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Modeling the Effects of Tool Shoulder and Probe Profile Geometries on Friction Stirred Aluminum Welds Using Response Surface Methodology

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Abstract: The present paper discusses the modeling of tool geometry effects on the friction stir aluminum welds using response surface methodology. The friction stir welding tools were designed with different shoulder and tool probe geometries based on a design matrix. The matrix for the tool designing was made for three types of tools, based on three types of probes, with three levels each for defining the shoulder surface type and probe profile geometries. Then, the effects of tool shoulder and probe geometries on friction stirred aluminum welds were experimentally investigated with respect to weld strength, weld cross section area, grain size of weld and grain size of thermo-mechanically affected zone. These effects were modeled using multiple and response surface regression analysis. The response surface regression modeling were found to be appropriate for defining the friction stir weldment characteristics.
Keywords: friction stir welding (FSW); tool geometries; mechanical properties; microstructures; response surface; regression modeling
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1 Introduction

Friction stir welding (FSW) process has gained popularity for joining the aluminum alloys used in structural fabrication. FSW was invented at the Welding Institute in the early 90's (Thomas *et al*., 1993), Cambridge. During FSW, to form the welded joint, a plunged rotating tool with shoulder and protruding pin is utilized. The rotation of the tool provides the frictional heat to the intended weld joint primarily through the shoulder and the plunged tool pin in between the mating surfaces of the joint, facilitates stirring of the joint (Fig. 1) material. The shoulder also prevents the material expulsion and assists material movement around the probe. The heat generated during the FSW process is not severe enough to produce defects those are generally observed during arc welding (Thomas *et al*., 1999).

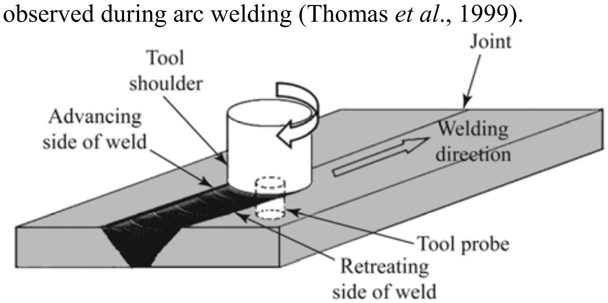

Fig. 1 Schematic of friction stir welding

The main process parameters of FSW (Rajakuma *et al*., 2010) are the rotational speed of the tool, tool traverse speed, and vertical pressure on the plates during welding. The FSW tool geometry which involves the geometry of the tool shoulder and tool pin probe is also of immense importance as the weld strength and grain size (Su *et al*., 2003a) of weld are affected by it. The designing of FSW tool is still an evolving field of research and there can be many possibilities of tool geometries. The effectiveness of FSW joint is strongly influenced by several tool geometry parameters; in particular geometrical parameters such as the height and the shape of the probe and the shoulder surface of the tool both on the metal flow and on the heat generation due to friction forces (Leal *et al*., 2008). The FSW machine setting parameters like rotational speed of tool, tool traverse speed, vertical pressure on the tool are also important which together with the geometries of tool affect the weld (Fujii *et al*., 2006). The microstructure evolution during the FSW process (Su *et al*., 2003b; Biswas and Mandal, 2009; Dawes and Thomas, 1999) is also controlled by the material physical and thermo-mechanical characteristics. The influence of the tool rotation speed (Sato *et al*., 2002), welding speed (Lee *et al*., 2003; Boz and Kurt, 2004) and both parameters simultaneously on the microstructure and mechanical properties of different aluminum alloy welds by considering the same tool geometry have been analyzed in detail by some authors. Limited research has been carried out on the effects of tool geometrical structures (Leal *et al*., 2008; Lee *et al*., 2003; Boz and Kurt, 2004; Scialpi *et al*., 2007) on friction stir welds, while much work, focused on the variation of rotation and welding speeds to optimize the

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welding parameters and study their microstructures for aluminum alloys, have been reported in the contemporary literature.

Even though some work has been done in the contemporary literature on the study of the tool shoulder and probe profile a comparative detailed modeling of different tool features and their effect has been rarely discussed. There is therefore a need of systematic investigation which can provide a mathematical model to predict the effects of FSW tool geometrical effects on the weld. In this work, mathematical modeling of FSW tool shoulder and probe geometry effects on the aluminum alloy weld is presented using analysis of variance (ANOVA) regression models. The FSW tool too is modeled with concave, partially concave and flat contact shoulder surface with three different shape and size of pin. A design matrix was developed keeping in view of limit of shoulder and pin diameter. The effect of these tools on the weld strength, weld cross-sectional area and grain size were observed keeping all other process parameters constant.

2 Application and advantage of FSW for marine construction

In marine and aerospace application the use of FSW is widely researched as it is thought to be the appropriate technique without defects which may occur in arc welding of aluminum alloys. The detrimental effects of arc welding like very high localized heating beyond the melting temperature, residual stresses and deformations are minimized in FSW, as the heat generated is not severe enough. In marine application, steel of marine grade is generally used for haul and superstructures. But aluminum has become a good choice as it is lightweight, and rusting of aluminum is minimal as compared to steel. The salt water environment is demanding and even marine grade aluminum is no match unless proper treatment is given to it to prevent pitting corrosion. The fatigue loading of marine structures in the marine environment makes the conventionally arc welded aluminum joints prone to brittle failure. It is well known that, extreme caution has to be taken during the arc welding of aluminum alloy to avoid hydrogen embrittlement. Hence FSW is gaining significance for replacing the arc welding procedures that are in use for marine structure fabrication. The present work provides a methodology to determine the effects of tool geometries on FSW of aluminum alloys. Moreover using the techniques implemented in the present work, an estimation of FSW weld strength, weld cross section area and grain sizes can be made considering a particular tool geometrical feature and process parameters.

3 Experimental details

The experimental setup consists of a vertical milling machine of capacity 7.5 HP in which tool is mounted in a vertical arbor with a suitable collate (Mohanty *et al.*, 2012). The vertical tool head can be moved along the vertical guide way (*Z* axis) the horizontal bed can be moved along *X* and *Y* axis. The aluminum alloy chosen for the experimental study was 6 mm thick plate of commercially available aluminum alloy as given in Table 2. The edge of the test pieces are machined to obtain a perfect square butt and clamped in horizontal bed with zero root gap aligned with the centre line of the FSW tool.

3.1 Tool design

The key components of FSW tool are pin and shoulder. The pin primary function is to deform the material around the tool and it's secondary function is to generate heat. Shoulder is the primary means of generating heat during the process and it prevents material expulsion and assists material movement around the tool. The uniformity of micro structure and properties as well as axial load are sum of the key factor for designing the FSW tool. Mild steel and die steel were used as the tool material but the probe profile deteriorated only after few trials and also did not produce good weld profiles. Similarly chromium steel was tried and found suitable for the present investigation. The properties of tool material are shown in Table 1 and 2. The chemical composition of the Al-alloy used in the present study was determined using a ARL 3460 Optical Emission Spectroscope. The chemical composition of the Al-alloy used in the present study is given in Table 3.

Table 1 Composition of FSW tool material by percentage

Fe	C	Cr	Mn	Ni	P	S	Si
48–53	0.25	24–26	2	19–22	0.045	0.03	1.5

Table 2 FSW tool material physical properties

Hardness, Brinell	Tensile strength, ultimate /MPa	Tensile strength, yield /MPa
160	655	275

Table 3 Composition of Al alloy by percentage

Al	Si	Cu	Cr	Fe
99.13	.4043	.011	.0013	.40
Mn	**Mg**	**Zn**	**Ni**	**As**
.0076	.00118	.007	.00214	.0027

In the present study twenty seven various FSW tool geometries were considered by varying the tool pin and shoulder profile (Mohanty *et al*., 2012). During initial trial the threaded tool was not that capable to retain its profile and the threads were filled with deformed aluminum materials and became cylindrical. Similar observations were also noticed for hexagonal tool profile. Keeping in view of above observation three types of profiles like straight cylindrical, taper cylindrical and trapezoidal tools were selected for the present investigation.

For the straight cylindrical tool the maximum diameter of the probe was set by making a series of experiment. Limit setting of tapered and trapezoidal tools were similarly made. The shoulder profiles were made as shown in Fig. 2 (Mohanty *et al*., 2012). The details configuration of designed FSW tool geometries matrix are given in Table 4. For all three types of tools, the complete flat surface from the edge of the tool shoulder to the base of the probe represents high level (+1) of shoulder flat surface, where as the medium level (0) and low level (−1) of shoulder flat surface are having partial flat surface of 5mm and 3mm respectively from the outer edge of the shoulder and at 10^0 concavity beyond it towards the base of the probe. Trapezoidal tools were having probe base size 10mm × 10mm,8mm × 8mm and 6mm × 6mm represent high (+1),medium (0) and low (−1) level respectively, with probe tip size of 5mm × 5mm. Tapered cylindrical tools were having probe base diameter 10mm,8mm and 6mm representing high (+1),medium (0) and low (−1) level respectively, with tip diameter of 5mm. Straight cylindrical probe diameter 7mm, 6mm and 5mm represent high (+1),medium (0) and low(−1) level respectively. A set of tools with different geometries used in the experiment is shown in Fig. 3.

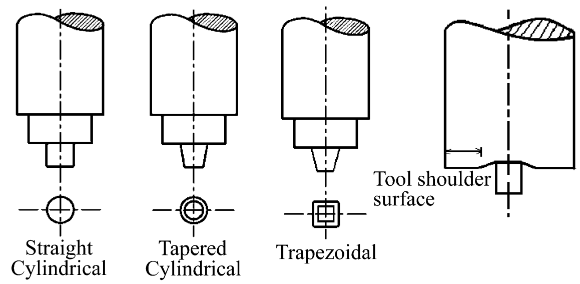
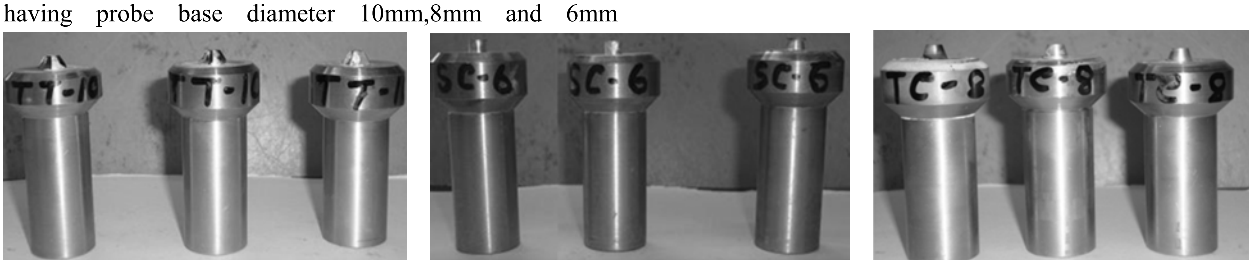


Fig. 2 Different FSW tool geometries used in the experiment (Mohanty *et al*., 2012)

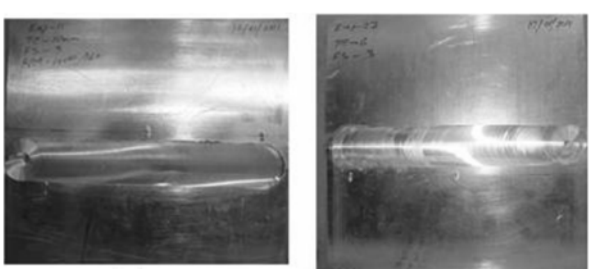


(a) Tools with trapezoidal probes (b) Tools with cylindrical probes (c) Tools with tapered cylindrical probes

Fig. 3 Designed and developed FSW tools (Mohanty *et al*., 2012)

Table 4 Tool probe and friction surface (Fig. 2) design matrix

Tool probe profile	Tool probe diameter			Tool shoulder flat surface		
	High	Medium	Low	High	Medium	Low
Trapezoidal Tool	+1	0	−1	+1	0	−1
Tapered cylindrical tool	+1	0	−1	+1	0	−1
Straight cylindrical tool	+1	0	−1	+1	0	−1



(a) Weld profile with straight cylindrical tool (b) Weld profile with a trapezoidal tool

Fig. 4 Weld profiles with different types of shoulder and tool probe profiles (Mohanty *et al*., 2012)

FSW is influenced by various parameters other than the main input parameters that affects the weld. The rigidity condition of the machine, clamping of the plates, and spindle tool mating condition, back lash of the traveling machine bed are some of the variables that might affect the weld reinforcement and strength. Often a very accurate machine setting with aforementioned variables are not possible from practical point of view. Hence it can be stated that the FSW process also inherently exhibits uncertainty to some extent. The numerical modeling for the determination of the FSW weld quality like weld strength might be difficult considering the aforementioned varying input process and other variables. Since in the present study the design of the experiment was done for each type of tool by taking three levels of tool probe diameter and tool shoulder flat surface, a comparison study of the main effect on the weld strength and weld cross section could be made. Weld profiles with different types of shoulder and tool probe profiles are shown in Fig. 4. Trial experiments were conducted to find the operating parameters like tool rotational speed, welding speed and tool axial plunging force. Feasible limits of the parameters were decided based on visual inspection of welds. Accordingly the tool rpm of 1400, welding speed of 160 mm/min and axial force of 3.5 kN were fixed for the above experiment. With the help of twenty seven different designed tools as per Table 4, the friction stir welds were performed using the above mentioned operating parameters. Tensile speciemen from each welded plate were prepared as per the ASTM E8M-04 standard. The ultimate tensile strength of FS welded joint were evaluated in a servo tensile test machine at a constant cross head displacement 10 mm/ min. Metallographic examination on the transverse cross sections was carried out to study the microstructures of different zones of the welded samples. The samples were thoroughly polished and then etched with Keller's reagent to study the microstructure and weld cross section. An optical image analyzer (Leica) was used for this purpose.

The contribution of intense plastic deformation and high temperature exposure within the stirred zone during FSW process results in re crystallization. Based on microstr uctural characterization of grain three distinct zones i.e. stirred (nugget) zone, thermomechanically affected zone (TMAZ) and heat affected zone have been identified as shown in Fig 5. Intense plastic deformation and friction during FSW results in generation of a recrystallized fine equiaxed grained microstructure within the stirred zone. This region is referred to as nugget zone. Adjacent to nugget zone there is thermomechanically affected zone (TMAZ) experiences both temperature and deformation during FSW process. Although this zone underwent plastic deformation, recrystallization did not occur in this zone due to in sufficient heat. In the present study the welds were cross sectioned as shown in Fig. 5 and the cross section area were measured using image analysis software. The experimental data of the 27 tools with designs and their effect on the weld strength (WS) weld cross section area (WCSA), grain size number of weld (GSW) and grain size number of TMAZ (GSTMAZ) are presented in Table 5.

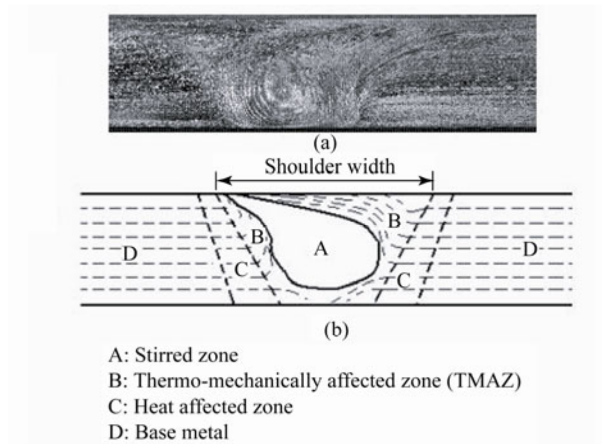


Fig. 5 (a) Macro-sections of a FS weld; (b) schematic of a FS weld

Table 5 Experimental data of the tools and their effects on the welds

Sl No	Exp. No	Tool type Number	Tool probe diameter	Shoulder flat surface	Weld strength	Weld cross section area	Grain size weld	Grain size TMAZ
1	25	1	−1	0	107.81	76.19	6.5	4.1
2	22	1	0	0	86.07	67.28	5.9	3.8
3	21	1	1	1	60.86	61.03	4.7	3.3
4	27	1	−1	1	90.89	71.52	6.2	4.1
5	26	1	−1	−1	108.53	78.03	6.6	4.3
6	24	1	0	1	62.52	60.09	4.7	3.2
7	19	1	1	0	73.49	64.2	5.8	4.7
8	23	1	0	−1	108.24	78.81	6.6	4.6
9	20	1	1	−1	76.9	65.2	5.2	4.7
10	17	2	−1	−1	56.2	56.03	4.3	3.3
11	10	2	1	0	103.86	68.76	6.4	5.1
12	15	2	0	1	94.37	64.48	4.9	4.1
13	18	2	−1	1	91.52	64.1	6.3	5.2
14	12	2	1	1	105.87	71.08	5.4	4.2
15	16	2	−1	0	61.33	66.07	4.8	3.9
16	11	2	1	−1	86.68	67.28	5.9	4
17	13	2	0	0	70.47	62.58	5.6	4.1
18	14	2	0	−1	61.5	61.03	4.8	3.8
19	1	3	1	0	62.96	60.09	4.9	4
20	4	3	0	0	94.39	64.38	6.3	5.1
21	3	3	1	1	90.31	63.26	6.2	5.2
22	7	3	−1	0	42.33	49.31	4.1	3.3
23	6	3	0	1	106.7	74.8	6.5	4.9
24	8	3	−1	−1	34.67	41.72	3.9	3.3
25	9	3	−1	1	67.76	62.52	5.2	4.2
26	2	3	1	−1	57.2	53.18	5.1	4.4
27	5	3	0	−1	45.67	50.38	4.9	3.9

4 Response surface modeling of FSW tool geometry effects

For the present investigation ANOVA was also used to observe the main effect of tool geometries on the weld strengths, weld cross sectional area, grain size of HAZ and thermomechanically affected zone (TMAZ). The manufacturing of straight cylindrical tool was easier as compared to tapered and trapezoidal tools. The vibration of the machine at the start of the weld with this tool was relatively high. Apart from initial high vibration of the machine, the straight cylindrical tool exhibited good weld surface finish and overall acceptable welds. In the present investigation a low deformation resistant aluminum alloy was used. The maximum tool probe diameter and shoulder friction surface were set based on the limit setting trial runs. The maximum diameter of the straight cylindrical tool considered was of 7 mm as the tool probe diameter exceeding 7 mm did not produce acceptable weld (Mohanty *et al*., 2012). Similarly the tool geometrical parameter limits were also set for tapered cylindrical and trapezoidal tools in the present investigation. Trial experiments were also conducted for the probe dimensions for each Type of tool to set the levels within which acceptable welds could be produced. Welding done beyond and below the set levels of the tool probe dimensions for each Type of tool did not produce acceptable welds.

4.1 Straight cylindrical (Type 1) tool:

The straight cylindrical used in the present investigation were having three distinct friction surfaces and probe diameter as shown in Table 4. It is observed that the cylindrical tool of 5 mm diameter with minimum shoulder flat contact surface produce welds with best mechanical properties. The main effect plots for type 1 tool for the responses is shown in Fig. 6. It is observed from Fig. 6 (a) and (b) that the effect of tool probe diameter and shoulder friction surface is significant in defining the weld strength and weld cross sectional area. The effect of tool probe diameter is more significant for grain size of weld as compared to the shoulder friction surface as observed in Fig .6 (c). The effect of tool probe diameter is least significant for the grain size determination of TMAZ as indicated in Fig. 6 (d). The surface response regression relations between the tool probe diameters, shoulder flat surface and responses like weld strength, weld cross section area, grin size of weld and grain size of TMAZ are shown in response surface plots in Fig. 7. The response surface regression equations for the two process variables (tool probe diameter, shoulder friction surface) for predicting the responses are given in equations (1)-(4). The analysis of variance (ANOVA) data for tool Type 1 is given in Table 6. The responses of the process are the weld characteristics like weld strength, weld cross sectional area, grain size number of weld and grain size number of TMAZ. The regression equations (1)-(4) predict the responses for a given input variables like tool probe diameter, shoulder friction surface. The equation indicated considerable accuracy for the prediction of output within average 5% of error.

$$\begin{aligned}\text{WS}=&88.59-16.00\times\text{TPD}-13.23\times\text{SFS}+0.8\times\text{TPD}^2-\\&4.47\times\text{SFS}^2+0.4(\text{TPD}\times\text{SFS})+\text{Error}\end{aligned}\tag{1}$$

where, WS is weld strength.

$$\begin{aligned}\text{WCSA}=&68.8-5.88\times\text{TPD}-4.9\times\text{SFS}+0.635\times\text{TPD}^2-\\&0.11\times\text{SFS}^2+0.58(\text{TPD}\times\text{SFS})+\text{Error}\end{aligned}\tag{2}$$

where, WCSA is weld cross setion area.

$$\begin{aligned}&\text{GSW}=6.000-0.6000\times\text{TPD}-0.4667\times\text{SFS}+\\&0.1000\times\text{TPD}^2-0.4000\times\text{SFS}^2-0.0250\times\text{TPD}\times\text{SFS}+\text{Error}\end{aligned}\tag{3}$$

where, GSW is Grain size number of weld.

$$\begin{aligned}&\text{GTMAZ}=3.9778+0.0333\times\text{TPD}-0.5000\times\text{SFS}+0.333\times\\&\text{TPD}^2-0.1667\times\text{SFS}^2-0.300\times\text{TPD}\times\text{SFS}+\text{Error}\end{aligned}\tag{4}$$

where, GTMAZ is Grain size number of TMAZ.

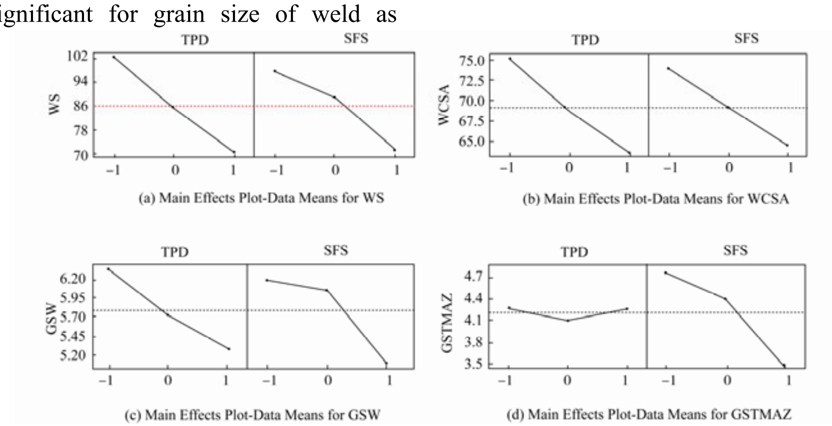


Fig. 6 Main effect plots for type 1 tool: (a) data means for weld strength (WS); (b) data means for weld cross section area (WCSA); (c) data means for weld zone grain size number (GSW); (d) Data means for TMAZ grain size number (GSTMAZ); with respect to tool probe diameters (TPD) and tool shoulder flat surfaces (SFS)

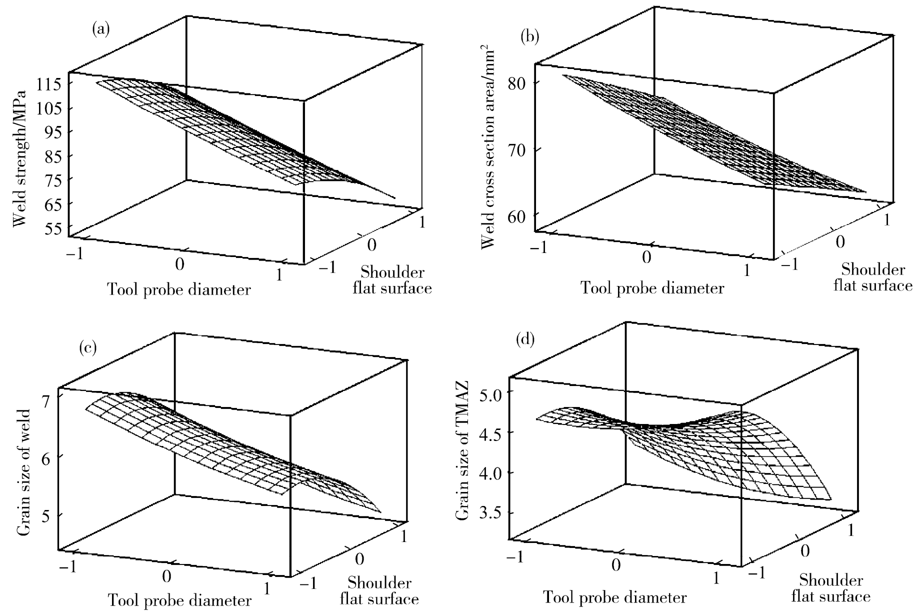


Fig. 7 Surface response plots for Type 1 tool, (a) Weld strength; (b) weld cross-section area; (c) Grain size number of weld; (d) Grain size number of TMAZ; vs tool probe diameter and shoulder flat surface

Table 6 Surface response regression analysis of variance data of Type 1 tool

Analysis of Variance for Weld Strength: (R-Sq =89.9% R-Sq(adj) =73.0%)						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	2627.92	2627.92	525.58	5.32	0.1
Linear	2	2586.09	2586.09	1293.04	13.09	0.033
Square	2	41.19	41.19	20.6	0.21	0.823
Interaction	1	0.64	0.64	0.64	0.01	0.941
Residual Error	3	296.34	296.34	98.78		
Total	8	2924.26				
Analysis of Variance for Weld Cross Section Area: (R-Sq =84.5%, R-Sq(adj) =58.7%)						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	354.059	354.059	70.812	3.27	0.179
Linear	2	351.859	351.859	175.93	8.13	0.061
Square	2	0.831	0.831	0.415	0.02	0.981
Interaction	1	1.369	1.369	1.369	0.06	0.818
Residual Error	3	64.909	64.909	21.636		
Total	8	418.968				
Analysis of Variance for Grain Size Number of Weld : (R-Sq = 80.7% , R-Sq(adj) =48.5%)						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	3.80917	3.80917	0.76183	2.51	0.24
Linear	2	3.46667	3.46667	1.73333	5.71	0.095
Square	2	0.34	0.34	0.17	0.56	0.621
Interaction	1	0.0025	0.0025	0.0025	0.01	0.933
Residual Error	3	0.91083	0.91083	0.30361		
Total	8	4.72				
Analysis of Variance for Grain Size Number of TMAZ : (R-Sq = 84.1%, R-Sq(adj) = 57.7%)						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	2.14444	2.14444	0.428889	3.18	0.185
Linear	2	1.50667	1.50667	0.753333	5.59	0.097
Square	2	0.27778	0.27778	0.138889	1.03	0.456
Interaction	1	0.36	0.36	0.36	2.67	0.201
Residual Error	3	0.40444	0.40444	0.134815		
Total	8	2.54889				

4.2 Tapered cylindrical (Type 2) tool

The effect of tapered cylindrical tools on weld strength and cross section area are given in Table 6. The interaction effect plots of tool pin diameter and shoulder flat contact surface on weld strength and weld cross sectional area for tapered cylindrical tool with three different tapper ratio with constant bottom diameter reveal that the higher pin diameter with high shoulder flat contact surface results into higher welding strength as shown in Figs 8 & 9. In FSW the pin diameter decides the volume of material that is being plasticized or stirred. If the pin diameter is larger then the volume of material stirred will be higher. Consequently higher welding strength and cross sectional areas are resulted due to bigger pin diameter. As reported in the literature the ratio of static to dynamic volume (material movement by the tool probe from leading to trailing edge) is equal to 1 for straight cylindrical, 1.32 for tapered cylindrical and 3.46 for trapezoidal profile. Since the tapered cylindrical and trapezoidal profiles sweeps less materials as compared to the straight cylindrical pins, to balance the material flow for achieving the tensile strength as that of straight cylindrical tool the bigger size of pins might be suitable for tapered cylindrical and trapezoidal tools. The main effect plots for type 2 tools for the responses are shown in Fig. 8. It is observed from Fig. 8 (a) and (b) that the effect of tool probe diameter and shoulder flat surface is significant in defining the weld strength and weld cross sectional area. The effect of tool probe diameter is more significant for grain size of weld as compared to the shoulder flat surface as observed in Fig. 8 (c).

The effect of tool probe diameter is also significant for the grain size determination of TMAZ in case of tapered cylindrical tools as exhibited in Fig. 8 (d). The quadratic relations between the tool probe diameters, shoulder flat surface and responses like weld strength, weld cross section area, grin size of weld and grain size of TMAZ are shown in response surface plots in Fig. 9. The response surface regression equations for the two process variables (tool probe diameter, shoulder friction surface) for predicting the responses are given in equations (5)-(8). The ANOVA data of tool Type 2 is given Table 7. The regression equations could predict the weld characteristics considering tool probe diameter and friction surface as the input variables within considerable average accuracy of 5 %.

Grain size number of weld (d) Grain size number of TMAZ; vs tool probe diameter and shoulder flat surface

$$\mathrm{WS}=72.689+14.56\times\mathrm{TPD}+14.563\times\mathrm{SFS}+8.797\times\mathrm{TPD}^2+4.137\times\mathrm{FS}\times\mathrm{SFS}-4.033\times\mathrm{TPD}\times\mathrm{SFS}+\mathrm{Error} \quad (5)$$

where, WS is weld strength.

$$\mathrm{WCSA}=63.899+3.487\times\mathrm{TPD}+2.553\times\mathrm{SFS}+2.857\times\mathrm{TPD}^2-1.803\times\mathrm{SFS}^2-1.067\times\mathrm{TPD}\times\mathrm{SFS}+\mathrm{Error} \quad (6)$$

where, WCSA is weld cross section area.

$$\mathrm{GSW}=5.3222+0.3833\times\mathrm{TPD}+0.2667\times\mathrm{SFS}+0.4167\times\mathrm{TPD}^2-0.3333\times\mathrm{SFS}^2-0.6250\times\mathrm{TPD}\times\mathrm{SFS}+\mathrm{Error} \quad (7)$$

where, GSW is grain size number of weld.

$$\mathrm{GTMAZ}=4.1778+0.1500\times\mathrm{TPD}+0.4000\times\mathrm{SFS}+0.2833\times\mathrm{TPD}^2-0.2667\times\mathrm{SFS}^2-0.4250\times\mathrm{TPD}\times\mathrm{SFS}+\mathrm{Error} \quad (8)$$

where, GTMAZ is grain size number of TMAZ.

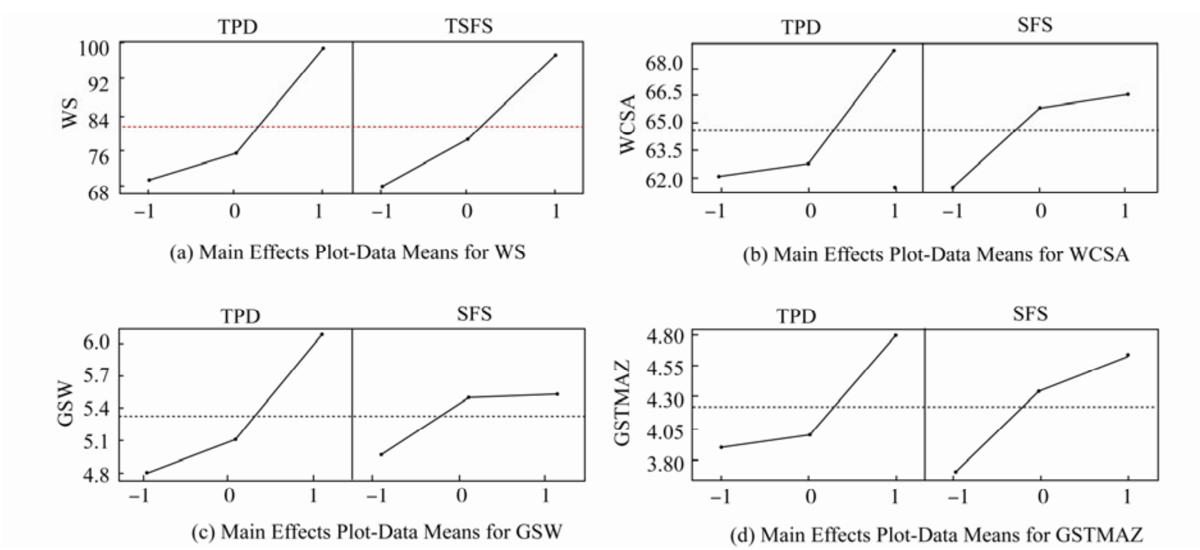


Fig. 8 Main effect plots for type 2 tool: (a) data means for weld strength (WS); (b) data means for weld cross section area (WCSA); (c) data means for weld zone grain size number (GSW); (d) data means for TMAZ grain size number (GSTMAZ); with respect to tool probe diameters (TPD) and tool shoulder flat surfaces (SFS)

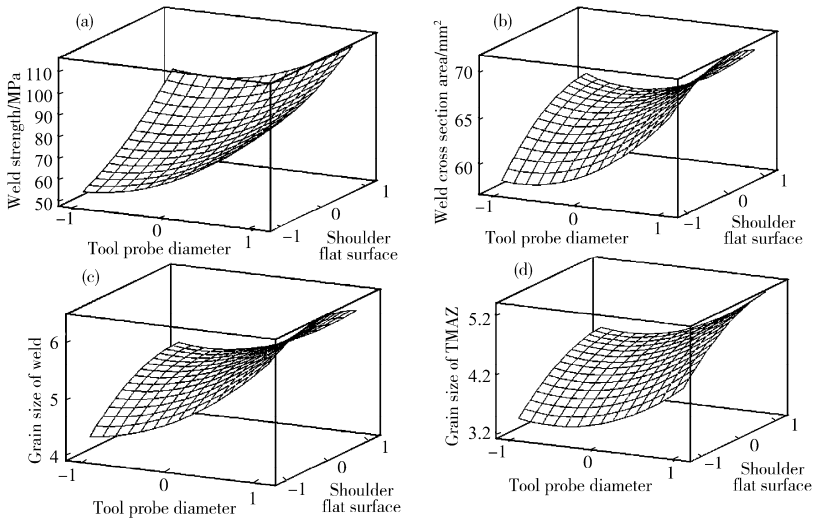


Fig. 9 Surface response plots for type 2 tool, (a) Weld strength (b) weld cross-section area (c)

Table 7 Surface response regression analysis of variance data of Type 2 tool

Analysis of Variance for Weld Strength: (R-Sq = 94.7%, R-Sq(adj) = 85.9%)						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	2798.54	2798.54	559.71	10.73	0.039
Linear	2	2544.51	2544.51	1272.25	24.39	0.014
Square	2	188.99	188.99	94.49	1.81	0.305
Interaction	1	65.04	65.04	65.04	1.25	0.345
Residual Error	3	156.46	156.46	52.15		
Total	8	2954.99				
Analysis of Variance for Weld Cross Section Area: (R-Sq =80.5% , R-Sq(adj) =47.9%)						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	139.441	139.441	27.8883	4.24	0.132
Linear	2	112.058	112.058	56.0291	8.52	0.058
Square	2	22.825	22.825	11.4126	1.74	0.316
Interaction	1	4.558	4.558	4.5582	0.69	0.466
Residual Error	3	19.732	19.732	6.5775		
Total	8	159.174				
Analysis of Variance for Grain Size Number of Weld : (R-Sq = 80.5%, R-Sq(adj) = 47.9%)						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	3.44028	3.44028	0.68806	2.47	0.243
Linear	2	1.30833	1.30833	0.65417	2.35	0.243
Square	2	0.56944	0.56944	0.28472	1.02	0.459
Interaction	1	1.5625	1.5625	1.5625	5.61	0.099
Residual Error	3	0.83528	0.83528	0.27843		
Total	8	4.27556				
Analysis of Variance for Grain Size Number of TMAZ : (R-Sq = 72.4%, R-Sq(adj) = 26.4%)						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	2.12028	2.12028	0.424056	1.57	0.376
Linear	2	1.095	1.095	0.5475	2.03	0.277
Square	2	0.30278	0.30278	0.151389	0.56	0.621
Interaction	1	0.7225	0.7225	0.7225	2.68	0.2
Residual Error	3	0.80861	0.80861	0.269537		
Total	8	2.92889				

4.3 Trapezoidal (Type 3) tool:

The reason behind choosing the trapezoidal tool probe profile was the four sides with sharp corner of the same would create higher friction and good material flow between plates compared to the straight cylindrical tool.

It is observed from the main effect plot (Fig. 10) that the pin having medium level (Table 4) shoulder flat contact surface exhibits maximum weld strength as compared to others. This might be due to the reason that the pin having more surface area creates excessive heat inputs which softens the material resulting tunnel defects. The quadratic relations between the tool probe diameters, shoulder flat surface and responses like weld strength, weld cross section area, grain size of weld and grain size of TMAZ are shown in response surface plots in Fig. 11. The response surface regression equations for the two process variables (tool probe diameter, shoulder flat surface) for predicting the responses are given in equations 9-12. The ANOVA data of Type 2 tool is given in Table 8. The regression equations could predict the weld characteristics considering tool probe diameter and shoulder flat surface as the input variables within considerable average accuracy of 5 %.

$$WS=81.93+10.95\times TPD+21.21\times SFS-23.05\times TPD^2+0.49\times SFS^2+0.00\times TPD\times SFS+Error \tag{9}$$

where, WS is weld strength.

$$WCSA=63.376+3.83\times TPD+9.217\times SFS-8.173\times TPD^2-0.283\times SFS^2-2.68\times TPD\times SFS+Error \tag{10}$$

where, WCSA is weld cross section area.

$$GSW=5.767+0.500\times TPD+0.667\times SFS-1.000\times TPD^2+0.200\times SFS^2-0.050\times TPD\times SFS+Error \tag{11}$$

where, GSW is grain size number of weld.

$$GTMAZ=4.5111+0.4667\times TPD+0.4500\times SFS-0.5667\times TPD^2+0.1833\times SFS^2-0.250\times TPD\times SFS+Error \tag{12}$$

where, GTMAZ is grain size number of TMAZ.

The adequacy of the regression equations for each type of tool was further investigated with some test case tool designs. These test case tools were tested for conformity test and outputs were noted. The test case tools are indicated in Table 9. The experimentally measured and predicted effects such as weld strength, weld cross sections area, grain size of the weld and grain size of the TMAZ were compared and close agreement between the two were observed.

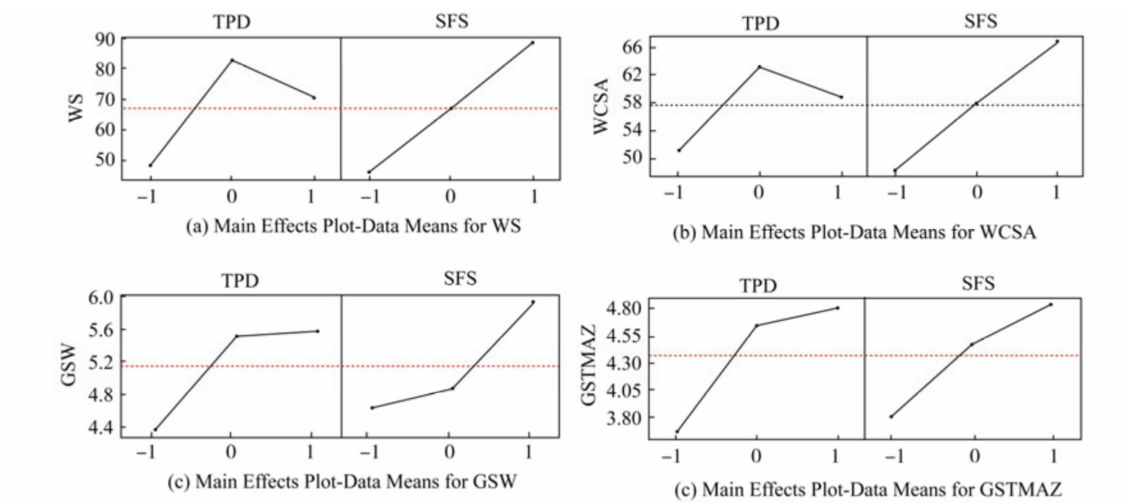


Fig. 10 Main effect plots for type 3 tool: (a) data means for weld strength (WS); (b) data means for weld cross section area (WCSA); (c) data means for weld zone grain size number (GSW); (d) data means for TMAZ grain size number (GSTMAZ); with respect to tool probe diameters (TPD) and tool shoulder flat surfaces (SFS)

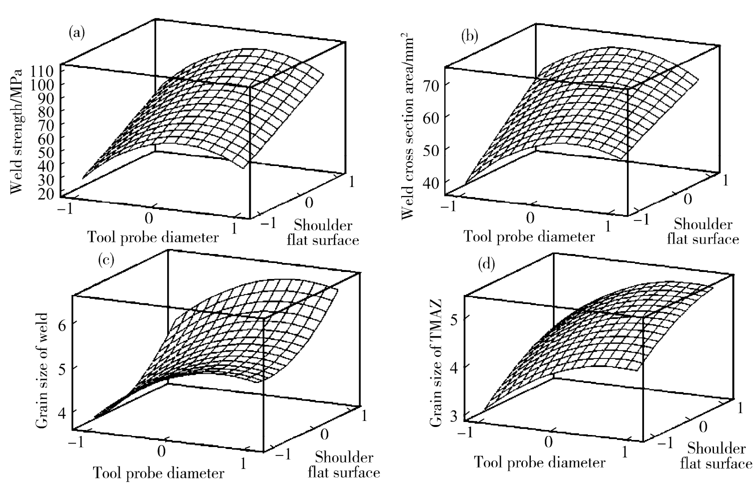


Fig. 11 Surface response plots for Type 3 tool: (a) Weld strength (b) weld cross-section area (c) grain size number of weld (d) grain size number of TMAZ; vs. tool probe diameter and shoulder flat surface

Table 8 Surface response regression analysis of variance data of Type 3 tool

Analysis of Variance for Weld Strength: (R-Sq = 88.0% R-Sq (adj) = 68.0%)						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	4480.48	4480.48	896.1	4.4	0.126
Linear	2	3417.55	3417.55	1708.77	8.39	0.059
Square	2	1062.93	1062.93	531.47	2.61	0.22
Interaction	1	0	0	0	0	0.999
Residual Error	3	610.81	610.81	203.6		
Total	8	5091.29				
Analysis of Variance for Weld Cross Section Area: (R-Sq = 95.4% R-Sq (adj) = 87.8%)						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	760.192	760.192	152.038	12.51	0.032
Linear	2	597.695	597.695	298.848	24.6	0.014
Square	2	133.767	133.767	66.884	5.5	0.099
Interaction	1	28.73	28.73	28.73	2.36	0.222
Residual Error	3	36.451	36.451	12.15		
Total	8	796.643				
Analysis of Variance for Grain Size Number of Weld : (R-Sq = 89.6% R-Sq (adj) = 72.4%)						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	6.25667	6.25667	1.25133	5.19	0.103
Linear	2	4.16667	4.16667	2.08333	8.64	0.057
Square	2	2.08	2.08	1.04	4.31	0.131
Interaction	1	0.01	0.01	0.01	0.04	0.852
Residual Error	3	0.72333	0.72333	0.24111		
Total	8	6.98				
Analysis of Variance for Grain Size Number of TMAZ : (R-Sq = 79.6% R-Sq (adj) = 45.6%)						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	3.23361	3.23361	0.64672	2.34	0.258
Linear	2	2.52167	2.52167	1.26083	4.56	0.123
Square	2	0.70944	0.70944	0.35472	1.28	0.395
Interaction	1	0.0025	0.0025	0.0025	0.01	0.93
Residual Error	3	0.82861	0.82861	0.2762		
Total	8	4.06222				

Table 9 Comparison of regression model results with experimental ones for test cases

Sl. No	Tool type	Tool probe diameter	Shoulder flat surface SFS	Weld strength /MPa			Weld cross section area /mm^2			Grain size of weld		
				Predicted	Measured	% Error	Predicted	Measured	% Error	Predicted	Measured	% Error
1	1	0.5	0.5	73.151	70.98	2.96	63.68	58.90	07.50	5.38	4.4	18.21
2	1	-0.5	-0.5	102.38	96.00	6.23	74.46	70.00	05.98	6.4521	6.1	05.45
3	2	-0.5	1.0	88.324	95.61	-8.24	64.68	71.45	-10.46	5.480	4.8	12.40
4	2	1.0	0.5	103.82	94.50	8.46	71.602	67.90	05.17	5.859	6.2	-05.82
5	3	0.5	1.0	103.29	96.20	6.86	70.84	76.00	-07.28	6.609	5.6	15.26
6	3	1.0	-0.5	59.147	54.89	7.19	55.693	49.20	11.65	5.008	5.8	-15.81

5 Conclusions

From the present investigation the following conclusions can be made:

1)Straight cylindrical FSW tool with minimum level of probe diameter, shoulder surface as per the design matrix, provided better weld strength as compared to other tools of it's type.

2)The FSW tool geometrical features like tool shoulder flat surface and diameter of the probe can be used as the input variables in the full factorial design matrix to develop mathematical regression models for estimating the related effects on the weld.

3)The quadratic surface response regression equations developed for each type of FSW tool were found to be adequate enough to predict the responses like weld strength weld cross sectional area and grain sizes in different zones of weld.

4)The modeling methodology developed in the present investigation can be successfully applied for different types of FSW tool geometries to predict their effects on aluminum alloy welds.

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