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Experimental investigation of Tool Geometry on Mechanical Properties of Friction Stir Welding of AA6061

Puneet Rohilla, Narinder Kumar

Abstract: AA 6061 has gathered wide acceptance in the fabrication of the light structures required to high strength. Compared to the fusion welding processes that are used for joining structural aluminium alloys, friction stir welding (FSW) process is an emerging solid state joining process in which the material that is being welded does not melt and recast. In this experimental work, an extensive investigation has been carried out on FSW butt joint. Welded joints were made with the help of tool made of high speed steel (HSS) alloy steel. Tools were of two different pin profiles viz. straight cylindrical, and square. The welded joints were made on aluminum grade AA 6061 plates of 6 mm thick. Tests were conducted to determine the tensile strength, percentage elongation and micro hardness. In my investigation, tool rotation and traverse speeds are kept constant i.e. 2000 rpm and 20 mm/min. The variables are shape of the tool and having passes one sided and both sided. Cylindrical tool pin profile exhibited superior tensile properties compared to other joints, irrespective of tool rotational speed in double pass. The joints fabricated by single pass have shown lower tensile strength and also percentage of elongation compared to the joints fabricated by double pass and this trend is common for all the tool profiles.

Keywords-Friction Stir Welding (FSW), Aluminium AA 6061, Tensile strength

I. INTRODUCTION

Aluminium 6061 alloy is widely used for commercial applications in the transportation, construction and similar engineering industries. It possesses excellent mechanical properties which allow it to be machined rapidly and economically. In addition to that, Al 6061 also has good corrosion resistance due to which the alloy finds extensive application in operating conditions where such properties are key essentials such as naval vessels manufacturing.

Friction stir welding (FSW) is a relatively new solid state welding process which is used for butt joints. FSW was invented by The Welding Institute, Cambridge, UK in 1991 [1] and has emerged as a new process for welding of aluminum alloys. This process has made possible to weld a number of aluminum alloys that were previously not recommended (2000 series & copper containing 7000 series aluminium alloys) for welding [2]. Because the material subjected to FSW does not melt and re-solidify, the resultant weld metal is free of porosity with lower distortion. An added advantage is that it is an environmentally friendly process. FSW is a solid state, localized thermo mechanical, joining process.

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In FSW, a non-consumable rotating shouldered-pin-tool is plunged into the interface between two plates being welded, until the shoulder touches the surface of the base material, and then tool is transverse along the weld line. In FSW, frictional heat is generated by rubbing of tool shoulder and base material surface. During traversing, softened material from the leading edge moves to the trailing edge due to the tool rotation and the transverse movement of the tool, and this transferred material is consolidated in the trailing edge of the tool by the application of an axial force. FSW parameters are tool geometry, axial force, rotational speed, transverse speed and tool tilt angle. General convention is, where the direction of the velocity vector of the tool and traverse direction are same that side is called the advancing side of the weld, and when the direction of the velocity vector opposite to the traverse direction, it is called the retreating side.

Many attempts have been made on FSW on aluminium alloys. S.Ugender [3] studied the influence of tool pin profiles on microstructure and mechanical properties of friction stir welded AA 6061-T6 Alloy. An attempt is made here to review the fundamental principle of this process its tensile strength and examination of its metallurgical consequences. An improved milling machine is fabricated for performing friction stir welding and its effectiveness in joining Al 6061-T6 Alloy plates is demonstrated.

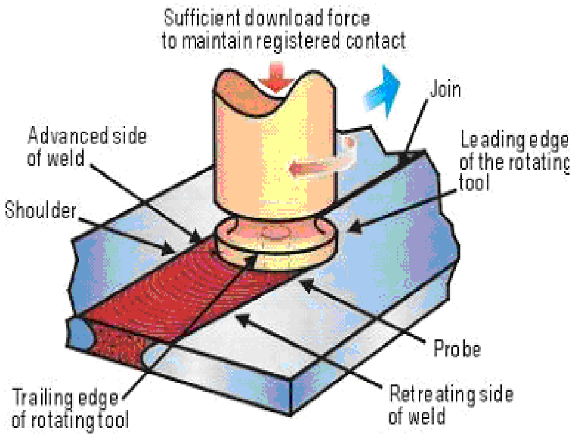

Fig1- Schematic representation of FSW

An attempt has been made to study the effect of tool rotational speed, traversing speed and tool pin profiles (Taper Thread profile) on FSW zone transformation in Al alloys. A. Heidarzadeh [4] attempted used to develop a mathematical model predicting the tensile properties of friction stir welded AA 6061-T4 aluminum alloy joints at 95% confidence level.

The three welding parameters considered were tool rotational speed, welding speed and axial force. Analysis of variance was applied to validate the predicted model. The effects of the welding parameters on tensile properties of friction stir welded joints were analyzed in detail. The results showed that the optimum parameters to get a maximum of tensile strength were 920 rev/min, 78 mm/min and 7.2 kN, where the maximum of tensile elongation was obtained at 1300 rev/min, 60 mm/min and 8 kN. Prashant Prakash [5] studied that in FSW parameters play an important role like tool design and material, tool rotational speed, welding speed and axial force. The paper focuses on process parameters that in required for producing effective friction stir welding joint. Thomas Bloodworth objective of this research was to quantify the material properties as well as the forces unique to immersed friction stir welding (IFSW) as compared to conventional friction stir welding (FSW) performed in air of AA6061. These results were compared by using ultimate tensile strength (UTS) and weld root properties such as joint line remnant length at the interface between the welded aluminum alloys which allows crack initiation. Metallurgic cross sections of the AA6061 welds were prepared and the weld nugget hardness between the two welding techniques was compared as well. K. Bhanumurthy, N. T. Kumbhar [6] observed that, during the friction stir welding, extensive deformation is experienced at the nugget zone and the evolved microstructure strongly affects the mechanical properties of the joint. FSW trials were carried out using a vertical milling machine on Al 6061 alloy. The tool geometry was carefully chosen and fabricated to have a nearly flat welded interface. Important process parameters that control the quality of the weld are a) axial force b) rotation speed (rpm) c) traverse speed (mm/min) and d) tool tilt angle and these process parameters were optimized to obtain defect free welded joints. K. Elangovan, V. Balasubramanian [7] studied the effect of tool pin profile and tool shoulder diameter on FSP zone formation in AA6061 aluminium alloy. They used five different tool pin profiles (straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square) with three different shoulder diameters fabricate the joints. The formation of FSP zone had been analyzed macroscopically. Tensile properties of the joints had been evaluated and correlated with the FSP zone formation. From this investigation they concluded that the square pin profiled tool with 18 mm shoulder diameter produced mechanically sound and metallurgically defect free welds compared to other tool pin profiles.

Single pass friction stir welding is not able to provide better results in case of thick work material plates which is mainly due to the difficulty in finding a suitable backing material. Obviously the thickness of plate that can be joined by FSW can be increased by passing the tool along both sides of the butted plates in sequence. The use of the sequential double pass weld can almost double the plate thickness that can be joined, thereby significantly increasing the industrial utility of the FSW joining process for other materials like steels etc. Considering these facts, the objective of the present study is to investigate the influence of tool shape on the tensile strength of AA 6061 in single and double sided friction stir welds.

II. EXPERIMENTAL SET-UP

The base material used in this study was aluminium alloy AA6061 plates thickness of 6mm. A pair of work pieces of dimension 200mm ×200mm ×5 mm were abutted and clamped rigidly on the backing plate for welding, having chemical composition as shown in table 1:

Element	Al	Si + Fe	Mg	Cu	Mo	Other elements
Weight %age	97.56%	0.8%	0.15%	0.15-0.40%	0.05%	0.15% max

Table-1-Composition of AA-6061

The base material tensile strength is 0.088KN/mm2 with the elongation of 33.200%. FSW trials were carried out on vertical milling machine with the square butt joint configuration.

The welding tool material is High Speed Steel of hardness 60-63 HRC. Two different profiles are used i.e. cylindrical and square shown in fig 2 a and fig 2 b:

Fig-2 a) Circular Tool Profile

Fig-2 b) Square Tools profile

The tool material is available in 20 mm diameter rod. Straight Cylindrical tool geometries were processed on central grinding machine according to the dimensions specified. Square tool were processed on milling machine by indexing. Specifications of the tool are given in the table 2:

Specifications	Values
Tool Material	High Speed Steel
Length of tool	50 mm
Tool shoulder diameter	18 mm
Pin diameter	7.2mm

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Pin length for single pass	5.7mm
Pin length for double pass	3.7mm

Table-2: Tool specifications

It is worth noting that for the double pass weld, the plates were turned over about an axis along the weld after the first pass was made, so that the two welding passes started at the same position along the joint interface, and the advancing side of the second pass was over the retreating side of the first pass weld. All of the welds were carried out along the rolling direction of the steel plate.

Tool rotation speed, traverse speeds and tool tilt angle were kept constant at 2000 rpm, 20 mm/min and zero angle respectively. The process variables were, shape of the tool and tool passes on single and double sided. In both cases, depth of depression was 0.05 mm. For Friction Stir Welding, single and double pass were adopted:

Single pass FSW

- Tool pin length was 5.7 mm
- Time taken was 10 min for length 200 mm.

Double pass FSW

- Tool pin length was 3.7 mm
- Time taken was double i.e. 20 min for length 200 mm.

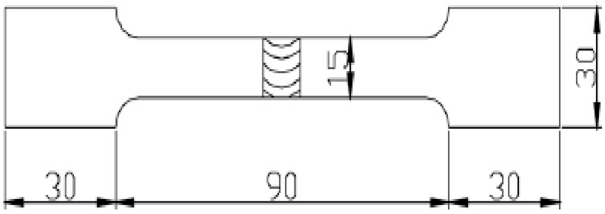

Fig-3 Dimensions of Tensile Specimen

Tensile test specimens were prepared according to the guidelines of the American Society for Testing of Materials (ASTM) shown in fig 3. Tensile test was carried out on 100 ton Universal Testing Machine at room temperature. The specimen was loaded as per ASTM so that tensile undergoes deformation. Then specimen finally failed after necking and the load v/s displacement was recorded. The ultimate tensile strength, percentage elongation and joint efficiency were evaluated. Specification of the tensile specimen:

- Cross sectional area = 5x15=75 mm^2
- Gauge length=50 mm

Micro hardness test was done on Viker's Hardness Tester. Micro hardness tester is based upon indentation method of testing. A diamond pyramid was used to create a permanent deformation in the surface of the test sample and then the hardness of the test sample was determined. The load used in Viker's hardness was 5kgF for 15 seconds.

III. RESULT

A) TENSILE TESTING

The specimens for tensile test were prepared according to the guidelines of American Society for Testing of Materials (ASTM) as shown in Fig. Test was carried out in 100 Ton; Universal Testing Machine at a room temperature. The specimen finally failed after necking and the load versus displacement was recorded UTM for t. Table 3 describes the specimen specifications used on the testing.

Table-3-Specimen specifications

Sample	Area (mm^2)	Width (mm)	Thickness (mm)	Gauge length (mm)	Final gauge length (mm)
Half square (HS)	90	15	6	50	57.5
Full square (FS)	90	15	6	50	54
Half Cylindrical (HC)	90	15	6	50	59.5
Full Cylindrical (FC)	90	15	6	50	62

Figure 4 shows the welded specimen after tensile testing on the UTM welded with the cylindrical tool profile (single pass).

Figure-4- Failure of Welded Specimen in Tensile Test (Single pass Cylindrical)

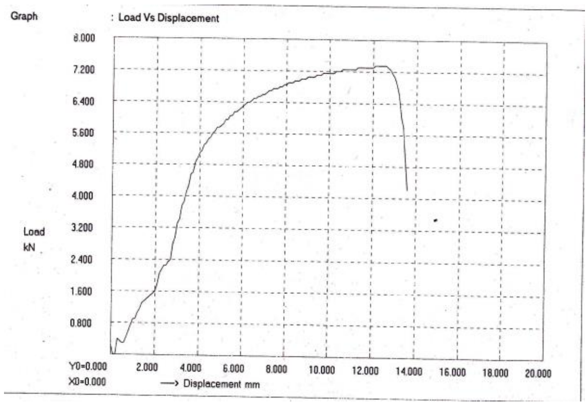

Fig-5-load v/s displacement (FC) Single pass

Figure 5 shows the graph recorded during the tensile testing of the welded specimen welded by the cylindrical tool profile (Single pass) where the tensile strength of the specimen is 0.082 KN/mm^2 at the load of 7.350 KN and the percentage elongation is 24%.

Figure 6 shows the e welded specimen after tensile testing on the UTM welded with the cylindrical tool profile (double pass).

Fig-6- Failure of Welded Specimen in Tensile Test (Double pass Cylindrical)

Figure 7 shows the graph recorded during tensile testing of the welded specimen on the UTM welded with the cylindrical tool profile (double pass) where the tensile strength of the specimen is 0.084 KN/mm^2 at the load of 7.600 KN and the percentage elongation is 19%.

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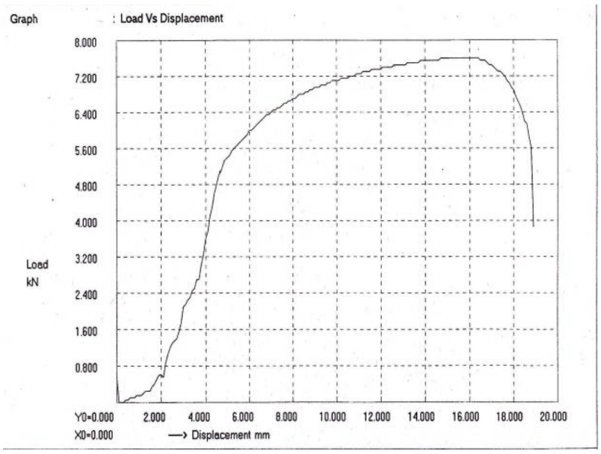

Fig-7-load v/s displacement (HC) Double pass

Figure 8 shows the welded specimen after tensile testing on the UTM welded with the Square tool profile (Single pass).

Fig-8- Failure of Welded Specimen in Tensile Test (Single pass Square)

Figure 9 shows the graph recorded during the tensile testing of the welded specimen on the UTM welded with the square tool profile (Single pass) where the tensile strength of the specimen is 0.059 KN/mm^2 at the load of 5.350 KN and the percentage elongation is 8%.

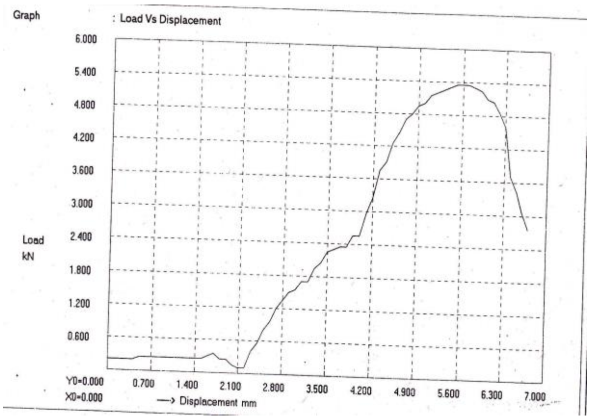

Fig-9-load v/s displacement (FS) Single pass

Figure 10 shows the welded specimen after tensile testing on the UTM welded with the square tool profile (Double pass).

Fig-10- Failure of Welded Specimen in Tensile Test (Double pass Square)

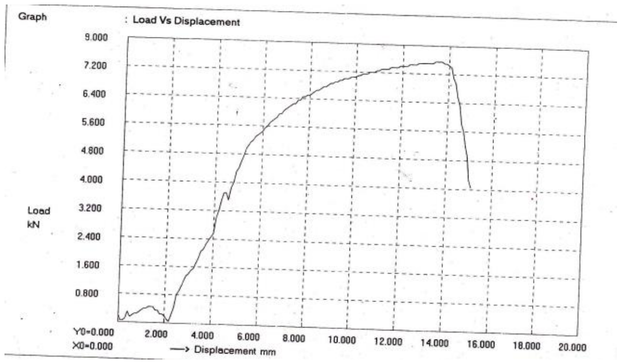

Fig-11- load v/s displacement (HS) Double pass

Figure 11 shows the graph recorded during tensile testing of the welded specimen on the UTM welded with the square tool profile (double pass) where the tensile strength of the specimen is 0.0838 KN/mm^2 at the load of 7.550 KN and the percentage elongation is 15%.

The tensile strength of the base material is 0.088 KN/mm^2 with percentage elongation of 33.200 %. Maximum force is 10.250 KN. The ultimate tensile strength, percentage elongation and joint efficiency were evaluated. In welding, joint efficiency is the ratio of the strength of a joint to the strength of the base metal, expressed in percentage:

Joint efficiency η = joint strength / parent strength

Transverse tensile properties of FSW joints i.e. ultimate strength, percentage elongation and the joint efficiency were evaluated shown in table 4 below.

Specimen No.	**Ultimate Tensile Strength**		**Percentage Elongation**	**Joint Efficiency**
	Load (KN)	**Stress (KN/mm^2)**	**% Elongation**	
Cylindrical (Single pass)	7.350	0.082	24	71.7%
Square (Single pass)	5.350	0.059	8	52.19%
Cylindrical (Double pass)	7.600	0.084	19	74.14%
Square (Double pass)	7.550	0.0838	15	73.65%

Table-4-Test Results

Figure 12 shows the variation in the tensile strength of the specimens. Half Cylindrical tool profile has the maximun tensile stress i.e. 0.084 KN/mm^2 and full square tool profile has the minimum tensile stress i.e. 0.059 KN/mm^2.

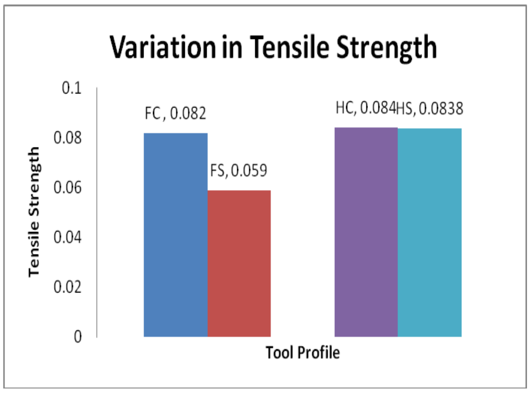

Fig-12: Variation of Tensile Strength

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In single pass, the highest tensile strength of the joints was obtained by using the cylindrical pin profile tool. The welding parameters have similar effects on the tensile properties for straight cylindrical and square pin profiles tools. The maximum and minimum ultimate tensile strength in using single pass was 0.082 KN/mm^2 and 0.059 respectively while maximum and minimum ultimate tensile strength in double pass was 0.084 KN/mm^2 and 0.0838 respectively

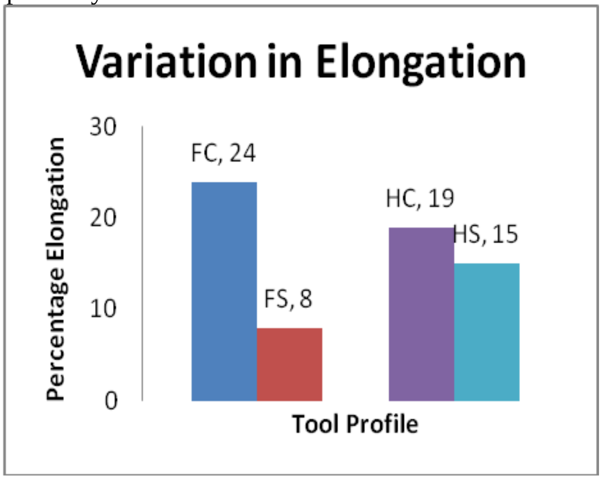

Fig-13-Variation in Percentage Elongation

Figure 13 shows the variation in the percenatge elongation of the specimens. Full cylindrical tool profile has the maximum percentage elongation i.e 24% and the full square tool profile has minimum percentage elongation i.e. 8%.

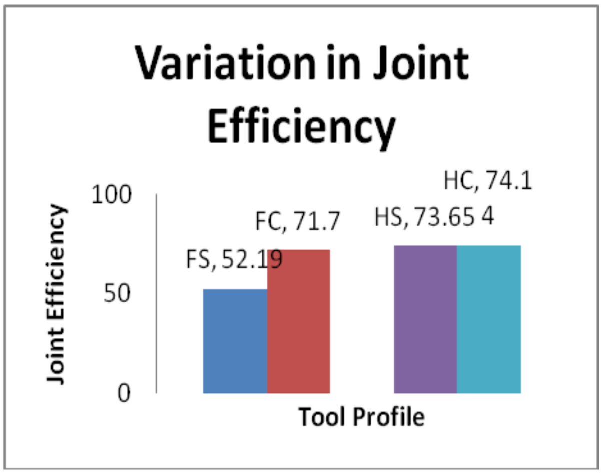

Fig-14-Variation in joint Efficiency

Figure 14 shows the variation in the joint efficiency of the specimens. Half cylindrical tool profile has the maximum efficiency i.e. 74.1 % and the full square tool profile has the minimum joint efficiency i.e. 52.19 %.

B) MICRO HARDNESS

Vickers micro-hardness profiles of the welded zones were measured on a cross- section perpendicular to the welding direction using a Vickers indenter with a 5kgf load for15 second. The micro hardness of base metal is 44.7 HV. Micro hardness of single pass and double pass is shown in table below. A plot of micro hardness as a function of position from the weld center line is plotted foe both single and double pass. A plot of micro hardness as function of position from the weld centre line in single pass is shown in figure 15-figure16, where

A-Advancing Side

0-centre

R-Retreating Side

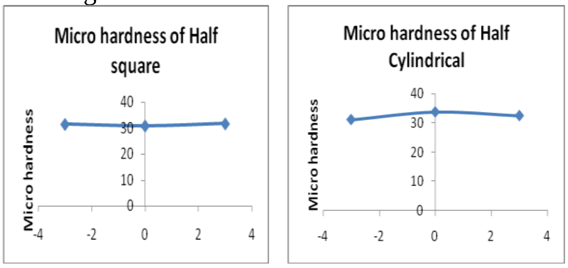

Fig-15-Micro hardness of specimen Half Square and Half Cylindrical

S.No.	Distance from centre	Half Square HV	Half Cylindrical HV
1	A	31.5	31.1
2	0	30.9	33.8
3	R	31.7	32.5

Table-5-Test Results Micro-hardness

Table 5 and table 6 describe the micro- hardness of the specimens done on the Viker's Hardness Testing Machine:

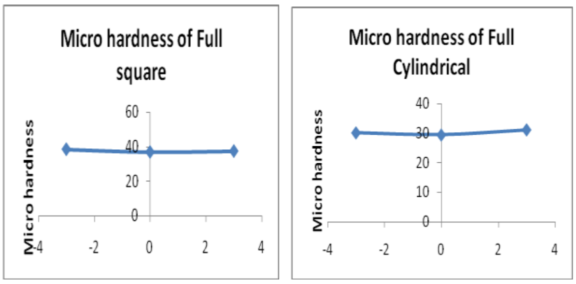

Fig-16-Micro hardness of specimen Full Square and Full Cylindrical

S.No.	Distance from centre	Full Square HV	Full Cylindrical HV
1	A	38.5	30.1
2	0	36.8	29.4
3	R	37.4	31.1

Table-6-Test results Micro hardness

IV. CONCLUSION

In this investigation an attempt has been made to study the effect of tool pin profile (straight cylindrical and square) on the formation of friction stir processing zone in a single and sequential double sided friction stir weld in AA6061. From this investigation, the following important conclusions are derived:

(i) Double side weld joint have more joint efficiency as compared to Single side weld by 74.14% of cylindrical (Double sided) pin profile as compared to other pin profiles (71.7% cylindrical single pass, 52.1% Square single pass and 73.65% Square double pass).

(ii) The joints fabricated by double passes have shown higher ultimate tensile strength as compared to the joints fabricated by single pass and this trend is common for all the tool profiles (0.0838 KN/mm^2 Square double pass, 0.0844 KN/mm^2 Cylindrical double pass, 0.059 KN/mm^2 Square Single pass, 0.082 KN/mm^2 Cylindrical single pass).

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(iii) Cylindrical tool profile single pass has more percentage elongation (24%) as compared to other tool profiles (8% square tool single pass, 15 % square tool double pass, 19% cylindrical tool double pass.)

(iv) Cylindrical tool profile single pass has maximum micro hardness value (37.5) as compared to other tool pin profiles (31.3 Square tool double pass, 32.4 cylindrical tool double pass, 30.2 square tool single pass)

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