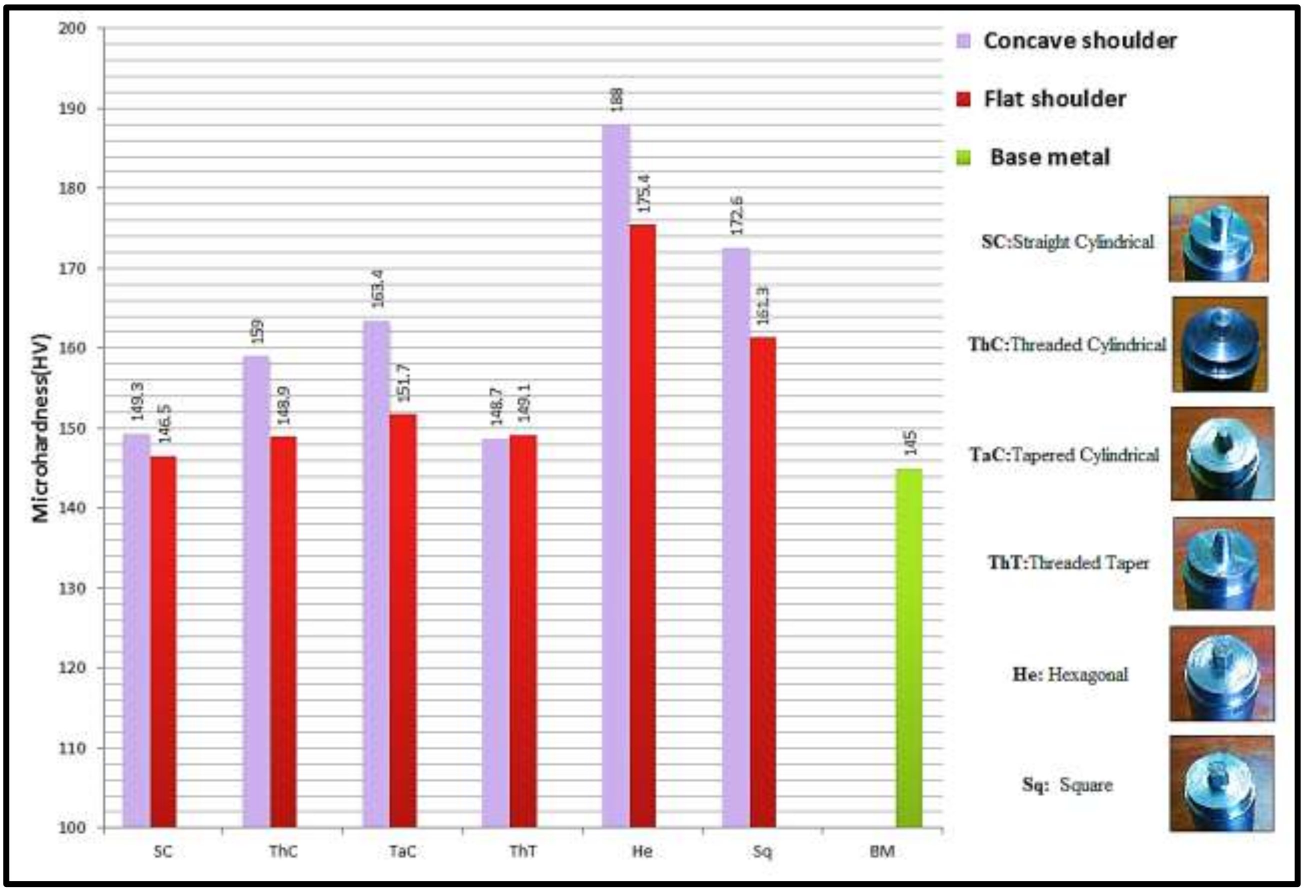


Figure 18: Variation of microhardness value for all types of tool.

(4) Conclusions:

From the obtained results of the present study on (FSW) tool geometry, several conclusions can be drawn regarding appearance of welds, mechanical and microstructural properties.

1. Welding process defects such as crack, shoulder void, flash, and surface roughness can be controlled by welding machine parameters.
2. The best mechanical properties obtained in this research are observed in the hexagonal pin profile concave shoulder .
3. Approximately, the mechanical properties (tensile strength and bending force) in the square pin profile are the same as those in the threaded and tapered cylinder profile.
4. A higher tensile strength and bending force values are found in the hexagonal pin profile. Whereas, the minimal values are found in the straight cylinder as compared with the other profiles.
5. The hardness values of weld zone are higher than that of base metal for all specimens.

6. As it is clear in all specimens the concave shoulders display a higher hardness than flat shoulders

(5) References:

[1] R. Kramer "*F*atigue and Fracture Behavior of Fusion and Friction Stir Welded Aluminum Components" , Ship Structure Committee, Report No. SSC–447 SR-1444, Performing Organization Code 5813C.FR, USA(2007).

[2] H. K. Mohanty, M. M. Mahapatra, P. Kumar1, P. Biswas and N. R. Mandal " Effect of Tool Shoulder and Pin Probe Profiles on Friction Stirred Aluminum Welds – a Comparative Study " ,Journal of Marine Science and Application (2012) 11: 200-207, DOI: 10.1007/s11804-012-1123-4.

[3] Jeroen De Backer "Robotic Friction Stir Welding for Automotive and Aviation Applications " , M.Sc Thesis, University West , Sweden (2009).

[4] Tracie Prater "An Investigation into the Friction Stir Welding of Al6061 and Al6061/Sic/17.5p Using Diamond Coatings" , M.Sc Thesis, Graduate School of Vanderbilt University, 2008.

[5] Rajiv S. Mishra and Murray W. Mahoney "Friction Stir Welding and Processing" , ASM Handbook, editors, p 1-5 DOI:10.1361/fswp2007p001.

[6] R.S. Mishra, and Z.Y. Ma " Friction Stir Welding and Processing " ,Materials Science and Engineering R 50 (2005) 1–78 , A Review Journal, doi:10.1016/j.mser. 2005.07.001 .

[7] Mandeep Singh Sidhu and Sukhpal Singh Chatha "Friction Stir Welding – Process and its Variables: A Review" , International Journal of Emerging Technology and Advanced Engineering, Volume 2, Issue 12, December 2012.

[8] American Society for Testing and Materials (ASTM) "Standard Specification for Tool Steels Alloy" , ASTM A681 – 94, 1999.

[9] American Society for Testing and Materials (ASTM) "Standard Specification for Aluminum and Aluminum-Alloy Sheet and Plate" , ASTM B209, 1996.

[10] American Welding Society "Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Hardware" , An American National Standard, AWS D17.3/D17.3M:2010.

[11] American Welding Society (AWS) "Standard Methods for Mechanical Testing of Welds" , AWS B4.0:2007.7th Edition, Approved by the American National Standards Institute(ANSI).

[12] American Society for Testing and Materials (ASTM) "Standard Test Method for Vickers Hardness of Metallic Materials" , ASTM E92–82, (2003).

(6) Abbreviations

AA ……. Aluminum Association Designation

FSW …….Friction Stir Welding

HAZ ….. Heat Affected Zone

NZ ………Nugget Zone

TMAZ...........Thermo-Mechanically Affected Zone