RESEARCH ARTICLE OPEN ACCESS

Experimental Study on the Effect of Welding Parameters and Tool Pin Profiles on Mechanical Properties of the FSW Joints

Deepak Chouhan, Surjya K Pal, Sandeep Garg
Scholar of Department of mechanical Engineering, Indian Institute of Technology Kharagpur(W.B.)
Associate Professor Department of mechanical Engineering, Indian Institute of Technology Kharagpur (W.B.)
Assistant Professor, Department of Mechanical Engineering, Shri Vaishnav Institute of Technology and Science, Indore(M.P.)

ABSTRACT
To optimize the tool geometry (Pin profile) and process parameters for the FSW process. In the present investigation, an attempt has been made to understand the effect of rotational speed, welding speed and there different pin profiles on the nugget zone formation in AA 6063-T4 aluminum alloy. Three different tool pin profiles (tapered cylindrical, tapered square and square) have been used to fabricate the joints at the different welding conditions and rotational speed. Tensile properties of the joints have been evaluated and correlated with the nugget zone formation. From this investigation it is found that the tapered cylindrical pin profile tool gives maximum strength as compared to other joints. Also the tensile tests are carried out to study the mechanical properties of the FSW joint.
Key Words: Friction stir welding . Pin profiles . Mechanical properties .

I. INTRODUCTION

The friction stir welding (FSW) process was developed by The Welding Institute (TWI) of Cambridge, England in 1991 [1]. This joining technique is simple, environment friendly, energy efficient, and becomes major attraction for automobile and aircraft industries. Due to the high strength of the FSW joints, it allows considerable weight savings in light weight construction compared to conventional joining technologies. In contrast to conventional joining welding process, there is no liquid state for the weld pool during FSW, the welding takes place in the solid phase below the melting point of the materials to be joined. Thus, all the problems related to the solidification of a fused material are avoided. Materials which are difficult to fusion weld like the high strength Aluminum alloys can be joined with minor loss in strength. In friction stir welding a non-consumable rotating tool with a specially profiled threaded/unthreaded pin and shoulder is rotated at a constant speed. The tool plunges into the two pieces of sheet or plate material and through frictional heat it locally plasticized the joint region. The tool then allowed to “stir” the joint surface along the joining direction. During tool plunge, the rotating tool undergoes only rotational motion at only one place till the shoulder touches the surface of the work material; this is called the dwelling period of the tool. During this stage of tool plunge it produces lateral force orthogonal to welding or joining direction. The upper surface of the weld consists of material that is dragged by the shoulder from the retreating side of the weld, and deposited on the advancing side. After the dwell period the tool traverse along the joining direction, the forward motion of the tool produces force parallel to the direction of travel known as traverse force. After the successful weld, the tool reaches to termination phase where it is withdrawn from the workpiece [2].

Mandal et al [3] investigated the axial force during plunging of the 2024 aluminum alloy of thickness 12.5mm. It is observed that plunging is completed in 14 s, the peak load of 25 KN is observed at 5 s mark. At the end of the 14 s, the load dropped to approximately 8 KN where it remains steady.

Yong et al. [4] studied the effect of rotational speed on weld joint properties. After analyzing result, found that grains of nugget zone decreases with increase of rotational speed. % of elongation of weld joints increases with increase of rotational speed but further increase of rotational speed it decreases due to grains size.

Elangovana et al [5] studied the influences of tool pin profile and welding speed on the formation of friction stir processing zone in AA2219 aluminum alloy. Tool pin profile plays major roles in deciding the weld quality. In this investigation, an attempt has been made to understand the effect of welding speed and tool pin profile on FSP zone formation in AA2219 aluminum alloy. Five different tool pin profiles (straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square) have been used to fabricate the joints at three different welding speeds. Joints have been evaluated and correlated with the FSP zone formation. From this investigation it is found that the square pin profiled tool produces mechanically sound and metallurgically defect free welds compared to other tool pin profiles.

Fujii et al [6] investigated the effect of tool shape on mechanical properties and microstructure of friction stir welded aluminum alloys, effect of the tool shape on the mechanical properties and microstructures of 5mm thick welded aluminum plates was investigated. The simplest shape (column without threads), the ordinary shape (column with threads) and the triangular prism shape probes were used to weld three types of aluminum alloys.

II. EXPERIMENTAL WORK

The FSW was conducted on 6063 aluminum alloy, with magnesium and silicon as the alloying elements. The specimen received in standard T4 heat treatment and with dimension 200 mm×100 mm×6 mm were welded under various processing conditions. Tool made of stainless steel SS316 have been used to fabricate the joints.

The chemical composition of workpiece material and tool material was analyzed by energy dispersive X-ray spectroscopy. The chemical composition of tool material is shown in Table 4. From the EDS analysis it is confirmed that the tool material is SS316 type. The chemical composition and mechanical properties of workpiece material are shown in Table 1 and 2 respectively. A tensile specimen of base material is also tested to check the mechanical properties of the 6063-T4 aluminum alloy. Vicker's microhardness test is also performed to check the microhardness of base material. Chemical compositions of SS316 tool and process parameters are shown in table 3 and table 4 respectively.

Table 1 Chemical compositions of work material AA-6063-T4 aluminum alloy

Element	Al	Ti	Si	Fe	Mg	Mn	Cu	Cr	Zn
%	Remainder	0.1	0.2-0.6	0.35	0.4-0.95	0.15	0.1	0.1	0.1

Table 2 Mechanical properties of work material AA-6063-T4 aluminum alloy

Properties	Ultimate tensile strength, MPa	Yield strength, MPa	% Elongation	Vicker's microhardness HV
Value	124	84	11	120

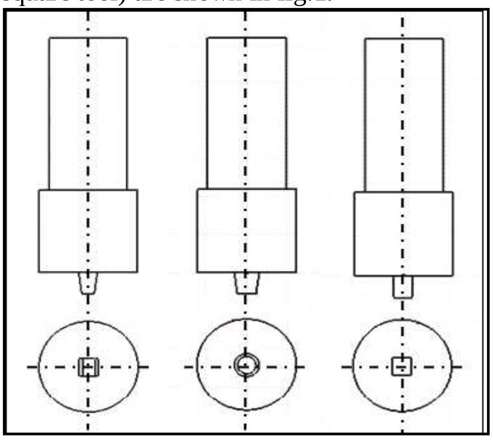
Table 3 Chemical compositions of SS316 tool material

Element	Si	P	Mn	Cr	Ni	Mo	Fe
%	2.13	0.27	8.95	16.29	0.20	0.14	72.01

Table 4 Process Parameters of FSW tool

Parameters	Tool rotational speed, rpm	Welding speed, mm/min	Tool shoulder diameter (D), mm	Tool pin diameter (d), mm	Tool pin length, mm	D/d
Value	562, 647, 806	18, 23, 28	24	6	5.6	4

Dimensions of friction stir welding tool and different tool profiles (taper cylindrical tool, taper square tool and square tool) are shown in fig.1.



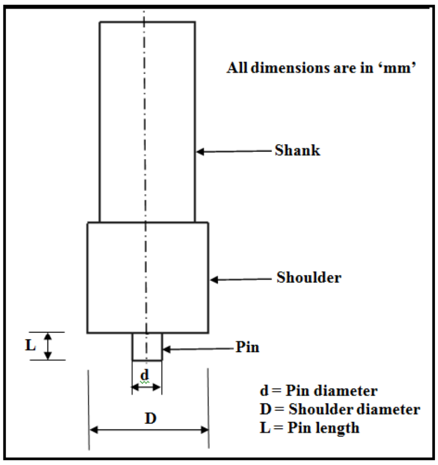


Fig. 1 Showing three different tool pin profiles and tool dimensions

The welded joints are sliced using band saw machine and then the configuration and size of the transverse tensile specimens were prepared with reference to American society for Testing of Materials (ASTM E8M-04) guidelines, tensile test specimen is shown in fig.2. The tensile test is carried out using a computer controlled testing machine (INSTRON 8862) at crosshead speed of 2 mm/min.

Fig.2 Tensile test specimen

III. RESULTS AND DISCUSSIONS

All the joints fabricated in this investigation are analyzed at low magnification (10×) using stereo zoom microscope (leica-S8APO) to reveal the quality of FSP regions. The tunnel and void defects are present in almost all the FSW joints except the joints fabricated by the taper cylindrical pin profile tool at the welding condition, rotational speed of 647 rpm and welding speed of 23 mm/min and rotational speed of 806 rpm and welding speed of 18 mm/min are found to be the defect free. In the case of taper square pin profile tool the joint fabricated at the welding condition, rotational speed of 562 rpm and welding speed of 18 mm/min is found to be defect free. So it can be concluded that the shorter pin length and insufficient heat generation are the main reasons for the defects. Therefore, the reasons behind the welding defects and effect of welding parameters (rotational speed and welding speed) on weld quality is also presented in the Table 5, 6 and 7. It is also visually observed that the insufficient heat generation is due to the loss of heat in the tool and the backing plate itself.

Table 5 Effect of rotational speed, welding speed and tool pin profiles (Taper Cylindrical Pin) on weld quality of the welded joints

Rotational speed (rpm)	Welding speed, mm/min.	FSW Tool Pin Profile(Taper Cylindrical Pin)		
		Name of the defect and location	Weld quality	Probable reasons
562	18	void appears at the bottom portion of the weld at advancing side	Very poor	Insufficient heat generation, improper material mixing
562	23	Visible voids at the bottom portion of the weld	poor	Shorter pin length
562	28	Tunnel in the bottom portion of the weld at the advancing side	Very poor	Insufficient heat generation, improper material flow
647	18	Cracks appears in the bottom portion of the weld at advancing side	poor	Insufficient heat generation, improper material mixing
647	23	Very small void in the bottom portion of the weld at the advancing side	considerable	Insufficient heat generation, improper material mixing
647	28	Vertical Tunnel in the bottom portion of the weld at the advancing side	Very poor	Insufficient heat generation, improper material mixing
806	18	No	good	Heat is sufficient, proper material mixing
806	23	Tunnel in the bottom portion of the weld at the advancing side	Very poor	Insufficient heat generation, improper material mixing
806	28	Crack appears at the middle portion of the weld at the advancing side	poor	Insufficient heat generation, improper material mixing

Table 6 Effect of rotational speed, welding speed and tool pin profiles (Taper Square Pin) on weld quality of the welded joint

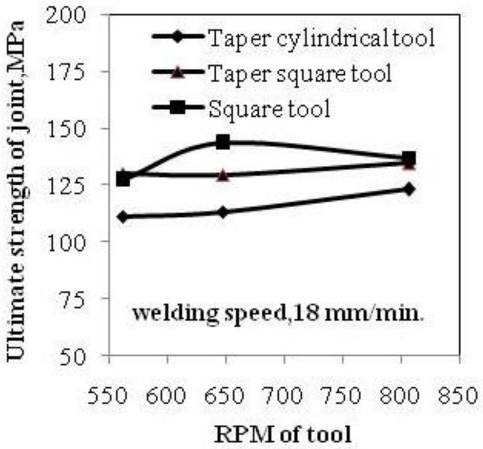
Rotational speed (rpm)	Welding speed, mm/min.	FSW Tool Pin Profile(Taper Square Pin)		
		Name of the defect and location	Weld quality	Probable reasons
562	18	No defect	good	Heat input is sufficient for vertical flow of the plasticized metal
562	23	Horizontal tunnel at the bottom portion of the weld	poor	Shorter pin length, insufficient heat generation
562	28	Horizontal tunnel at the bottom portion of the weld	poor	Shorter pin length, insufficient heat generation
647	18	Horizontal tunnel at the bottom portion of the weld	poor	Shorter pin length, insufficient heat generation
647	23	Big tunnel at the bottom portion of the weld	Very poor	Shorter pin length, insufficient heat generation
647	28	Tunnel appears at the bottom portion of the weld	Very poor	Insufficient heat generation
806	18	Horizontal crack at the bottom portion of the weld	poor	Shorter pin length
806	23	Tunnel appears at the bottom portion of the weld	Very poor	Insufficient heat generation, improper material mixing
806	28	Tunnel appears at the bottom portion of the weld	poor	Insufficient heat generation, improper material mixing

Table 7 Effect of rotational speed, welding speed and tool pin profiles (Square Pin) on weld quality of the welded joints.

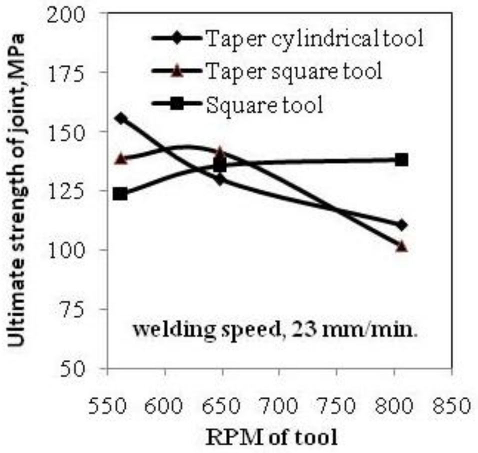
Rotational speed (rpm)	Welding speed, mm/min.	FSW Tool Pin Profile(Square Pin)		
		Name of the defect and location	Weld quality	Probable reasons
562	18	Tunnel at the bottom portion of the weld at the advancing side	poor	Insufficient heat generation, improper material mixing
562	23	Horizontal tunnel at the bottom portion of the weld	poor	Shorter pin length, insufficient heat generation
562	28	Visible void at the bottom portion of the weld at advancing side	Very poor	Shorter pin length, insufficient heat generation
647	18	Visible void at the bottom portion of the weld at advancing side	considerable	
647	23	Horizontal crack appears at the bottom portion of the weld	Very poor	Shorter pin length,
647	28	Vertical tunnel appear at the advancing side of the weld	Very poor	Insufficient heat generation
806	18	Horizontal crack appears at the bottom portion of the weld	poor	Shorter pin length
806	23	Visible crack at the bottom portion of the weld	poor	Insufficient heat generation, improper material mixing

806	28	No defect	good	Heat is sufficient

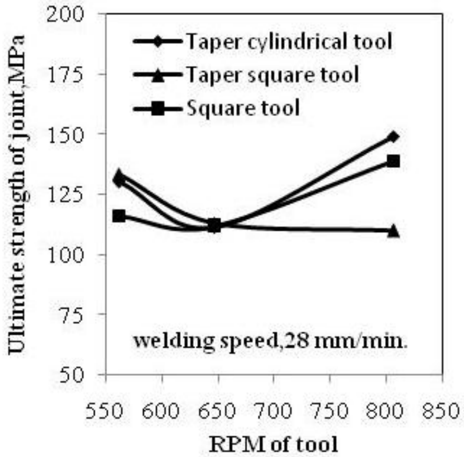
Conducting the tensile test on tensile specimen, it is observed that the FSW joints with defects exhibit better tensile properties. The maximum tensile strength of 156 MPa with the joint efficiency of 129.16% is observed in the case of joint fabricated by the taper cylindrical pin profile tool at the welding condition, rotational speed is 562 rpm and welding speed is 23 mm/min. It is also investigated that the crack appears at the middle portion of the weld for the same weld joint. So it can be concluded that the grain refinement is highest in the nugget zone in all 27 joints. The maximum hardness value of 80.24 HV is also recorded in the nugget zone. The maximum tensile strength of 141 MPa with the joint efficiency of 117 % is observed for the joint fabricated by the taper square tool pin profile at the welding condition, rotational speed 647 rpm and welding speed 23 mm/min. The least joint strength of 102 MPa with the joint efficiency of 85% is observed in the case of joint fabricated by taper square pin profile tool at the welding condition, rotational speed 806 rpm and welding speed 23 mm/min. In the case of square pin profile tool, the maximum strength of 141 MPa with the joint efficiency 117% is obtained at the welding condition, tool rotational speed 647 rpm and welding speed 18 mm/min. It is found that joint fabricated is free from defect. The joint efficiency also observed the same value recorded for the taper and square pin profile tool. So it can be concluded that the grain refinement in the nugget zone is same in both the case. It can also be considered true because the grain size observed the approximately the same value in both cases. The Vickers microhardness values are also recorded at the different points from the weld centre line for all the 27 joints. The maximum hardness value of 82 HV is recorded corresponding to the maximum tensile strength value in the case joint fabricated by taper cylindrical pin profile tool.



(a)

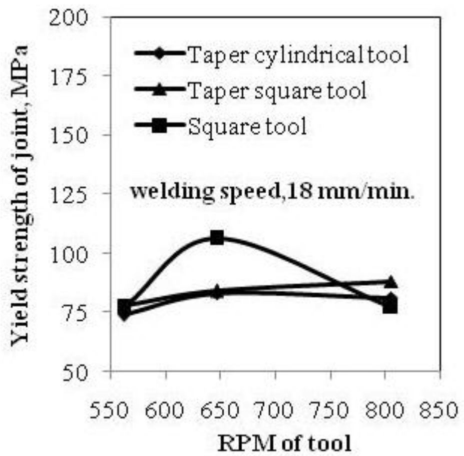


(b)

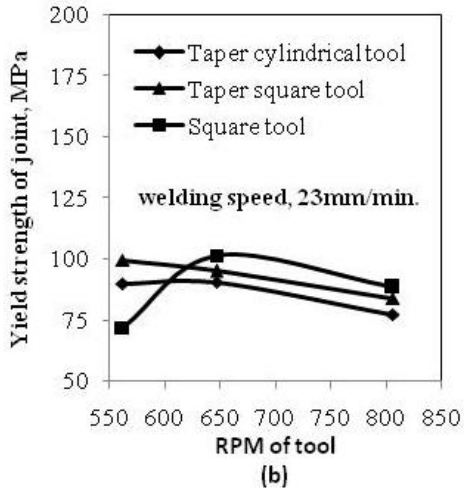


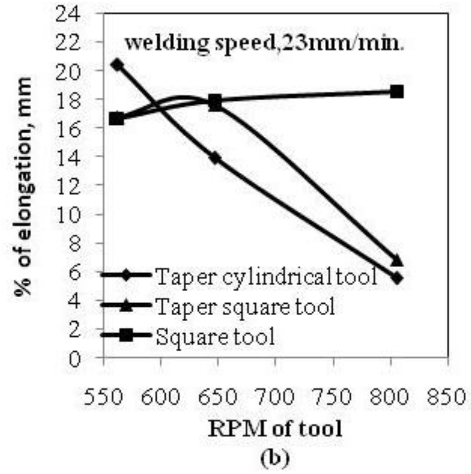
(c)

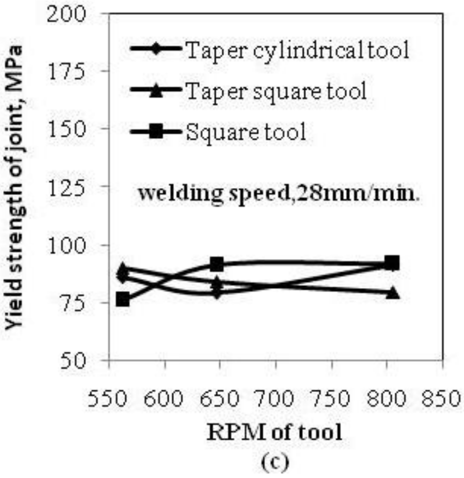
Fig.3 Effect of tool pin profiles and rotational speeds of friction stir welding tool on ultimate tensile strength of welded joints at (a) 18 mm/min., (b) 23 mm/min., and (c) 28 mm/min. welding speed.



(a)







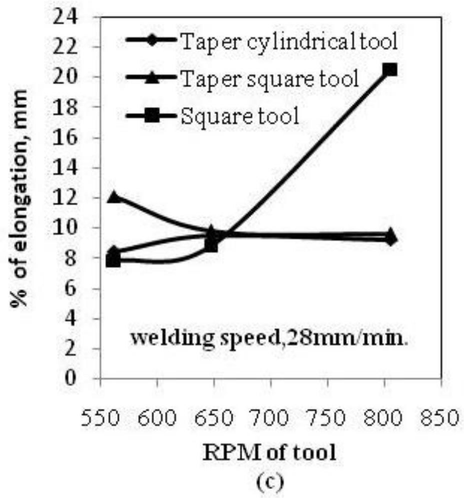
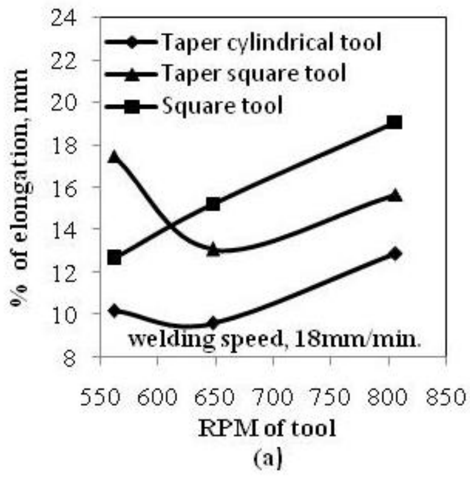


Fig.4 Effect of tool pin profiles and rotational speeds of friction stir welding tool on yield strength of welded joints at (a) 18 mm/min., (b) 23 mm/min., and (c) 28 mm/min. welding speed.

Fig.5 Effect of tool pin profiles and rotational speeds of friction stir welding tool on % of elongation of welded joints at (a) 18 mm/min., (b) 23 mm/min., and (c) 28 mm/min. welding speed.



IV. CONCLUSIONS

In this investigation, an attempt has been made to study the effect of tool pin profiles, rotational speed and welding speed on the formation of friction stir processing zone in AA6063 aluminum alloy. From this investigation, the following important conclusions are derived:

(i) Tool pin profiles greatly influenced the tensile properties of joints.

(ii) The tensile specimen with the tunnel defect shows the low load bearing capacity.

(v) The maximum joint efficiency is 129.16% is observed at a rotational speed of 562 rpm and welding speed of 23 mm/min in the case of tapered cylindrical tool profile.

(vi) Out of the 27 joints, the joint fabricated using tapered cylindrical pin profiled tool at a welding speed of 18 mm/min shows no defects.

(vii) The joint efficiency is found about 85.10-129.16% in all the cases.

(viii) Higher temperature is to be found on advancing side than on retreating side in all the cases.

(ix) Temperature would be around 400^0C for a successful FSW process.
(x) Surface roughness (Ra) increases with the increasing welding speed.

V. SCOPE FOR FUTURE WORK

Tool geometry is very important factor for producing sound welds. Furthermore, selection of tool material is another very important issue in the FSW joints. Material transport around rotating tool is the crucial factor for the optimization of FSW parameters and tool geometry. The optimization of FSW parameters and tool geometry will be beneficial to increase the productivity and weld quality. New experimental techniques are needed to understand the material flow.

VI. ACKNOWLEDGEMENT

Authors would like to thank Steel Technology Centre and department of mechanical engineering of IIT Kharagpur for providing resources and infrastructure for carrying out experiments and various tests.

REFERENCES

[1] W.M. Thomas, E.D. Nicholas, J.C. Needham, M.G. Murch, P. Templesmith, C.J. Dawes, G.B. (1991) Patent Application No.91259788.
[2] R.S. Mishra, Z.Y. Ma (2005) Friction stir welding and processing. Material Science and Engineering 50:1-78.
[3] S. Mandal, J. Rice, A.A. Elmustafa, Experimental and numerical investigation of the plunge stage friction stir welding. Material Processing Technology, 203(2008): 411-419.
[4] Yong-Jai Kwon, Seong-Beom Shim, Dong-Hwan Park, Friction stir welding of 5052 aluminium alloy plates. Transactions of non-ferrous metal society of China,19: 23-27
[5] K. Elangovana, V. Balasubramanianb, Influence of tool pin profile and welding speed on the formation of friction stir processing zone in AA2219 aluminium ally. Processing technology, 20(2008): 163-175.
[6] H. Fujii, L. Cui, M. Maeda, K. Nogi, Effect of tool shape on mechanical properties and microstructure of friction stir welded aluminium alloy. Material science and engineering, 419(2006): 25-31.
[7] A. Arora, A. De and T. DeyRoy, Towards optimum friction stir welding tool shoulder diameter. Scripta materialia, 64(2011): 9-12.
[8] A. Scialpi, L.A.C. De Filippis, P. Cavaliere, Influence of shoulder geometry on microstructure and mechanical properties of friction stir welded 6082 aluminium alloy. Material & design, 28(2007): 1124-1129.
[9] I. Galvao, R.M. Leal, D.M. Rodrigues, A. Loureiro, Influence of tool shoulder geometry on properties of friction stir welds in thin copper sheets , Material processing technology, 213(2013): 129-135.
[10] P. Cavalierea, A. Squillaceb, F. Panellaa, Effect of welding parameters on mechanical and microstructural properties of AA6068 joints produced by friction stir welding, Material Processing Technology, 200(2008): 364-372.