Proc. International Conference on Mechanical, Automotive and Mechatronics Engineering (ICMAME 2023)
29-30 April 2023, Dubai, UAE

Parametric Optimization of Friction Stir Welding (FSW) of Dissimilar Aluminum Alloys with Newly Developed Tool

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***Abstract*— Friction stir welding is a rising solid-state material joining procedure which has revolutionized the world. It's majorly utilized for joining aluminum and alike soft materials for industrial and commercial use. The present study comprised of experimental investigation of FSW operation parameters like tool rotational speed, tool transversal speed, and tool pin geometry profile on the tensile strength of friction stir welded joint between Al alloy 6061-T651 and Al alloy 5083-H321. Two newly developed pin profiles that are cylindrical quad slotted and cylindrical threaded quad slotted are used along with cyclindrical threaded tool pin profiles. Tool rotation speed selected for the operation are 600, 900 and 1200 revolution per minute and tool transversal speeds are 20, 40 and 60 milimetre per minute. Tools were produced from TS (Tool Steel) H-13. The FSW operation was conducted on vertical-axis milling machine. Tensile test, most widely used to experimentally varrify the strength of material is applied to check the weld strength performed through FSW. Taguchi design of experiment was used in order to investigate the optimum parameters with minimum number of experiments. Analysis of variance (ANOVA) and regression analysis are applied for evaluating the relative significance and importance of individual parameters affecting mechanical behavior of the weld joints. The result imply that tool's pin geometry profile has a significant impact on the strength of weld joint cylindrical threaded quad slotted tool pin profile produced the best weld joints. This study also suggests that the increased motion of plasticized phase of Al in horizontal and vertical trajectory simultaneously, which was achieved with the help of cylindrical treaded quad slotted pin profile gives the best weld joint under the same circumstances in relation to other tools under studies. The study also suggests that best weld was achieved with highest tool rotational speed and lowest tool transversal speed.**

Keywords*— *FSW, parameters, optimization, dissimilar, aluminum alloys, AA6061, AA5083, Taguchi, tool profile, ANOVA, regression analysis

I. INTRODUCTION

FSW is a contemporary solid phase joining technique. In this technique, weld joint is created through mixing of deformed plasticized material. Cylindrical tool comprising of flat shoulder and unique profile pin is placed between two adjacent plates. This profiled tool is rotated and plunged between the two plates that are tightly clenched together. Then tool moves concurrently with the weld line in transverse path. This relative movement of workpiece-tool interface generates frictional and deformational heat on the tool and work piece. This heat marginally softens the base material and thus results in mixing of material from both adjacent plates. The rotation of tool allows to move material in horizontal direction and the shoulder acts as the forging member of tool, thus leaving the fine-grained welded joint. This technique comes as the revolution as prior to that there was no conventional method for the joining of certain material like aluminum and its alloys. Moreover, during the entire process the welding material is not melted, therefore certain defect like porosity, cracking and distortion can be avoided.

In this research work, three parameters that are tool rotational speed, tool transversal speed and tool pin geometry profile were selected to experimentally and statistically validate the optimum subset of condition to produce the best weld strength. The rest of the manuscript includes: a detailed literature review in section II, the design methodology explained in section III, results discussed in section IV, and finally, the study is concluded in section V.

II. LITERATURE REVIEW

Since the development of friction stir welding, researchers are trying hard to modernize this process. By the end of 2007, The Welding Institute (TWI) had issued more than 200 liscenses to different manufacturing firms and 1900 patent applications had been filed, [1]. Cylindrical tool comprising of unique tool pin profile is placed between two adjacent plates tightly held together. Tool is rotated at certain rpm and serenely inserted into the intersection of two plates and advances along the weld line in transverse direction. This movement of tool generates frictional and deformational heat on the tool-workpiece interface which soften substrate material and mixes the material from both plates. The rotation of tool allows to move material in horizontal direction and

shoulders acts as the forging member, thus leaving the fine grained weld joint [2,3].

Researchers have performed FSW on conventionally incompatible joining materials like aluminum alloys and various soft metals like copper and studied the effect of tool pin geometry profile. The result indicate that cylindrical and cylindrical threaded tool pin geometric profiles out performed other tool pin profile shape in term of weld strength. The tool rotation speed ranges between 600 to 1500 rpm and tool transverse speed ranges between 20 to 90 mm/min [4-10].

Most of the researchers have selected tool steel H-13 as tool material for friction stir welding of relatively soft materials like aluminum, copper, magnesium due to its high toughness, ductility, resistance to abrasion at high temperature and resistance to thermal fatigue [11-17].

Manufacturers face a range of complex challenges during the welding of aluminum alloys, such as heat-affected zones with large porosity, microsize porosities, embrittlement, solidification cracking, joint defects, and surface crack defects. These issues can significantly reduce the welding strength and quality, making the process more difficult. [18-20] However, FSW is found successful to attain high leak path in tube-to-tubesheet welds [21,22], to join metal matrix composites [23], to weld thermoplastics [24-26]. For these application, statistical approaches and machine learning are beneficial for determining optimum parameters resulting in quality welds [27-35].

In the current study, process control parameters like tool rotational speed, tool transversal speed and tool pin geometry profile are optimized by using Taguchi's L9 orthogonal array for design of experiment based on the tensile strength exhibited by the weld joint.

III. Design Methodology

Taguchi design of experiment, tensile test and Anova analysis is used in this experimental study to check the mechanical strength and behavior of friction stir weld under various parametric conditions. Design methodology consists of parameters range and material selection, Taguchi's L-9 orthogonal array for experiments conduction, tool development and coupon preparation, performing friction stir welding procedure, tensile test specimen preparation as per ASTM specification criteria, conduction of tensile experiments, performing analysis of variance for the results of tensile test to obtain optimum condition and impact of independent input parameters on the weld joint strength.

A. Parameters range and material Selection

Upon through literature review it was identified that input parameters that most affect the strength of weld joint are tool pin geometry profile, tool rotational speed and tool transversal speed. Therefore these parameters were chosen for srudy. Cylindrical threaded, cylindrical quad slotted and cylindrical threaded quad slotted tool pin profile were selected as tool pin profile shape. Three tool rotational speeds of 600, 900 and 1200 revolution per minutes were selected along with three tool transversal speeds of 20, 40 and 60 milimeter per minutes. All tools were made from tool steel H-13 where as the base material selected was aluminum alloy 6061-T651 and aluminum alloy 5083-H321. Material composition of AA6061-T651 and AA5083-H321 are given in Fig. 1 and Fig. 2 and in table 1, 2 and 3.

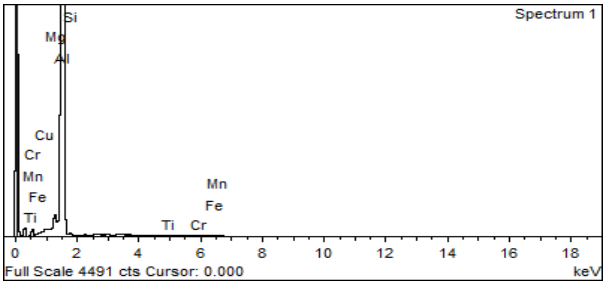

Fig. 1. EDX spectrum of AA 6061-T651

Table I. Chemical composition of AA6061-T651

Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Al
0.35	0.4	0.7	1.2	0.15	0.8	0.15	0.25	bal

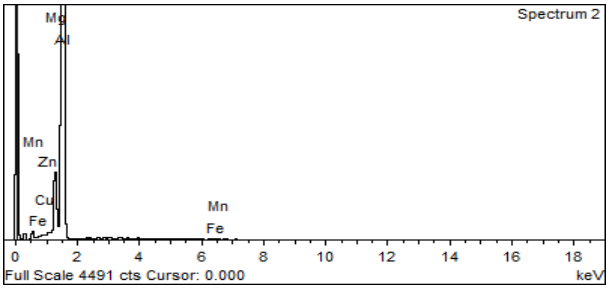

Fig. 2. EDX spectrum of AA 5083-H321

Table II. Chemical composition of AA5083-H321

Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Al
0.25	0.1	0.4	4.9	0.8	0.4	0.15	0.25	bal

Table III. Chemical composition of Tool Steel H-13

C	Si	Mn	P	S	Cr	Mo	V
0.45	1.2	0.5	0.025	0.025	5.5	1.75	1.2

B. Taguchi Design of Experiment

Taguchi design of experiment (DOE) is a statistical model utilized to investigate and optimize the process parameters. Minitab, a statistical applicaiton used to implement Taguchi design of experiment for the given experimentation. Three distinct level and L-9 orthogonal array are mentioned in table 4 and table 5.

Table IV. Taguchi Design Of Experiment Levels

	Tool	Velocity (rpm)	Feed (mm/min)
Level 1	Cylindrical threaded	600	20
Level 2	Cylindrical quad slotted	900	40
Level 3	Cylindrical threaded quad slotted	1200	60

TableV. Taguchi Design of Experiment L-9 orthogonal array

Sr.	Tools	Rotation Velocity (rpm)	Transverse Velocity (mm/min)
1	Cylindrical Threaded	600	20
2	Cylindrical Threaded	900	40
3	Cylindrical Threaded	1200	60
4	Cylindrical Quad Slotted	600	40
5	Cylindrical Quad Slotted	900	60
6	Cylindrical Quad Slotted	1200	20
7	Cylindrical threaded Quad Slotted	600	60
8	Cylindrical threaded Quad Slotted	900	20
9	Cylindrical threaded Quad Slotted	1200	40

C. *Tool development and coupon preparation*

Main elements of FSW tool are pin geometric profile and shoulder shape. The mian task of tool pin is to soften, deform and move the plastisized material and secondary task is to induce heat along with shoulder. The shoulder also provide the necessary forging force needed to perform welding procedure. In the current study three distinctive tool pin profiles are used and in two of them vertical slots and threads are introduced to investigate the addictional motion of plastisized material in vertical and horizontal direction. The dia (D) of shoulder and pin geometric profile (d) and lengths of all tool pin profile is same. The dia of shoulder (D) and pin (d) is 16 mm and 6 mm respectively. Length of the pin is 6 mm. Tools are first designed on creo and then fabrication and machining was performed on CNC lathe and CNC milling machines. All tools were fabricated from Tool Steel H-13 material.

The base plate coupon from aluminum sheets were cut into 150 mm x 75 mm pieces with the help of bend saw machine and their lateral sides were smoothen with the help of grinding paper to ensure zero separation between two butted plates.

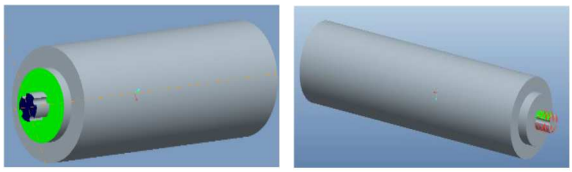

Fig. 3. Cylindrical quad slotted and Cylindrical threaded quad slotted tool pin profile Creo model

Fig. 4. Cylindrical quad slotted and Cylindrical threaded quad slotted tool pin profile

Three axis CNC vertical milling machine was selected to perform friction stir welding operation. The machine was available in Heavy Industries Taxila (HIT).

E. *ASTM Standard used*

The specimen for tensile test were cut through CNC (computer numerical control) milling machine according to ASTM standard E8-15. These samples were tested on UTM (universal testing machine) at a strain rate of 0.5 milimeter per minute. [36]

F. *Preparation of specimen*

Tensile test specimen was extracted from the welding plate by cutting it by employing CNC vertical milling machine to keep the specimen dimension as close to the standard.

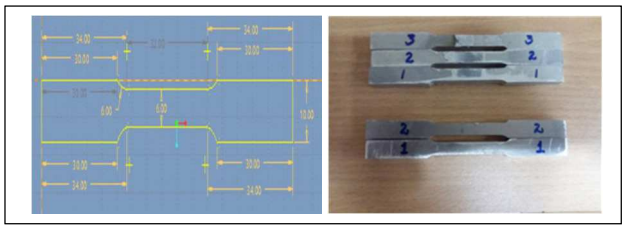

Fig. 5. Preparation of tensile specimen

In real life ther are many possibilities in which loads are applied on the material, however, tensile, compressive and shear loads are the most common types of load application. Mechanical traits of weld joint can be determined by these load application factor and tensile test is the most common type of test in order to evaluate these properties.

H. *Analysis of variance (ANOVA)*

ANOVA (Analysis of Variance, a statistical application is used to determine the impact of one or more independent variable on a dependent variable. In the current study tool rotational speed, tool transversal speed and tool pin profile are the independent variables whereas the tensile strength (ultimate tensile strength) is the dependent variable.

I. *Regression analysis (general linear regression model)*

Regression analysis, a statistical approach is used to model and evaluate the relation ship amongst dependent variable and one or more independent variable. In current study the dependent variable is ultimate tensile strength and dependent variables are tool pin geometry profile, tool rotational speed and tool transversal speed. From regression analysis we will find out the parameter with relatively significant impact.

IV. Results and Discussion

Tensile test was performed as per ASTM standard E8-15 on universal testing machine (UTM). All test were conducted at the strain rate of 0.5 milimeter per minute. For comparison, initially tensile tests of base material were performed. Average ultimate tensile strength (UTS) of AA6061 is 316 MPa with percentage elongation of 26% and agerage ultimate tensile strength (UTS) of AA5083 is 305 MPa with percentage elongation of 24%. Figure 6 represent tensile test results performed at universal testing machine whereas, table 6 present tensile test result along with in Taguchi L-9 orthogonal matrix. The Taguchi L-9 orthogonal generate a set of experiment for given parametric conditions and levels. It collect data on the response from expermiment in term of ultimate tensile strength. The data is then analyzed using statistical tool to determine the relative importance of each variable and to identify the optimal combinationof process condition to produce highest quality friction stir weld joint.

Fig. 6. Tensile test at universal testing machine

Table VI. Taguchi Analysis: Tensile test result

Sr. No.	Tool probe profile	Tool Rotational velocity (rpm)	Tool Transverse Velocity (mm/min)	Ultimate Tensile Strength (MPa)	Signal to Noise Ratio (SNR) (larger is better)
1	1	600	20	149.638	44.0847
2	1	900	40	162.335	45.8277
3	1	1200	60	163.983	45.8616
4	2	600	40	95.492	40.4155
5	2	900	60	113.233	42.4548
6	2	1200	20	130.153	43.9261
7	3	600	60	157.680	45.4896
8	3	900	20	187.092	46.3478
9	3	1200	40	195.461	47.1277

Feedback response table for signal to noise ratio (larger is better) and response table for means from Taguchi analysis are shown in table 7 and table 8 respectively. These tables are used to summarize the results of Taguchi design of experiment, and provide representation of relationships between independent and dependent variable as a two dimensional matrix. One dimension represent the level of independent variable that are tool pin geometry profile, tool rotational speed and tool transversal speed and other dimension represent the response of our experiment that is ultimate tensile strength.

Table VII. Feedback response table for signal to noise ratio (larger is better)

Level	Tool	RPM	Feed
1	45.40	43.74	45.16
2	42.40	45.02	44.60
3	46.49	45.53	44.53
Delta	4.08	1.79	0.64
Rank	1	2	3

Table VIII. Response table for means (FSW of AA6061-AA5083)

Level	Tool	RPM	Feed
1	186.4	157.6	183.3
2	133.0	182.1	177.4
3	211.9	191.6	170.5
Delta	78.9	34.0	12.8
Rank	1	2	3

The response from table 7 and table 8 suggest us the optimized pair of independent variable. The table signifies the tool level three (cylindrical threaded quad slotted tool pin profile), RPM level three (1200 rpm tool rotation speed) and Feed level one (20 mm/min tool transversal speed), which are consequently the combination of optimized parametric relation for best friction stir weld joint. Moreover in figure 7 mean effective plot for signal to noise ratio from Taguchi analysis graphically represent optimized response of independent variable which support the above interpretation.

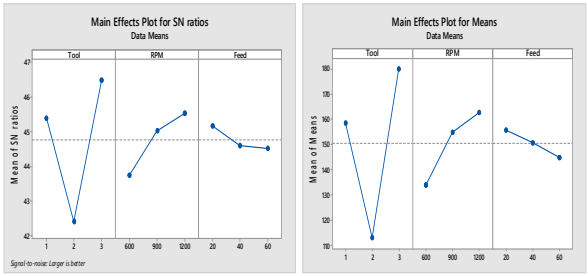

Fig. 7. Mean effet plots for signal to noise ration and means

ANOVA (analysis of variance) is a computational method, utilized investigate influence of individual parameters affecting the process parameters under investigation. In current study tool pin geometry profile, tool rotational speed and tool transversal speed are the independent input parameters that in certain combination affect the tensile loading and strength of weld joint. For the current study we are using ANOVA General Linear Model (GLM). Following table represent the result of ANOVA general linear model. Table 9 represent the ANOVA f-value ana p-value from general linear model for UTS of friction stir weld joint. The F-value and P-value suggest the relative importantance of input parameter influencing the strength of friction stri welding joint. In the current study the critically important parameter that is influencing the strength of the weld is tool pin profile follow up by tool rotational speed. The least important parameter is the tool transversal speed (feed).

Table IX. ANOVA general linear model for FSW AA606-AA5083

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Tool	2	9732.4	4866.19	280.00	0.004
RPM	2	1849.1	924.54	53.20	0.018
Feed	2	246.2	123.08	7.08	0.124
Error	2	34.8	17.38		
Total	8	11862.4			

ANOVA interaction plot allow us to visualize the relationship between ultimate tensile strength to the different levels of tool pin geometry profile, tool rotational speed and tool transversal speed with different lines and symbol representing each independent parameter. Figure 8 show the ANOVA interaction plot for FSW of AA6061-AA5083. ANOVA interaction plot suggest that tool 3 that is cylindrical threaded quad slotted tool pin geometry profile outperformed other tool pin profiles, the optimum results were attained around 1200 rpm tool rotational speed and 40 mm/min tool transversal speed.

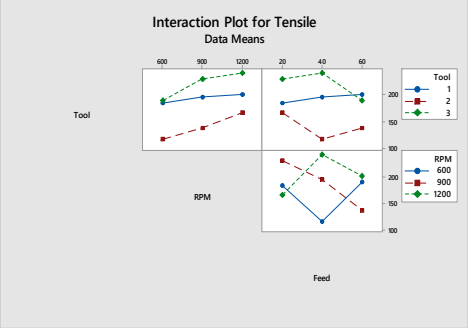

Fig. 8. ANOVA interaction plot

In the current study linear regression analysis is used to anlalyze the relationship between ultimate tensile strength and different tool pin profile, tool rotational speed and tool transversal speed. Table 8 represent the coefficient of regression equation.

Table X. Coefficient of regression equation for FSW of AA6161-AA5083

Tool 1 (Cylindrical Treaded)	A_1
Tool 2 (Cylindrical Quad Slotted)	A_2
Tool 3 (Cylindrical Threaded Quad Slotted)	A_3
RPM 1 (600)	B_1
RPM 2 (900)	B_2
RPM 3 (1200)	B_3
Feed 1 (20 mm/min)	C_1
Feed 2 (40 mm/min)	C_2
Feed 3 (60 mm/min)	C_3

$$UTS = 150.52 + 7.92A_1 - 37.50A_2 + 29.58A_3 - 16.59B_1 + 4.27B_2 + 12.32B_3 + 5.31C_1 - 0.26C_2 - 5.57C_3 \quad (1)$$

The above regression equation utilized to determine the ultimate tensile strength for any combination of tool pin geometry profile, tool rotational speed and tool transversal speed mentioned in the Taguchi L-9 orthogonal array. To use the above equation, at particular time we can only have one tool pin geometry profile, one tool rotational speed and one tool transversal speed. Therefore the other variable related to other tool pin profile, tool rotational speed and tool transversal speed will be neglected and there corresponding factor will become zero. For cylindrical threaded quad slotted tool pin geometry profile, 900 rpm tool rotational speed and 40 milimeter per minute, tool transversal speed, the regression equation is shown in following equation

$$UTS = 150.52 + 29.58A_3 + 4.27B_2 - 0.26C_2 \quad (2)$$

$$UTS = 184.11\ MPa \quad (3)$$

Taguchi investigation and analysis of variance suggested the combination of optimum parameters that are cylindrical threaded quad slotted tool pin profile, 1200 rpm tool rotational speed and 20 mm/min of tool transversal speed. Table 11 represent the results of tensile test of friction stir weld joint for combination of optimum parameters.

Table XI. Optimum Parameters for FSW of AA6161-AA5083

Tool Probe Profile	Cylindrical Threaded Quad Slotted
Tool rotation velocity	1200 rpm
Tool transverse velocity	20 mm/min
Ultimate tensile strength (Sample 1)	214 MPa
Percentage elongation (Sample 1)	20.44 %
Ultimate tensile strength (Sample 2)	212 MPa
Percentage elongation (Sample 2)	21.40 %

V. CONCLUSIONS

This study examines the parametric optimization of FSW joint with two newly fabricated tools with the help of tensile test by implementing Taguchi design of experiment technique and analysis of variance (ANOVA).

Both newly developed tool pin profiles (cylindrical quad slotted and cylindrical threaded quad slotted) and cylindrical threaded tool pin profile successfully produced fine friction stir welding joint, however, cylindrical threaded quad slotted tool pin profile surpassed all other tool pin profiles used in this study.

Ultimate tensile strength of friction stir weld joint was inferior to individual base material irrespective of process parametric variation. The maximum ultimate tensile strength for friction stir weld joint of AA6061-AA5083 with optimum parameter 214 MPa, which correspond to 69% of the average ultimate tensile strength of base material.

Tensile test of cylindrical threaded tool pin profile yielded good weld without defect. The maximum ultimate tensile strength for this tool was 171 MPa with 900 rpm and 60 mm/min feed rate. This conclusion corresponds to the concluding argument given by M. Panda et al. that maximum Ultimate Tensile Strength during FSW of aluminum alloy 6061 is acquired at 900 rpm tool rotational velocity and 60 mm/min tool transversal velocity [37]. The better features of weld are seen in the cylindrical threaded tool profile is due to the reason that thread appeared on the probe help the material to move along in the vertical direction simultaneously with tangent direction. Moreover, better results were acquired because the pitch selected was 1.5 mm, which is an intermediate pitch as concluded by Md. Reza-E-Rabby et al. [38] rather than selecting low pitch of 1 mm as selected by M. Panda. The greater pitch for threaded tool allows more plastisized material to flow for better mixing.

The least mechanical characteristics were exhibit by newly developed Cylindrical Quad Slotted tool with the maximum Ultimate Tensile Strength of 142 MPa at tool rotational velocity of 1200 rpm and tool transversal velocity of 20 mm/min. As this result is slightly lower than plan cylindrical tool probe profile as concluded by M. Panda et al. who has acquired maximum Ultimate Tensile Strength of 148 MPa from straight cylindrical tool probe profile [37]. From this it can be infer that only thrusting the plasticized material in the horizontal direction is not sufficient for obtaining high tensile strength, rather it will surely hinder the flow of plasticized material in the tangential direction as well, which consequently decreases the tensile strength of friction stir weld.

The reason for newly developed Cylindrical Quad Slotted tool probe profile to exhibit poor mechanical characteristics

than other two probe profile was that Cylindrical Quad Slotted tool probe profile lacks the ability to transfer multi layers of plasticized material in the vertical direction along the motion of tool in welding direction. From this information we can infer that the motion of plasticized material in nugget zone and in thermo mechanically affected zone in the vertical direction possess more importance than the motion of plasticized material in the horizontal direction. However additional motion of plasticized material in the horizontal direction improves the weld quality than having no motion of plasticized material in the horizontal direction as depicted by the straight cylindrical tool probe profile.

The best quality welds were acquired by newly developed Cylindrical Threaded Quad Slotted tool probe profile. The reason for exhibiting the best mechanical characteristics is the additional horizontal and vertical direction motion of plasticized material aside from natural tangential direction motion of plasticized material. The maximum Ultimate Tensile Strength acquired by Cylindrical Threaded Quad Slotted tool probe profile at optimum parameters (tool rotational velocity of 1200 rpm and tool transversal velocity of 20 mm/min) is 212 MPa which corresponds to 69% of the average Ultimate Tensile Strength of base material for dissimilar aluminum alloy welding of 6061 and 5083.

Newly developed Cylindrical Threaded Quad Slotted is a hybrid tool which possesses the good features of first two tool probe profiles (Cylindrical Threaded and Cylindrical Quad Slotted). The four slots present at the edges of tool probe mutually at 90^0 provides an extra thrust in the horizontal direction (similar to Cylindrical Quad Slotted) for the motion of plasticized material, whereas threads present at the periphery of tool probe (similar to Cylindrical Threaded) provides an extra up thrust for plasticized material to move in the vertical direction. This hybrid combination overall provides the perfect combination for homogeneous mixing of plasticized material along the weld line.

Flat Shoulder of tool provides the necessary forging pressure in order to complete the FSW operation. From literature review it is concluded that flat shoulder provides better forging quality than that of concave shoulder. This argument is also supported by R. M. Leal et al. [39]

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