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Effect of Tool Shoulder and Pin Probe Profiles on Friction Stirred Aluminum Welds – a Comparative Study

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Abstract: In marine application, marine grade steel is generally used for haul and superstructures. However, aluminum has also become a good choice due to its lightweight qualities, while rusting of aluminum is minimal compared to steel. In this paper a study on friction stir welding of aluminum alloys was presented. The present investigation deals with the effects of different friction stir welding tool geometries on mechanical strength and the microstructure properties of aluminum alloy welds. Three distinct tool geometries with different types of shoulder and tool probe profiles were used in the investigation according to the design matrix. The effects of each tool shoulder and probe geometry on the weld was evaluated. It was also observed that the friction stir weld tool geometry has a significant effect on the weldment reinforcement, microhardness, and weld strength.
Keywords: friction stir welding; tool geometries; weld strength; weld cross section area
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1 Introduction

The friction stir welding (FSW) process is a solid state joining process which utilizes frictional heat of a rotating tool and the stirring effect of the tool probe for solid state joining. The FSW process was invented at the Welding Institute at Cambridge in the early 1990s (Thomas *et al*., 1993). Over the years FSW has gained significance for joining such as aluminum alloys as the heat generated during the process is not severe enough to produce the defects which are generally observed in these materials during arc welding (Thomas *et al*., 1999).

During FSW the joining of plates takes place below the melting point of the materials. The maximum temperature reached during the process is 0.8 of the melting temperature of the work pieces. The welds are created by the combined action of frictional heating and mechanical deformation due to a rotating tool. The detrimental effects of arc welding such as distortion and residual stresses are due to the rapid heating beyond the melting temperature and cooling of the joints. These detrimental effects are minimized in FSW, as the heat generated is not severe enough. Moreover, no special preparation of the sample is required during the FSW process. FSW of aluminum alloys offers the advantages of low heat input and reduced distortion, leading to low residual stresses and higher mechanical properties compared to conventional fusion welding methods.
Rotational speed of the tool, tool traverse speed, and vertical pressure on the plates during welding are the main process parameters of FSW (Rajakumar *et al*., 2010). However the tool geometry which involves the geometry of the FSW tool shoulder and tool pin probe profile is also an important characteristic which affects the weld strength. Hence study of the FSW process also involves the analysis and study of tool characteristics (Su *et al*., 2003). The effectiveness of an FSW joint is strongly affected by several tool parameters; in particular, geometrical parameters such as the height and the shape of the pin (cylindrical, trapezoidal, screwed, *etc*.) and the shoulder surface of the tool have a relevant influence both on the metal flow and on the heat generation due to friction forces (Leal *et al*., 2008). Furthermore both rotating speed and feed rate have to be properly chosen in order to obtain effective joints (Fujii *et al*., 2006). Finally, material physical and thermomechanical characteristics have to be considered in order to control the microstructure evolution during the joining process (Su *et al*., 2003). FSW can potentially replace the riveting and resistance spot welding of aluminum and steel sheets in the aircraft and automotive industries, respectively (Biswas *et al*., 2009).

The FSW tool is a crucial part of this welding process. Dawes *et al*. (1999) described in detail the tool development approach taken at The Welding Institute (TWI) and outlined the tool design aspects of the scroll shoulder concept. Some authors have analyzed the influence of the tool rotation speed (Sato *et al.*, 2002), welding speed (Lee *et al*., 2003; Boz *et al*., 2004), and both parameters simultaneously on the microstructure and mechanical properties of series 6XXX and 5XXX aluminum welds by considering the same tool geometry. Sato *et al.* (2002) studied the aluminum (Al) alloys 6063-T5 and T4 at different tool rotation speeds and then distributions of the microstructure and hardness were

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examined in these welds. They discovered that different rotational speed values did not result in significant differences in the hardness profile of FSW welds, except for the width of the softened region in the weld of 6063-T5 Al. Lee *et al.* (2003) studied the microstructural change related to the hardness profile for a friction stir welded, age hardenable 6005 Al alloy. They suggested that frictional heat and plastic flow during friction stir welding created fine and equiaxed grains in the stir zone, and elongated grains in the thermomechanically affected zone (TMAZ).

In order to obtain a defect-free weld, the process parameters, i.e. tool rpm, tool translational speed, and downward plunge force, on the tool must be chosen carefully. While there have been several studies focused on the variation of rotation and welding speeds to optimize the welding parameters and study their microstructures for aluminum alloys, limited research has been carried out on the effects of tool structure (Leal *et al.,* 2008; Boz *et al*., 2004; Barcellona *et al.,* 2004). A large majority of research conducted on the FSW process has focused specifically on visualizing the material flow around the FSW tool (Nunes *et al.,* 2002). It is well understood that plastically deforming material is forced to flow in the direction of tool rotation from front to the rear of the FSW tool.

Even though some work has been done in contemporary literature on the study of the tool shoulder and probe profile, a comparative detailed study of different basic tool features for a given material is rarely found. There is, therefore, a need to systematically investigate the effect of tool shoulder and pin profile geometries on the FS weld. In the present investigation, the effects of various tool geometries on mechanical properties and microstructural characteristics of the welded joint made from commercial aluminum alloy were studied.

The FSW tool shoulder geometry and probe geometry need not to be same for all alloys of a particular material. In fact, it can be said that the FSW tool shoulder and probe geometry are material dependent to some extent (Scialpi *et al*., 2007; Barcellona *et al.,* 2004). Also, FSW tool manufacturing and designing is a costly process, and prolonging use of the tool also facilitates its wearing. Hence, for a given material the FSW tool shoulder and probe geometry should be such that its manufacturing cost can be minimized. For example aluminum alloys with greater hardness might require a special tool probe design for a better stirring effect (Su *et al*., 2003). An aluminum alloy with moderate to adequate strength might require somewhat simple tool geometry which is easy to manufacture.

The present investigation deals with the study of geometrical features of the tool shoulder and probe and the related effects on weld strength of commercial grade aluminum alloy. Some commonly followed tool features such as a conical shoulder surface, multi-face probe profiles, and tapered tool pin profiles were investigated for determining the related effects on weld strength. A design matrix was followed, keeping the limits of shoulder and pin dimensions in view. The effects of these tools with respect to a constant vertical load, rpm, and tool traverse speed on the weld strength, weld cross-sectional area, and micro-hardness were observed. Also, conclusions with respect to the different tool features were made.

2 Process advantages of FSW

The process advantages are a result of the fact that the FSW process takes place in the solid phase below the melting point of the materials to be joined. The benefits therefore include the ability to join materials which are difficult to fusion weld, such as aluminum alloys. The process is suitable for automation and adaptable for robot use. The advantages are as follows:

i) No porosity, (ii) No spatter, (iii) Low shrinkage. (iv) Can operate in all positions, (v) Energy efficient, (vi) Non-consumable tool, (vii) No filler wire, (viii) No gas shielding for welding aluminum, (ix) Low distortion even in long welds, (x) Excellent mechanical properties as proven by fatigue, tensile, and bend tests, (xi) No arc, (xii) No fume, (xiii) No welder certification required, (xiv) No grinding, brushing, or pickling required in mass production.

2.1 Application and advantages in marine science

In marine application, steel of marine grade is generally used for haul and superstructures. However, aluminum has become a good choice because of its lightweight qualities, and rusting of aluminum is minimal compared to steel. The salt water environment is demanding and even marine grade aluminum is not suitable unless proper treatment is given to it to prevent pitting corrosion. It is very difficult and costly to treat corroded aluminum and its prevention is always desired. Hence, even the marine grade aluminum alloys are given protection by anodizing and powder coating. The commercial grade aluminum, on the other hand (Table 3), has a better corrosion resistance and might not require anodizing and coating when used in the ship super structure. Compared to marine grade aluminum the commercial grade aluminum (Table 3) is almost three times cheaper and the composition available is quite suitable for ship super structure fabrication. Even though studies have been conducted in contemporary literature regarding the 5XXX and 6XXX series of aluminum alloys, few studies have been made regarding the commercially available aluminum alloy which is widely used in making furniture, doors, and light structures. There is therefore a need to investigate the effect of the tool shoulder and probe the geometry profile on weld strength and weldment characteristics.

Table 1 Composition of FSW tool material by percentage

Fe	C	Cr	Mn	Ni
48-53	0.25	24-26	2	19-22

Table 2 FSW tool material physical properties

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

Table 3 Composition of Al alloy by percentage

Material	Percentage
Si	0.4
Cu	0.011
Cr	0.001
Fe	0.4
Mn	0.076
Mg	0.001
Zn	0.007
Ni	0.002
Others	<0.1

3 Experimental details

A vertical milling machine with a 7.5 HP motor capacity was used to carry out the FSW experiments. The tool was mounted in the vertical arbor of the machine. The edges of the test pieces were machined to obtain a perfect square butt. They were clamped to the horizontal bed with zero root gaps. The butt line was aligned with the centre line of the FSW tool. The clamping of the test pieces was done such that the movement of the plates was totally restricted under both plunging and translational forces of the FSW tool. The tool rpm and translational speed of the bed were set prior to each run of welding. A typical FSW setup is shown in Fig.1. After plunging the rotating tool at the plate butt and visually ensuring the full contact of the tool shoulder with the plate surface, the bed movement was switched on.

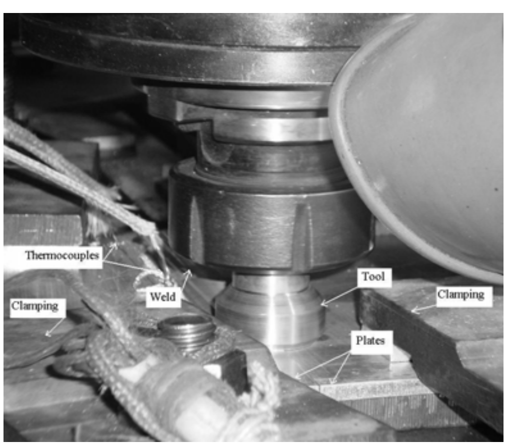


Fig.1 The friction stir welding setup

3.1 Tool design

The FSW tool geometry plays a critical role on the microstructure and tensile strength of various aluminum alloys. An FSW tool consists of a shoulder and a pin. As mentioned earlier, the tool has two primary functions: (a) localized heating, and (b) material flow. In the initial stage of the tool plunge, the heating is a result primarily of the friction between the pin and work piece. Some additional heating is caused by deformation of the material. The friction between the shoulder and work piece results in the biggest component of heating. From the heating aspect, the relative size of the pin and shoulder is important. The tool shoulder can also provide confinement for the heated volume of the material. The second function of the tool is to 'stir' and 'move' the material. The uniformity of the microstructure and properties as well as process loads is governed by the tool design. With increasing experience and some improvement in understanding of material flow, tool geometry has evolved significantly. During the trial runs mild steel and die steel were also tested as tool materials. The mild steel tool probe profile deteriorated after only a few trials and weld profiles were not good. The die steel tools were similar in behavior. Chromium steel was tried as the tool material and found to be suitable. The material composition and the relevant physical properties of the material used for manufacturing the tool are shown in Tables 1 and 2, respectively. The chemical composition of the Al-alloy used in the present study was determined using an ARL 3460 Optical Emission Spectroscope. The chemical composition of the Al-alloy used in the present study is given in Table 3.

The different tool geometries and the sample tools for FSW of aluminum alloys are shown in Figs.2 and 3, respectively. Complex features have been added to alter material flow and mixing while reducing process loads. In the present study 27 various FSW tool geometries were considered by varying the tool pin and shoulder profile. During the initial trials the threaded tool was not very capable of retaining the profiles, as these were filled with the deformed aluminum material in the process of stirring, and the probes profile became cylindrical. Similar observations were also made with respect to hexagonal tool probe profiles during the trial runs. Hence three types of tool profiles (straight cylindrical, tapered cylindrical, and trapezoidal) were selected for the experiments. For the straight cylindrical tool the maximum diameter of the probe was decided by carrying out a series of experiments. Limited settings of tapered and trapezoidal tools were similarly made. The influence of the shoulder on the weld formation is important since it drags materials into the shear layer that originates in the weld nugget through the leading side of the weld to the trailing side. The shoulder profiles were made as shown in Fig.2. Some designed and developed FSW tools are shown in Fig.3. The detailed configuration of the designed FSW tool geometric matrix is given in Table 4.

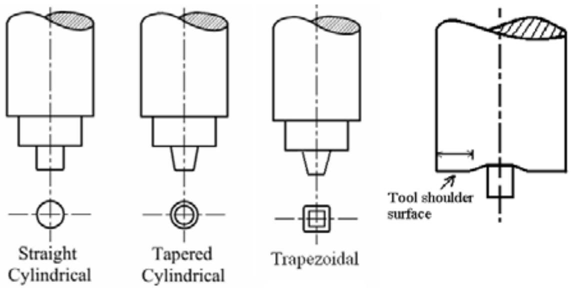


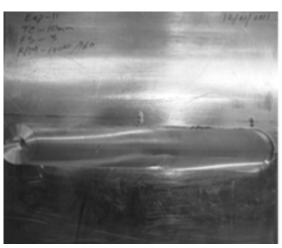
Fig.2 Different FSW tool geometries used in the experiment

(a) Tools with trapezoidal probes;

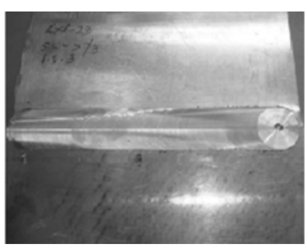
(b) Tools with cylindrical probes;

(c) Tools with tapered cylindrical probes

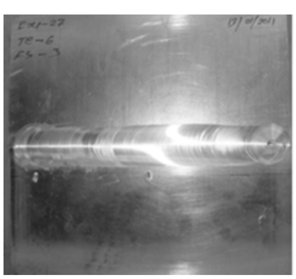
Fig.3 Designed and developed FSW tools



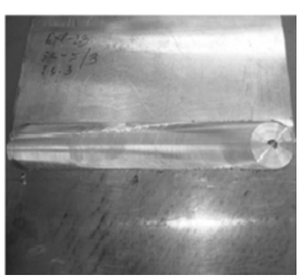
(a) Weld profile with straight cylindrical tool



(b) Profile with straight cylindrical tool and side depression



(c) Weld profile with a trapezoidal tool



(d) Weld profile with a tapered cylindrical tool

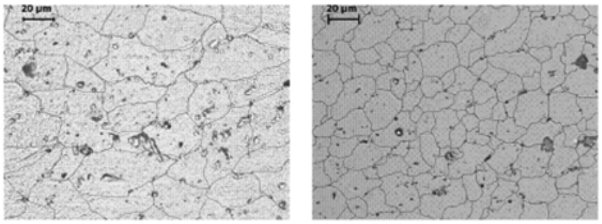
Fig.4 Weld profiles with different types of shoulder and tool probe profiles.

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

4 Results and discussions

FSW, though a solid state joining process, is associated with many parameters other than the main input parameters that affect the weld. The rigidity condition of the machine, clamping of the plates, spindle tool mating condition, and backlash 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 the aforementioned variables is not possible from a 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 such as weld strength might be difficult considering the aforementioned varying input process and other variables. Since in the present investigation 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. It must be stated here that the analysis of variance (ANOVA) was used for the present experiments only to see the interaction effects of the tool features on the weld strength and resulting weld cross sectional area. Test samples 300 mm long and 150 mm wide were welded with the above-mentioned FSW tools (Table 4) using a tool with an rpm of 1400, translational speed of the bed, i.e. welding speed of 160 mm per minute, and axial load of 3.5kN. Necessary test pieces were cut from the welded samples to carry out metallographic examination, hardness, and tensile tests. The tensile test specimens were sectioned in the transverse direction, that is, perpendicular to the welding direction from friction stir welded aluminum alloy test samples. All tensile tests were performed at a constant crosshead displacement rate of 10 mm/min using a servo tensile testing machine. Tensile tests were carried out on friction stir welded aluminum alloy test samples to study the effect of variation of FSW tool geometries keeping tool rotational speed and transverse speed fixed and the effect of different tool rotational speed and transverse speed keeping the tool geometry fixed on the mechanical properties of welded samples. The relationship between the static and dynamic volume of material during FSW decides the path for flow of material from the leading edge to the trailing edge of the rotating tool.

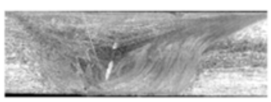


(a) HAZ grains (b) Weld zone grains

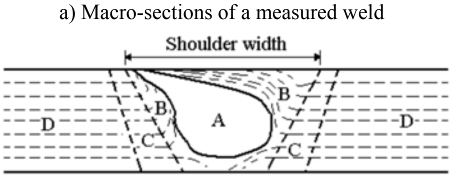
Fig.5 Microstructures of some FS investigated welds (tool rotational speed 1400rpm and traverse speed 160 mm/min)

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. An optical image analyzer (Leica) was used for this purpose. As an example the effect of cylindrical pin geometry on microstructures of different zones of the welding is shown in Fig.5.

The grain size of the welds were also measured and it was observed that the grain size in the centre of the stir zone are similar for all type of tools while the grain size at the bottom of the stir zone for the trapezoidal tool is slightly smaller than that of cylindrical and tapered cylindrical tools with a similar bottom side diameter.



a) Macro-sections of a measured weld



A: Stirred zone
B: Thermo-mechanically zone (TMAZ)
C: Heat affected zone
D: Base metal

(b) Schematic of an FS weld

Fig.6 Weld cross-section and macrostructure zones

The FSW nugget is the region through which the tool pin passes and does experience high deformation and high heat. It generally consists of equiaxed grain due to full recrystallization. The thermo-mechanically affected zone (TMAZ) adjacent to the nugget is the region where the metal is plasticized and deformed as well as heated but not recrystallized. The weld cross section area represents the material that is affected by the FSW process and thought to be also dependent on the tool shoulder and pin probe geometries. In the present study the welds were cross sectioned as shown in Fig.6 and the cross section area was measured using image analysis software. It was observed that the weld cross section area varies almost proportionally to the weld strength and is influenced by the FSW tool geometry.

4.1 Straight cylindrical tool

The straight cylindrical tools used in the present investigation have three distinct friction surfaces and probe diameters as shown in Table 4. The manufacturing of a straight cylindrical tool was easier compared to tapered and trapezoidal tools. The initial penetration of the straight cylindrical tool was difficult at the start of the weld. 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. It is observed that the cylindrical tool of 5 mm diameter with minimum shoulder flat contact surface produces welds with the best mechanical properties. The maximum diameter of the straight cylindrical tool considered was 7 mm as a tool probe diameter exceeding 7 mm did not produce an acceptable weld as shown in Fig. 7. Similarly, the tool geometrical parameter limits were also set for tapered cylindrical and trapezoidal tools in the present investigation. The effect of straight cylindrical tools on weld strength and cross section area are given in Table 5. The interaction effects of the tool pin diameter and shoulder flat contact surface on the weld strength of joints decreases with the increase in the pin diameter and shoulder flat contact surface as shown in Fig. 8. This is due to severe stirring and higher heat generation in a shoulder flat contact surface. A similar trend is also observed for weld cross section area as shown in Fig.9.

Table 5 Straight cylindrical tools and experimental results

Serial Number	Experiment Number	Tool probe diameter	Shoulder flat surface	Weld strength /MPa)	Weld cross section area /mm^2
1	25	−1	0	107.81	76.19
2	22	0	0	86.07	67.28
3	21	1	1	60.86	61.03
4	27	−1	1	90.89	71.52
5	26	−1	−1	108.53	78.03
6	24	0	1	62.52	60.09
7	19	1	0	73.49	64.20
8	23	0	−1	108.24	78.81
9	20	1	−1	76.90	65.20

Fig.7 Limit setting of probe diameter for straight cylindrical tool

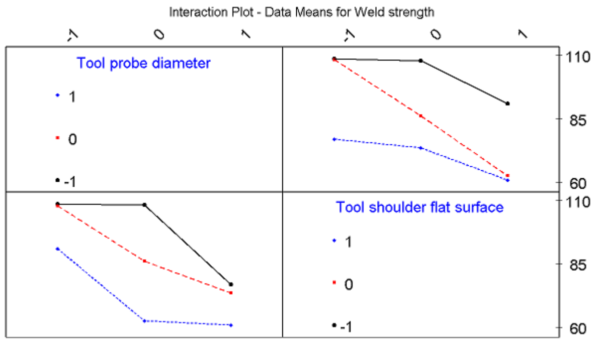


Fig.8 Interaction effect plot of weld strength for straight cylindrical tool

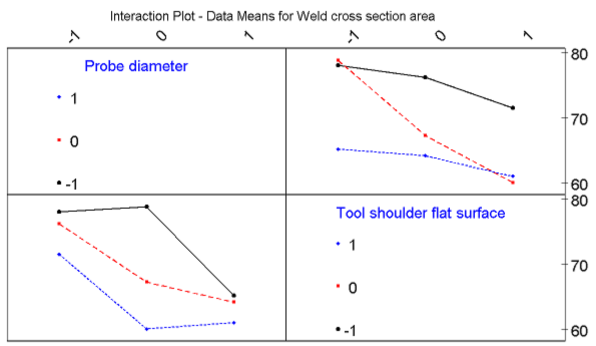


Fig.9 Interaction effect plot of weld cross sectional area for straight cylindrical tool

4.2 Tapered cylindrical tool

The effect of tapered cylindrical tools on weld strength and cross section area are given in Table 6. The interaction effect plots of the tool pin diameter and shoulder flat contact surface on weld strength and weld cross sectional area for a tapered cylindrical tool with three different tapper ratios and a constant bottom diameter reveal that the higher pin diameter with a high shoulder flat contact surface results in a higher welding strength as shown in Figs. 10 and 11.

In the 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 generated, resulting from a larger pin diameter. As reported in the research literature, the ratio of static to dynamic volume (material movement by the tool probe from the leading to trailing edge) is equal to 1 for a straight cylindrical profile, 1.32 for a tapered cylindrical profile, and 3.46 for a trapezoidal profile (Rajakumar *et al*., 2010).

Since the tapered cylindrical and trapezoidal profiles sweep less materials compared to the straight cylindrical pins, to balance the material flow for achieving the tensile strength as that of a straight cylindrical tool the larger size of pins might be suitable for tapered cylindrical and trapezoidal tools.

Table 6 Tapered cylindrical tools and experimental results

Sl. No	Exp. No	Tool probe diameter	Shoulder flat surface	Weld strength /MPa	Weld cross section area /mm^2
1	17	−1	−1	56.20	56.03
2	10	1	0	103.86	68.76
3	15	0	1	94.37	64.48
4	18	−1	1	91.52	64.10
5	12	1	1	105.87	71.08
6	16	−1	0	61.33	66.07
7	11	1	−1	86.68	67.28
8	13	0	0	70.47	62.58
9	14	0	−1	61.50	61.03

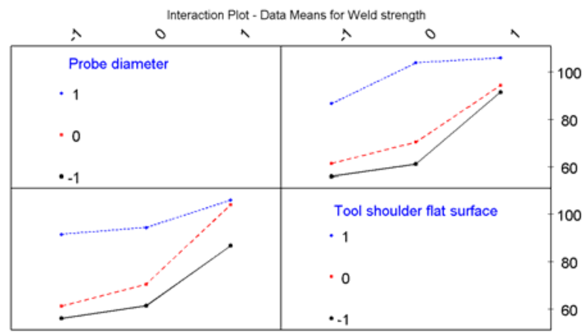


Fig.10 Interaction effect plot of weld strength for tapered cylindrical tool

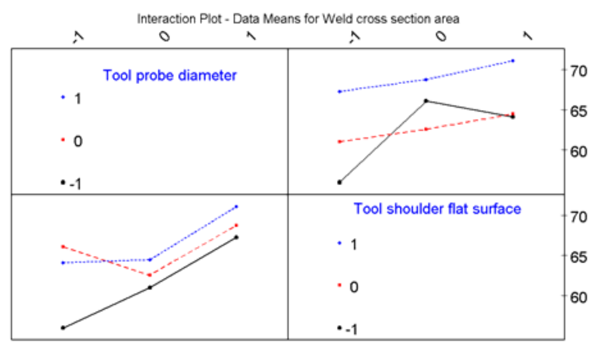


Fig.11 Interaction effect plot of weld cross sectional area for tapered cylindrical tool

Table 7 Trapezoidal tools and experimental results

Sl. No	Exp. No	Tool probe diameter	Shoulder flat surface	Weld strength /MPa	Weld cross section area /mm^2
1	1	1	0	62.96	60.09
2	4	0	0	94.39	64.38
3	3	1	1	90.31	63.26
4	7	−1	0	42.33	49.31
5	6	0	1	106.7	74.80
6	8	−1	−1	34.67	41.72
7	9	−1	1	67.76	62.52
8	2	1	−1	57.20	53.18
9	5	0	−1	45.67	50.38

4.3 Trapezoidal tool

The reason behind choosing the trapezoidal tool probe profile was that the four sides with a sharp corner of the probe would create a higher friction and good material flow between plates compared to the straight cylindrical tool. The effect of trapezoidal tools on weld strength and cross section area are given in Table 7. It is observed from the interaction plots (Figs. 12 and 13) that the pin having 8mm sides with a maximum shoulder flat contact surface exhibits maximum weld strength compared with the others. The pin having a larger surface area creates excessive heat input which softens the material resulting in tunnel defects. Moreover, the pin having less surface area generates insufficient heat and metal transportation resulting in piping defects. For trapezoidal tools, cracks such as small defects on the bottom of the weld might also occur.

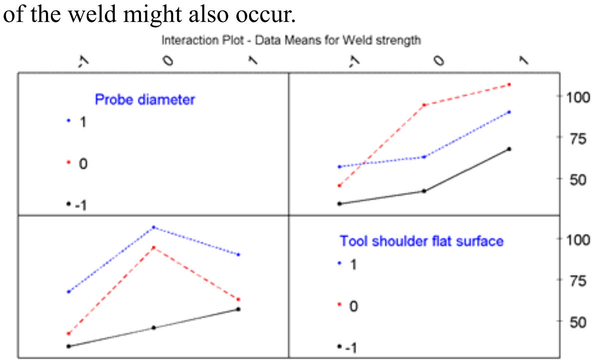


Fig.12 Interaction effect plot of weld strength for trapezoidal tool

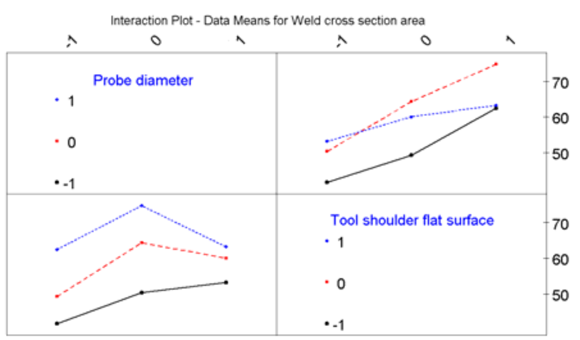


Fig.13 Interaction effect plot of weld cross section area for trapezoidal tool

4.4 Vickers microhardness of samples

The hardness was determined by means of an indenter entering the material to be tested with a specific load and dwell time. After removing the indenter, the produced imprint was measured and the "hardness number" calculated. The changes produced by the indenter entering the material mainly depend on the elastoplastic characteristics of the material. The Vickers indenter is a four-sided pyramid with a square base and an apex angle between opposite sides of α = 136 deg ($\pm 15'$). The hardness number (HV) was calculated by dividing the load (indentation force) by the surface of the imprint. The surface being tested requires a metallographic finish; the smaller the load used, the higher the surface finish required. Hardness measurements were taken on the cross sections perpendicular to the welding direction. The hardness in the different zones of welded samples obtained from this study is given in Fig.14.

The microhardness of weld nugget TMAZ obtained with different tool profiles is shown in Fig.14. It is observed that the weld nugget exhibits a higher microhardness compared to the thermo-mechanically affected zone (TMAZ) and the base metal. It must be considered here that the microhardness of the weld nugget and TMAZ are material specific to some extent and the material used for the investigation was commercial grade aluminum alloy. The microhardness characteristics of the weld and TMAZ might be different for other non-heat treatable aluminum alloys.

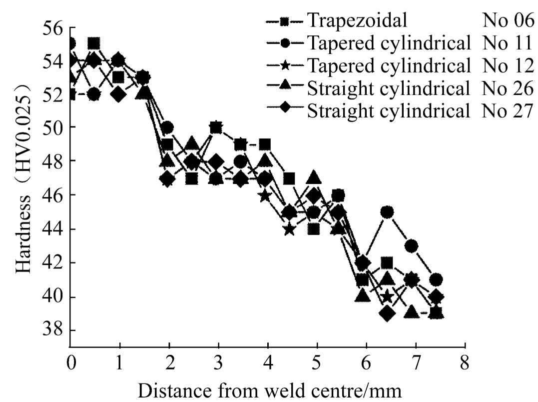


Fig.14 Microhardness obtained with some different tool profiles

5 Conclusions

From the present investigation the following conclusions can be drawn:

1) Among 27 different tool pin profiles, use of a straight cylindrical tool with a 5 mm diameter and having a minimum shoulder flat contact surface leads to the highest tensile strength.
2) It was observed that the weld cross sectional area varies proportionally with the tensile strength of the joint.
3) For low deformation resistance, the alloy cylindrical tool produces welds with the best mechanical properties.
4) The microhardness of the weld nugget and TMAZ was found to be slightly higher compared to the base metal used in the experiment.
5) Use of a trapezoidal and tapered cylindrical tool instead of straight cylindrical tools does not necessarily enhance weld properties for commercial grade aluminum alloys. However, at the start of the welding, the plunging force of the tool is smaller with trapezoidal and cylindrical tools.
6) For the material used in the present investigation, the concave shoulder is not affected much by the weld strength but acts as an escape volume for the material displaced during plunging and subsequent traversing.

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