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Research Article

Influence of shoulder interface geometry on microstructural and mechanical properties of 2014 Al alloy fabricated via friction stir welding

Anudeep.B[Ȧ*], Kumar Adepu[Ȧ] and P.Naresh[Ȧ]

[Ȧ]Mechanical Engineering Department, NIT - Warangal, India

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Abstract

Friction stir tool is that the essential tool of friction stir welding process. In this research work primarily explores the effect of the variant pin geometries on the mechanical and microstructural properties of AA 2014 Al alloy. By varying the interface geometry between the pin and shoulders of the tools, such as threaded tapered straight cylindrical and threaded tapered concave cylindrical, the joints were fabricated. In this investigation, microscopic examination of the weld zone and the mechanical properties test results shown that, the best weld were obtained with threaded tapered concave cylindrical (R= 3.5 mm) stir pin at the tool rotational speed of 900 rpm and tool traverse speed of 40 mm/min.

Keywords: *Friction stir weld, interface geometry, weld zone.*

1. Introduction

Aluminum has a unique combination property of light weight and high machinability; it makes aluminum as a most popular metal. Aluminum has some attractive properties are low density, good electrical conductivity, high corrosive resistance and low price. The properties as well as availability in a large quantity of aluminum eye – catching the industries to use aluminum in several applications like automobile, aerospace and mineral processing industries. However, relatively low strength and uneven mechanical properties of pure aluminum and its alloy causing some troubles in engineering applications. The mechanical properties can be enhanced by alloying copper, magnesium, and silicon etc. In conventional machining process, it is very difficult to join 2XXX and 7XXX series aluminum alloys because of solidification microstructure is very poor and porosity in the fusion zone (weld zone). To overcome these conventional welding problems, Wayne Thomas was invented Friction Stir Welding in 1991 at The Welding Institute (TWI) in UK .

In this process a rotation tool having high hardness than the base metal is used to produce sound welds. A tool is designed like that; it has a specially designed pin profile having circular shoulder. The friction is generated between the workpiece and tool shoulder and the material get often without reaching the melting point[5].So many researchers have mainly addressed the microstructure and mechanical properties of tool geometry and its influences on base material. A narrow literature has focused on the interface geometry between the pin and shoulder of the tool. The objective of the research work various tools were used while varying the interface geometry between the pin and shoulder of the tools, the joints were fabricated.

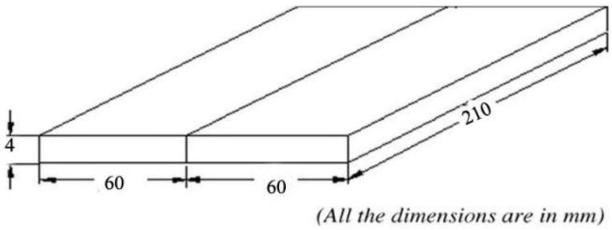

Fig. 1 Schematic diagram of aluminum alloy plates

Table. 1 Chemical composition of 2014-T6 Al alloy (in wt. %)

Si%	0.5-1.2
Mn%	0.4-1.2
Cu%	3.9-5.0
Fe%	0.7
Mg%	0.2-0.8
Cr%	0.1
Zn%	0.25
Ti%	0.5
Al%	Bal

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*Corresponding author: Anudeep.B

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2. Experimental

The base metal 2014-T6 aluminum alloy was used to fabricate the weld. The experiment was carried out FSW process. Two aluminum plates, having the dimensions are 4 mm in thickness, 210 mm length and 60 mm in width, were place on a flat metal plate as shown Fig. 1. These two aluminum plates were cleaned before starting the FSW process by using ethanol to remove the oxides formed on the surface of the plates.

In this investigation two variant interface geometries between the pin and shoulder tools were used and the tool pin profiles (threaded straight cylindrical, and threaded tapered cylindrical) with varying pin geometries (R=3.0, R=3.5 and R 4.0), were used to fabricate the joints (Fig. 2). The H13 tool was made of standard tool steel and both the shoulder and the pin. The H13 tool process parameters employed in this study are given in Table 2. The shoulder of the tool was the same with the diameter of 24 mm. The length of the pin was 3.8 mm as the required welding depth of the plates. The welding process was carried out rotating the tool at 900 rpm and at a feed rate of 40 mm/min, with a 2^0 tilt angle. The butt-welded were produced on FSW machine (Bharat Fritz Werner Ltd).

Fig.2 Fabricated FSW tools

Table.2 Detail of FSW process parameters and tools

Rotational speed (rpm)	900
Welding speed (mm/min)	40
Axial force (KN)	5
Tool shoulder diameter, D (mm)	24
Pin diameter, d (mm)	6
D/d ratio of tool	3.0
Pin length, L (mm)	3.8
Tool inclined angle (degrees)	2
Shoulder deepness inserted into the surface of base metal (mm)	0.2
Included angle of taper pin (degrees)	7.5
Tool pin geometry	Threaded straight cylindrical, and threaded tapered cylindrical
Pitch (mm) and included angle (degrees) of threaded pin	1 and 60

After welding, for the metallographic test and mechanical tests (tensile, impact, microhardness) the specimens were cut along the cross-sections of the traverse direction. Before the metallographic test specimens were polished with a diamond paste, and etched with killers' reagent (3 ml hydrochloric (HCL) acid, 5 ml nitric acid (HNO_3), 2 ml hydrofluoric acid (HF) and 175 ml water (H_2O)). For microscopy examination an inverted optical microscope was used.

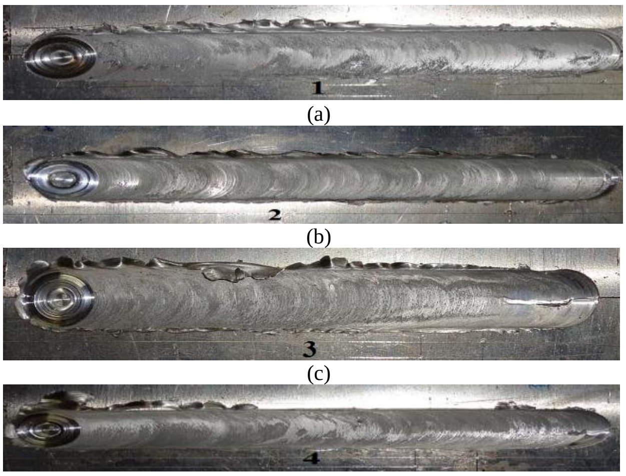
Table. 3 Detail of FSW process parameters and tools

S.No.	Description of the pin	Bigger diameter of the pin(mm)	Smaller diameter of the pin(mm)	Radius of the curvature (mm)
1	Threaded taper concave cylindrical pin	8	6	3.0
2	Threaded taper concave cylindrical pin	8	6	3.5
3	Threaded taper concave cylindrical pin	8	6	4.0
4	Threaded taper straight cylindrical pin	8	6	3.0
5	Threaded taper straight cylindrical pin	8	6	3.5

3. Results and discussion

3.1 Effect of the pin geometry on the appearance of the weld

Fig. 3 display the macrostructures of the welds made by different friction stir tools and defect free welds are formed. From the visual examination it was discerned that, the welds were formed with roots and crowns according to the Lloyd's register. The quality of the weld is defined by the material flow around the weld zone and it was deformed by the tool shoulder.



(a) (b) (c) (d)

(e)

Fig. 3 (a), (b), (c) Welds are formed by using threaded taper concave cylindrical pin with R= 3.0 mm, R = 3.5 mm and R = 4.0 mm. (d) And (e) welds are formed by using threaded taper straight cylindrical pin with R = 3 mm and R= 3.5 mm.

It was observed from the fig. 3(c), (d) and (e) that, when the radius of curvature of the interface between pin and shoulder reaches maximum and minimum, initially a crack is propagated. But a smooth welded surface was obtained by using profile pin (B) shown in Fig.3, than compared to the other welded surfaces produced by various profile pins and it was shown Fig. 3(b)

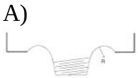
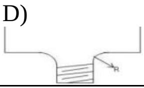
3.2. Effect of the pin geometry on mechanical properties

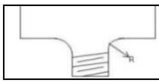
3.2.1. Tensile properties

The transverse tensile properties such as yield strength, ultimate tensile strength, and percentage of elongation, of friction stir welded AA2014 alloy joints were evaluated with rotational speed of 900 rpm, and traverse speed 40 mm/min by using different interface geometry between the pin and shoulder of the tools. The change in the tool geometry had an impressive effect on strength and ductility. The tensile properties are summarized at the room temperature are show in the table. 4

Table 4 Mechanical properties of AA2014 Friction stir weldments

Tool profile	Yield stress (N/mm^2)	UTS (N/mm^2)	% of Elongation	Impact strength (joule)	Hardness
A	266.48	325.25	3.56	3.0	124.15
B	305.90	351.69	3.85	5.0	146.05
C	89.70	135.99	1.28	4.0	122.16
D	214.01	258.72	2.45	4.5	130.20
E	254.80	304.37	2.87	3.0	129.80

Tool profile	Condition
A) 	R=3mm, Concave shoulder taper cylindrical threaded pin (Cryogenic treatment)
B) 	R=3.5mm, Concave shoulder taper cylindrical threaded pin (Cryogenic treatment)
C) 	R=4mm, Concave shoulder taper cylindrical threaded pin (Cryogenic treatment)
D) 	R=3mm,Flat shoulder, Straight cylindrical threaded pin
E)	R=3.5mm,Flat shoulder, Straight cylindrical threaded pin

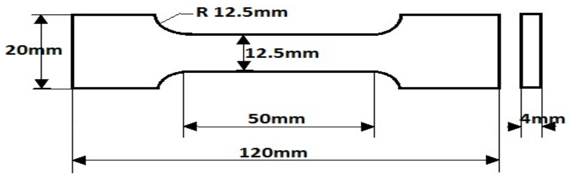
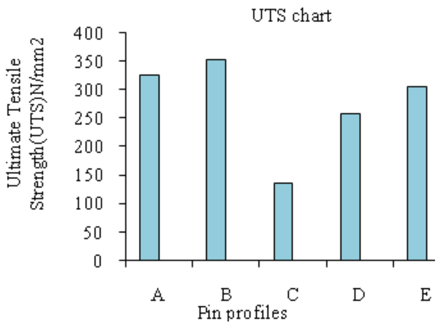
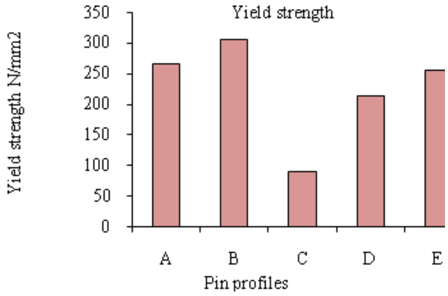


Fig. 4(a). Tensile test specimen standard dimension

Fig.4(b). Specimen after tensile testing





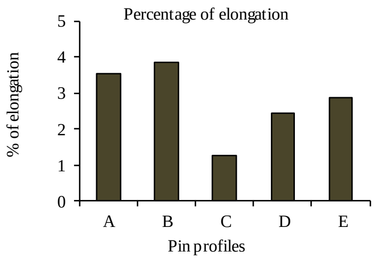


Fig.5. Comparing the various pin profiles and Mechanical properties; (a) UTS and pin profiles, (b) yield strength and pin profiles, and (c) % of elongation and pin profiles.

The Fig. 4(a) displays the specimen dimensions for tensile test. The outcomes shown that the tensile strength (UTS) extensively increases from 135.99MPa to 351.69 MPa and % of elongation also increases from 1.28 % to 3.85% because of the lower heat input by using the concave shoulder taper cylindrical threaded pin tool under cryogenic treatment with the radius of curvature R = 3.5 mm. From the results it was assessed that while varying the radius of curvature of the interface geometry between the pin and shoulder of the tools, from R = 3mm, R = 3.5mm and R = 4mm, the tensile properties are drastically changed and best results were obtained at R = 3.5mm. Meanwhile it is furthermore discerned that superior result were obtained by using concave shoulder taper cylindrical threaded pin tool than concave shoulder straight cylindrical threaded pin tool when radius of curvature R = 3.5mm. The tested specimens were shown in the Fig. 4(b).

From the Fig. 5 it is clearly shown that the better mechanical properties (UTS, YS and percentage of elongation) were obtained by using pin profile B than other pin profiles.

3. 2. 2 Hardness Test

The transverse cross-section of Vickers hardness profile of the joints was measured at the nugget zone (NZ). There is a progressively increasing hardness from the base metal (BM) across the HAZ to NZ. The hardness of the BM is more than the softening region at different welding tools. It has been investigated that the hardness has been influenced by the tool shoulder due to the dominant influence of the tool shoulder on the thermal input during welding [10]. The highest hardness value of 146 HV has been recorded in the joint fabricated by using concave shoulder taper cylindrical threaded pin with radius of curvature R=3mm pin profiled tool (A) and the lowest hardness value of 122 HV has been recorded in the joint fabricated by using concave shoulder taper cylindrical threaded pin with radius of curvature R= 4 mm pin profiled tool (C). At a distance of about 5 mm advancing side and 5 mm retreating side from the weld center, the hardness dips to a minimum value about 95 HV and 98.5 HV respectively.

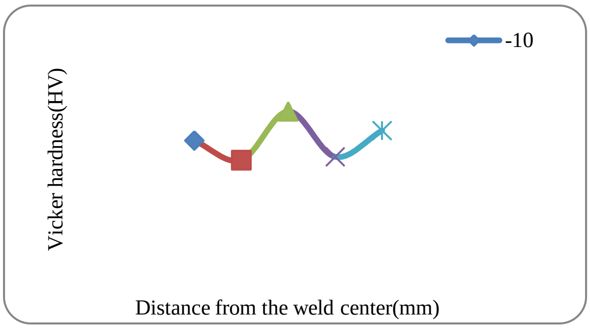


Fig.6 Vickers microhardness

The softening in the HAZ is usually explained based on coarsening of the metastable phases due to temperature rise during welding as a result of frictional heat. The width of soft zone depends on peak temperature and thermal cycle duration. The width of softened region on advancing side is more compared to the retreating side due to high heat input on the advancing side because of greater relative velocity between the tool and the work piece.

The Fig. 6 shows that the graphical representation of hardness and it clearly indicates that higher hardness was achieved for the joint fabricated by using concave shoulder taper cylindrical threaded pin with radius of curvature R= 3 mm pin profiled tool (A) and the lowest hardness value of 122 HV has been recorded in the joint fabricated by using concave shoulder taper cylindrical threaded pin with radius of curvature R= 4 mm pin profiled tool (C).

3. 2. 3 Impact Test

Impact toughness was observed at the TMAZ of AA2014-T6 weldments with different pin profiles at tool rotational speed of 900 rpm and welding speed of 40 mm/min. From the Fig7, it was observed that the higher impact toughness of the TMAZ is achieved by using pin profile B (5 joules) than other pin profiles because of the presence of fine grain size at the TMZA.

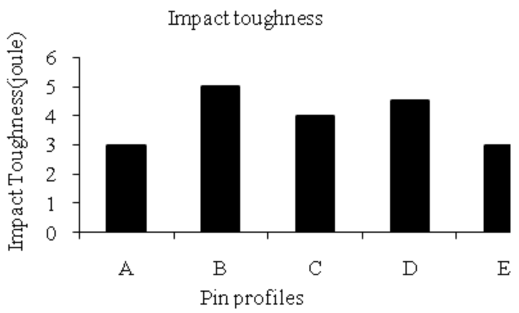
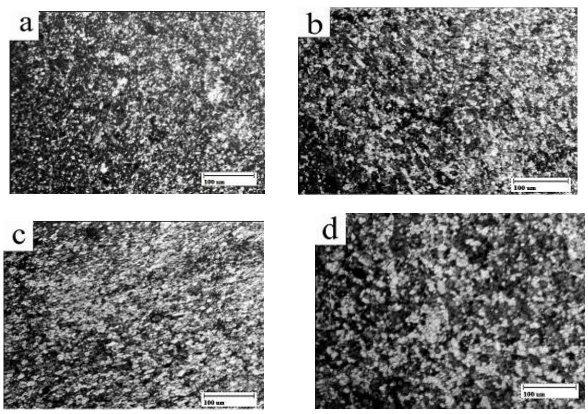


Fig. 7 Impact toughness chart

3.3 Microstructure characterization of welds

Optical microscopy evaluation was conducted to study the influence of the tool pin profile on microstructure of FSW welds.



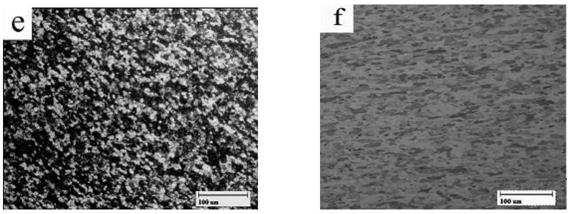
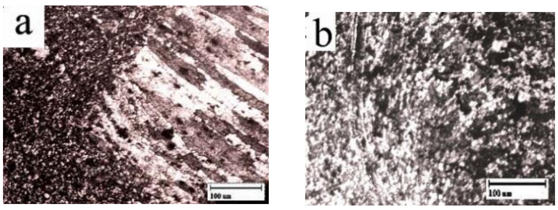


Fig. 8: Microstructure of weld nugget zone (a) concave shoulder taper cylindrical threaded pin with radius 3mm (b) concave shoulder taper cylindrical threaded pin with radius 3.5mm (c) concave shoulder taper cylindrical threaded pin with radius 4mm (d) straight cylindrical threads with radius of curvature 3mm and (e) straight cylindrical threads with radius of curvature 3.5mm (f) Microstructure of AA2014-T6 base material

Fig. 8 shows the microstructure of the AA2014-T6 weldments produced by five different tool pin profiles at tool rotational speed of 900 rpm and weld speed is 40 mm/min. The material flow and the size of the particles in nugget zone are different due to the influence of pin profile.

The nugget region has experienced high temperatures and extensive plastic deformation, and is characterized by dynamically recrystallized grains. The nugget microstructure of weldments made with the concave shoulder taper cylindrical threaded pin with radius of curvature 3 mm, 3.5 mm and 4 mm (Fig. 8 a, b, c) and straight cylindrical threads with radius of curvature 3 mm and 3.5 mm (Fig.8 d,e). The pin geometry affects the nugget microstructures greatly. From Fig. 8 it was investigated that, fine grain structure acquired in the nugget zone welded by ‘B’ friction tool, and the size of the grain is very small.

One of the important characters of the FSW is the different relative speed of plastic material on advanced side and on retreated side, which results in the different structures. On the advanced side, the speed grade is greater than on the retreated side, microstructure changes rapidly, lack of necessary transition, the zone between the nugget and the TMAZ often has the poor property, which can be tested by mechanical examination.



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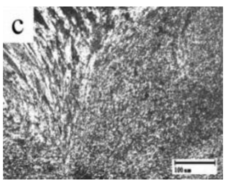
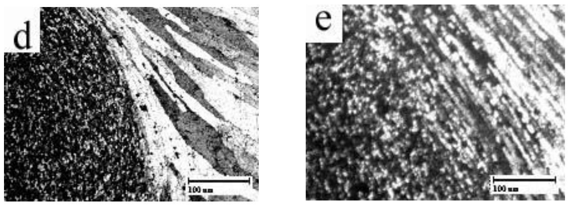


(3)



(4) (5)

Fig.9: Microstructures in weld nugget-TMAZ interface (1) welded by friction stir tool A (2) welded by friction stir tool B (3) welded by friction stir tool C (4) welded by friction stir tool D (5) welded by friction stir tool E.

Fig. 9 shows the microstructures in weld Nugget-TMAZ and interface on weldments. The grains in the nugget zone are finer than in TMAZ. The size of the grain changes step by step from nugget to TMAZ, this will not affect the property very much. But an obvious boundary can be seen between nugget and TMAZ in Fig. 9(2). The nugget grain experienced high temperatures and violent plastic deformation, then after dynamically recrystallized fine grain come into being. It can be seen from Fig. 9 that microstructures change smoothly from nugget to TMAZ. The TMAZ experiences both temperature and deformation during FSW/FSP. A typical micrograph of TMAZ is shown in Fig. 9 (4) the TMAZ is characterized by a highly deformed structure. The parent metal elongated grains were deformed in an upward flowing pattern around the nugget zone. Although the TMAZ underwent plastic deformation, recrystallization did not occur in this zone due to insufficient deformation strain.

4. Conclusions

The effect of the variant pin geometries on the mechanical and microstructural properties of AA 2014 alloy welds was investigated via FSW.

1. The addition of the interface geometry between the pin and shoulder of the tools has been found to significantly increase the tool life.
2. By using optical microscopy, the transition tool geometry effect on the grain size of the nugget zone was investigated. The increase and decrease in interface geometry leads to poor mechanical and microstructural properties.
3. The effect of tool pin profile and process parameters on the appearance of the weld is presented and no obvious defect was found. The results indicate that the shape of the pin has a significant effect on the joint structure and the mechanical properties.
4. For the given set of parameters, tool rotation speed as 900 rpm, welding speed as 40 mm/min, of the five tool profiles used concave shoulder taper cylindrical threaded tool pin profile (R = 3.5mm) gave good mechanical properties.

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