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Effect of Tool Pin Profile and Welding Parameters on Friction Stir Processing Zone, Tensile Properties and Micro-hardness of AA5083 Joints Produced by Friction Stir Welding

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Abstract*—AA5083 aluminium alloy has gathered wide acceptance in the fabrication of light weight structures requiring a high strength to weight ratio. Compared to the fusion welding processes that are routinely 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. This process uses a non-consumable tool to generate frictional heat in the abutting surfaces. The welding parameters and tool pin profile play major roles in deciding the weld quality. In this investigation, an attempt has been made to understand the effect of tool speed (rpm) and tool pin profile on Friction Stir Processing (FSP) zone formation in AA5083 aluminium alloy. Friction stir welding between 5083 aluminium alloy plates with a thickness of 2.5 mm was performed. Five different tool pin profiles (straight cylindrical, tapered cylindrical, triangular, square and cone) have been used to fabricate the joints at three different rotational speeds i.e. 900, 1400 and 1800 rpm under a constant traverse speed of 16 mm/min. The formation of FSP zone has been analysed macroscopically. Tensile properties of the joints have been evaluated and correlated with the FSP zone formation. From this investigation it has been found that the tool pin profiled designs had little effect on heat input and tensile properties, weld properties were dominated by thermal input rather than the mechanical deformation by the tool for the plate thickness of 2.5 mm. straight cylindrical pin profiled tool produces mechanically sound and metallurgically defect free welds compared to other tool pin profiles.

***Index Terms*— AA5083 aluminium alloy, friction stir welding, macrostructure, micro-hardness, tensile properties, tool pin profile**

I. INTRODUCTION

Aluminium alloy AA5083 is commonly used in the manufacturing of pressure vessels, marine vessels, armorer vehicles, aircraft cryogenics, drilling rigs, structures and even in missile components etc. Aluminium alloy AA5083 is considered as non-heat treatable alloy and therefore conventional post welding treatments are not used. The Friction Stir Welding (FSW) technology is being targeted by modern aerospace industry for high performance structural applications [1]. If compared to traditional welding techniques, FSW strongly reduces the presence of distortions and residual stresses [2–4]. Detailed description of FSW process is shown in Fig.1 (a).

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Based on friction heating at the faying surfaces of two sheets to be joined, in the FSW process a tool with a specially designed rotating probe travels down the length of contacting metal plates, producing a highly plastically deformed zone through the associated stirring action. The localized thermo mechanical affected zone is produced by friction between the tool shoulder and the plate top surface, as well as plastic deformation of the material in contact with the tool [5]. The probe is typically slightly shorter than the thickness of the work-piece and its diameter is typically slight larger than the thickness of the work-piece [6].

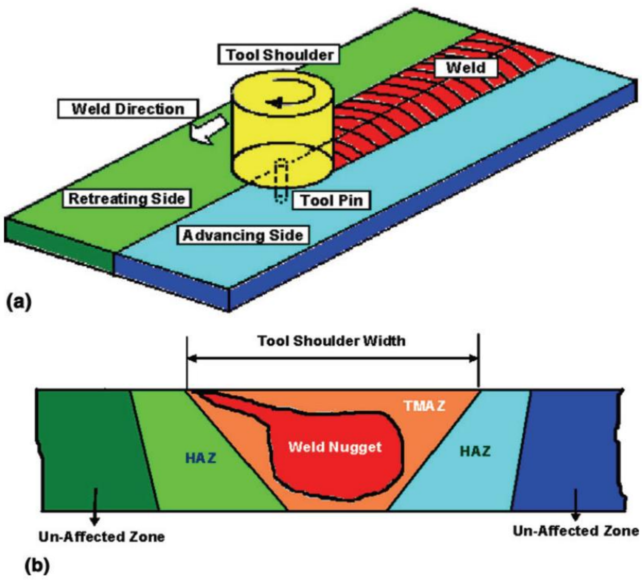

Fig.1 (a) A schematic of the friction stir welding (FSW) process, and (b) the main microstructural zones associated with the typical FSW joint [7]

Microstructural examination of the FSW joints revealed the presence of four distinct zones, Fig. 1(b): In a decreasing order of the distance from the initial position of the butting surfaces the four zones are: (a) the unaffected zone; (b) The heat-affected zone, HAZ; (c) The thermo-mechanically affected zone, TMAZ; and (d) The weld-nugget/stir zone. The present work is aimed at the evaluation of mechanical and macrostructural behaviour and hardness of AA5083 plates obtained by employing different FSW parameters and tool pin profile. In FSW the work-piece does not reach the melting point and the mechanical properties of the welded zone are much higher compared to those provided by traditional techniques.

In fact, the undesirable low mechanical properties microstructure resulting from melting and re-solidification is absent in FSW welds leading to improved mechanical properties, such as ductility and strength in some alloys [8–10]. In this way, the welds are characterized by low distortion, lower residual stresses and absence of micro defects and then of retained products dimensional stability.

II. EXPERIMENTAL WORK

The rolled plates of 2.5 mm thickness, AA5083 aluminium alloy, have been cut into the required size (200mm×100mm×2.5mm) by power hacksaw cutting and milling. Square butt joint was formed by FSW in a single pass welding procedure. No special treatment was carried out before welding and testing. Non-consumable tools made of stainless steel SS316 have been used to fabricate the joints and the chemical composition of tool material (SS316) and workpiece material was analyzed by energy dispersive X-ray spectroscopy. Their chemical composition is shown in table 1.

Table I
Chemical compositions (weight %) of the tool material (SS316)

Element	Si	Fe	P	Mn	Cr	Ni	Mo	Fe
Tool SS316	2.13	0.27	8.95	16.3	0.20	0.20	0.14	Bal

Table II
Chemical compositions (weight %) of the workpiece material (AA5083)

Element	Si	Fe	Mn	Mg	Zn	Ti	Cr	Al
Base Metal AA5083	0.4	0.4	0.72	4.37	0.25	0.15	0.17	Bal

Table III
Welding parameters and tool dimension

Process parameters	Values
Rotational speed (rpm)	900, 1400, 1800
Welding speed (mm/min)	16
D/d ratio of tool	3.75
Pin length, L (mm)	2
Tool shoulder diameter, D (mm)	15
Pin diameter, d (mm)	5

Table IV
Mechanical properties of AA5083 material

Parameters	Values
Tensile yield strength	121 MPa
Ultimate tensile strength	175 MPa
Elongation (%)	6.37
Vickers hardness	75 HV

All the detailed analysis about different pin profiled tool such as tool dimensions, pin volume , swept volume and ratio of swept volume to pin volume is given in table 5 and detailed analysis about tool surface area, pin surface area and shoulder surface area is given in table 6. It has been found that tool with triangular pin profile has highest shoulder surface area and least pin volume.

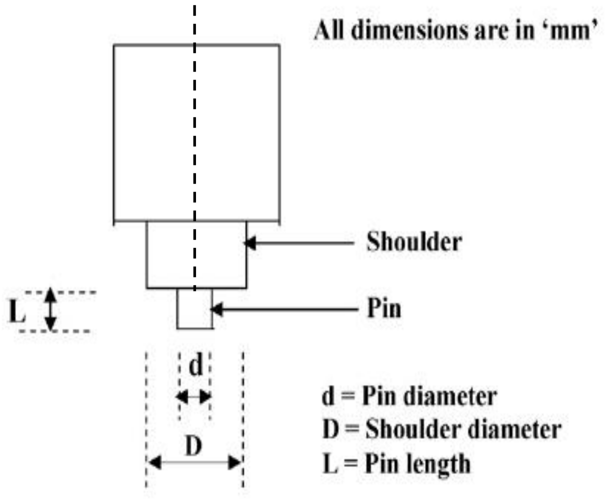

Fig. 2 FSW tool dimensions

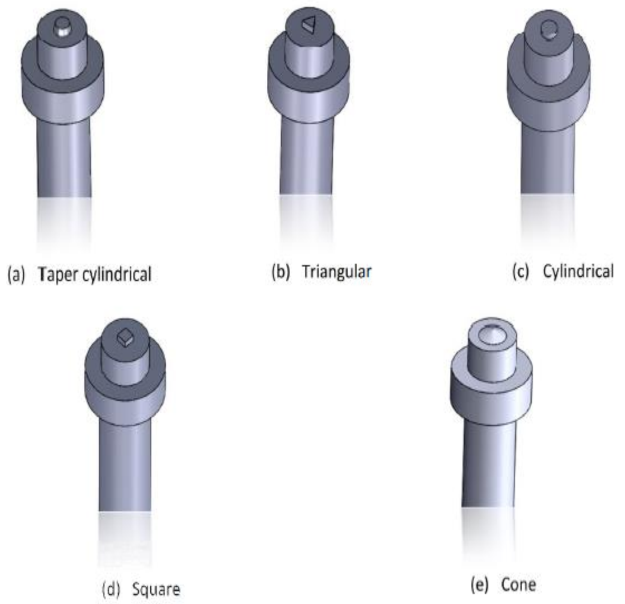

Fig.3 FSW tool pin profile

Five different tool pin profiles (Taper cylindrical, triangular, straight cylindrical, square and cone) as shown in fig. 3 and fig. 4 have been used to fabricate the joints. Using each tool, three joints have been fabricated at three different rotational speeds and in total 15 joints (5×3) have been fabricated in this investigation. The welding parameters and tool dimensions are presented in table 3. The chemical composition and mechanical properties of workpiece material (AA5083) is represented in table 2 and 4.

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Table V
Effect of pin profile on dynamic to static volume ratio

Tool pin profile	Dimensions (mm)	Pin volume mm^3	Swept volume mm^3	Swept volume/ Pin volume	Area occupied by pin in static condition	Area occupied by pin in dynamic condition
Square	Pin Height : 2 3.55 mm sq.	25	39.269	1.57		
Straight cylindrical	Pin Height : 2 Pin Dia. : 5	39.269	39.269	1		
Triangular	Pin Height : 2 Triangle Side : 4.33	16.237	39.269	2.418		
Taper cylindrical	Pin height : 2 Root Dia. : 5.5 Tip Dia. : 4.483	39.269	39.269	1		
Cone	Pin height : 2 Root Dia. : 8.660	39.269	39.269	1		

Table VI
Pin, shoulder and tool surface area for different pin profiled tool

Sr. No.	Tool pin profile	Shoulder surface area (mm^2)	Pin surface area (mm^2)	Tool surface area (mm^2)
1	Square	164.219	40.776	204.995
2	Cylindrical	157.081	51.05	202.131
3	Triangular	168.597	34.098	202.695
4	Taper cylindrical	152.957	48.11	201.067
5	Cone	117.814	129.746	247.56

A. Tensile Test

The welded joints are sliced using power hacksaw and then machined to the required dimensions to prepare tensile specimens as shown in fig.5. American Society for Testing of Materials (ASTM E8M-04) guidelines is followed for preparing the test specimens. Tensile test has been carried out in 100kN; electro-mechanical controlled Universal Testing Machine (INSTRON). The specimen is loaded at the strain rate of 2mm/min as per ASTM specifications & extensometer is attached to specimen, so that tensile specimen undergoes deformation. The specimen finally fails after necking and the load versus displacement has been recorded. The 0.2% offset yield strength; ultimate tensile strength and percentage of elongation have been evaluated.

B. Macrostructure

Macrostructural analysis has been carried out using a light optical microscope (LEICA DFC-295) in corporate with an image analyzing software (Leica QWin-V3). The specimens for metallographic examination are sectioned to the required sizes from the joint comprising FSP zone, TMAZ, HAZ and base metal regions and polished using different grades of emery papers. Final polishing has been done using the diamond compound (100 micron particle size) in the variable speed grinder polishing machine as shown in fig.8. Specimens are etched with Keller's reagent to reveal the macrostructures.

C. Microhardness

The microhardness profiles of the FSW joints were measured in the cross sections in order to evaluate the material behaviour as a function of the different welding parameters. Microhardness testing has done on Vicker's microhardness testing apparatus.

III. Result And Discussion

A. Tensile Properties

Transverse tensile properties of FSW joints such as yield strength, ultimate tensile strength, percentage of elongation and joint efficiency have been evaluated. Two specimens were tested at each condition and average of the results of two specimens is presented. It can be inferred that the tool pin profile and rotational speed are having influence on tensile properties of the FSW joints. Of the fifteen (5x3) joints, the joints fabricated by square tool profile and cylindrical pin profile exhibited superior tensile properties compared to other joints irrespective of rotational speed. The joints fabricated at a rotational speed of 900 rpm have shown lower tensile strength and elongation compared to the joints fabricated at a rotational speed of 1400 rpm and this trend is common for all the tool profiles except triangular pin tool. Similarly, the joints fabricated at a rotational speed of 1800 rpm have also shown lower tensile strength and elongation compared to the joints fabricated at a rotational speed of 1400 rpm. The effect of welding speed is concerned, the joint fabricated at a rotational speed of 1400 rpm is showing superior tensile properties compared to other joints, irrespective of tool profiles except triangular pin tool is shown in fig.7.7. During tensile test, most of the specimens failed in the FSP region but not in the weld line. Most of the specimens were failed in HAZ at advancing side and very few specimens were failed at centre line of the weld. Fig.7.7 is showing top and bottom surface of weld. Fig.7.8 is showing specimen fractures in HAZ at advancing side and specimen fractures along weld line. Weldability is significantly affected by the rotational speed. At high rotational speed (1800 rpm) straight cylindrical tool is the best; at the middle rotational speed (1400 rpm) straight cylindrical and square tool are the best; while for low rotational speed (900 rpm) triangular and square tool are the best. But the joints fabricated by taper cylindrical and cone pin profiled tools exhibited inferior tensile properties compared to their counterparts, irrespective of rotational speed used. Tensile strength of the AA5083 joints fabricated by triangular pin tool significantly decreases as rpm increases. Triangular pin tool showed highest tensile strength at 900 rpm and then decreases for the joints fabricated at 1400 rpm and 1800 rpm. This is because as triangular pin has highest shoulder area so it generates sufficient heat for welding at 900 rpm and produces defect free joint. As rpm increase excessive heat generation causes the formation of defects which will be discussed latter in detail, due to that tensile properties gets deteriorated.

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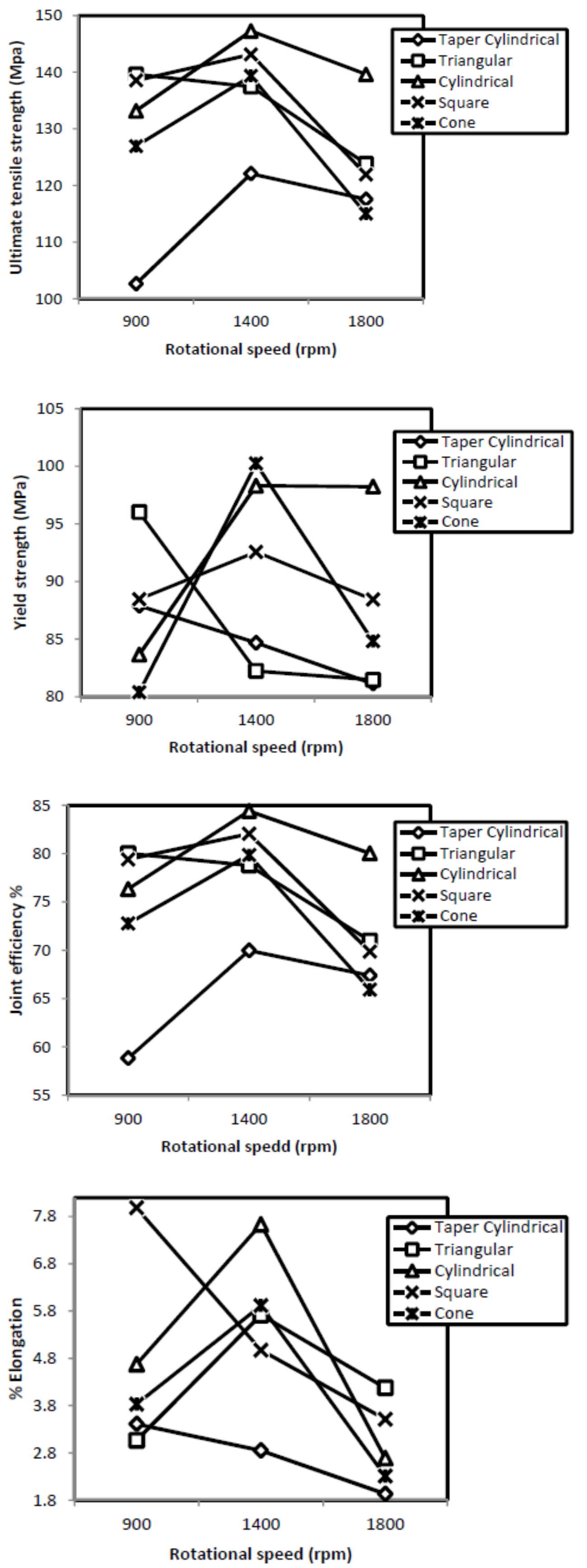

Fig. 4 Effect of rotational speed and tool pin profile on tensile properties (a) Ultimate tensile strength (b) Yield strength (c) Joint efficiency % (d) % Elongation

As the rotational speed increases, the heat input also increases. However, the calculated maximum temperatures are nearly the same in all the rotational speeds. This phenomenon can be explained by the following two reasons: first, the co-efficient of friction decreases when a local melt occurs, and subsequently decreases a local input; secondly, the latent heat absorbs some heat input. When the rotational speed increases, the heat input within the stirred zone also increases due to the higher friction heat which in turn result in more intense stirring and mixing of materials. As the spindle speed increases from 900 rpm to 1400 rpm, both the strength and joint efficiency improved, reaching maximum before falling again at high rotational speeds i.e. 1800 rpm. Higher tool rotational speed resulted in higher heat generation and this led to the excessive release of stirred material to the upper surface, which resultantly produced micro voids in the stir zone. Moreover, the higher heat generation caused slow cooling rate and this lead to the formation of coarse grains. Presence of micro voids deteriorated the tensile properties of the joint fabricated at a rotational speed of 1800 rpm compared to the joint fabricated at a rotational speed of 1400 rpm. The joint fabricated with a rotational speed of 1400 rpm produced higher strength properties of the joints.

B. Macrostructure

Table's 7 - 11 shows the effects of process and tool parameters on macrostructure of the friction stir welded joints. It is generally known that the fusion welding of aluminium alloys accompanied by the defects like porosity, slag inclusion, solidification cracks, etc., deteriorates the weld quality and joint properties. Usually, friction stir welded joints are free from solidification related defects since, there is no melting takes place during welding and the metals are joined in solid state itself due to the heat generated by the friction and flow of metal by the stirring action. However, FSW joints are prone to other defects like pin hole, tunnel defect, piping defect, kissing bond, Zig-Zag line and cracks, etc., due to improper flow of metal and insufficient consolidation of metal in the FSP (weld nugget) region. The kissing bond generally means a partial remnant of the un-welded butt surface below the stir zone, which is mainly attributed to insufficient plunging of the welding tool during FSW.

Table VII

Taper cylindrical pin tool

Rotational speed (rpm)	Macrostructure of joint cross-section	Name of the defect & location	Probable reasons
900		Crack like defect	Insufficient heat input and improper mixing of material
1400		Crack like defect	Insufficient heat input and improper mixing of material
1800		No defect	Sufficient heat input and proper mixing of plasticised material

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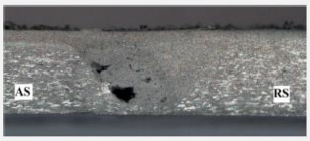
Table VIII
Triangular pin tool

Rotational speed (rpm)	Macrostructure of joint cross-section	Name of the defect & location	Probable reasons
900		Tunnel in bottom of weld and kissing bond	Insufficient heat generation
1400		No defect	Sufficient heat input and proper mixing of plasticised material
1800		No defect	Sufficient heat input and proper mixing of plasticised material

Table IX
Cylindrical pin tool

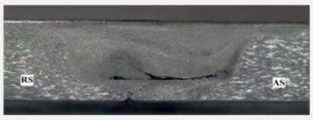
Rotational speed (rpm)	Macrostructure of joint cross-section	Name of the defect & location	Probable reasons
900		No defect	Sufficient heat input and proper mixing of plasticized material
1400		No defect	Sufficient heat input and proper mixing of plasticized material
1800		Pin hole at retreating side	Excessive heat input and excessive stirring of material

Table X
Square pin tool

Rotational speed (rpm)	Macrostructure of joint cross-section	Name of the defect & location	Probable reasons
900		Tunnel in the bottom portion of weld at advancing side	Insufficient heat input
1400		No defect	Heat input is just sufficient to produce good quality weld
1800		Pin hole at advancing side	Insufficient vertical flow of material and low heat input

The mechanism of the kissing bond is related to the insufficient breakup of oxide layer by the insufficient stretch of the contacting surfaces around the welding pin. The reduction of the heat input results in the insufficient breakup of the oxide layer during FSW. There is a high possibility that the sufficient breakup of the oxide layer is not achieved in the root part of the weld. It is observed that the continuous oxide film, which resulted due to insufficient stirring hence, the oxide layers on the initial butt surfaces, could be directly bonded without the metallic bond between oxide free surfaces in the root part of the weld. Therefore, continuous oxide film is a feature of the kissing bond and is possible to fracture along the Zigzag line.

Table XI
Cone pin tool

Rotational speed (rpm)	Macrostructure of joint cross-section	Name of the defect & location	Probable reasons
900		Tunnel at bottom of the weld	Insufficient heat input due to low rotational speed
1400		No defect	Excessive heat input and proper mixing of plasticised material
1800		No defect	Excessive heat input and proper mixing of plasticised material

C. Microhardness

The 5083 alloys are strengthened with magnesium additions from 4% to 5 % and are non-heat-treatable, work hardened alloys. Thus 5083 aluminium alloys would be expected to behave differently than the heat treatable alloys following a thermal cycle associated with welding. Post-FSW hardness has been reported by a number of investigators.

Sato at al. [11] reported the same constant hardness results in transverse hardness measurements extending beyond the HAZ for 5083-0 from the weld root to the weld crown, but the scatter in the data was considerable, varying from 50 to 70 HV. This is the expected response from a fully annealed work hardenable alloy.

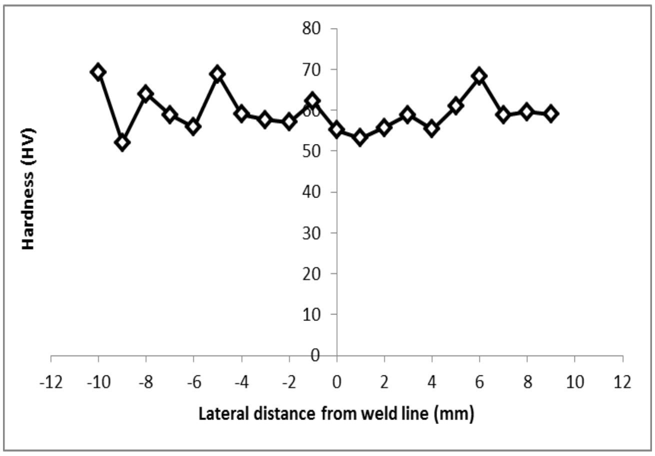


Fig. 5 Hardness variation as a function of lateral distance from weld line at mid-thickness

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IV. Conclusion

In this investigation an attempt has been made to study the effect of tool pin profiles and rotational speed on the formation of friction stir processing zone in AA5083 aluminium alloy. From this investigation, the following important conclusions are derived.

1. Of the five tool pin profiles used to fabricate the joints, cylindrical pin profiled tool produced defect free FSP region, irrespective of welding speeds.
2. Of the three rotational speeds used to fabricate the joints, the joints fabricated at a rotational speed of 1400 rpm showed superior tensile properties, irrespective of tool pin profiles except triangular pin profiled tool.
3. At high rotational speed (1800 rpm) cylindrical tool is the best; at the middle rotational speed (1400 rpm) cylindrical and square tool are the best; while for low rotational speed (900 rpm) triangular and square tool are the best.
4. Of the 15 joints, the joint fabricated using cylindrical pin profiled tool at a rotational speed 1400 rpm exhibited maximum tensile strength and defect free FSP region.

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