Strength Analysis of Friction Stir Welding (FSW) Joint Under Minimize Rotation Speed of FSW Tool

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Friction stir welding (FSW) broadly used in the same grade as aluminium alloy but for aluminium alloy material it requires high speed rotation of FSW tool which develops high temperature on tool. In this paper process parameter of FSW are studied based on the strength of welding joint and predict FSW tool speed as low as possible according to the past literature. Constant machining parameters are tool rotation of FSW is 800 rpm and welding speed 15 mm/min. In this work analysing the strength variation of welding joint under two mode of pre-heating temperature on the work-piece then variation of cooling medium apply after preheating to change the grain structure of work-piece. In this work the FSW process is passed over two pieces of aluminum at once and the effect of tool rotation and temperature of the tool is discussed by preparing the sample for testing according to the ASTM dimension.

Introduction

Friction stir welding gives the high-quality welding and has improved mechanical properties, metallurgical & environmental advantages as compared to conventional fusion welding procedures and joints obtained using FSW is probably free from defects. Below melting point temperature FSW process proceeded under solid-phase condition which mostly uses to construct marine, rocket and ship. It is also energy efficient process which does not require filler material to provide low distortion and good stability of the welding structure [**18**]. The modern FSW tool consists of the cylindrical piece formed by threaded pin and shoulder moved along adjoining surfaces of work-pieces as illustrated in **Fig. 1**.

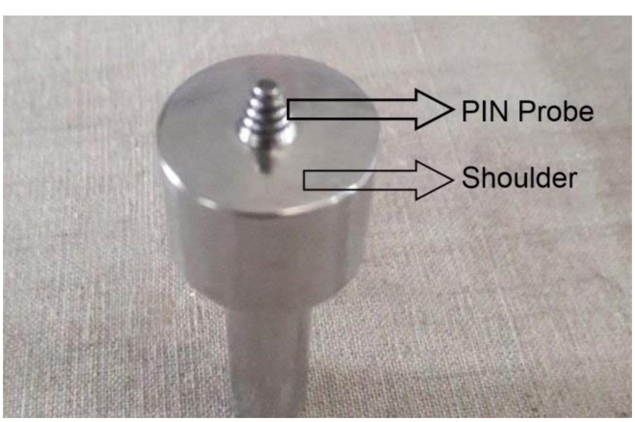


Fig. 1. FSW Tool conical Pin.

Nomenclature

oC	Degree Centigrate
T	Temperature
M	Cooling Medium
Ht	Holding time
Tt	Tensile test

Most of the researches apply FSW on steel material by using high grade FSW tool because of their properties steel material possess many challenges in FSW process. These tools are high grade steel material which required high speed of rotation above 3000 rpm [**16**]. So, the high speed of rotation causes high temperature on tool which exists above 1000°C [**20**]. Heat production depends upon the rotation speed and tool material which can distress the strength of the welding. The tool rotation speed and material selected should have good shear strength, wear resistance and oxidation resistance under high temperature. These two problems are pointed in this review work because these two conditions increases the cost of FSW process but showing good result as compared to fusion welding in different type of material that has to join. Also, the high temperature occurs on FSW tool causes the tool wear and reduces the tool life. Many research papers have been reviewed which shows that Friction Welding process shows best result in welding of steel. FSW welding process, one of the innovative fastest growing metal joining processes, the contact pin of FSW tool on work-piece generate welded joint by developing friction between two work-pieces.

Review of related studies

McPherson *et. al.* [**17**] examined the segregation of material DH36 steel by heat input application [**36**] and thermal stress [**8**] on work-piece increases from 1400 °C to 1450 °C, also high temperature with high speed reported by another author [**35**] with similar cooling rates in FSW process. Azevedo *et. al.* [**3**] presented work on friction Stir Welding expanding the steel and titanium material database. Also, the tool geometry has affected by high rotating speed and temperature. Maximum peak temperature obtained in proposed CFD modelling in FSW for 304 stainless steel tool and work-piece contact surface exceeds 400 RPM of tool rotation. Avila *et. al.* [**4**], found the fracture in FSW process under -20 °C also used high speed of rotation but due to negative atmospheric condition tool temperature could not exceed and obtained defective welding. Prasanthi *et. al.* [**22**] done defect free FSW joint between mild steel (MS) and titanium (Ti) by varying parameters found slower grain growth. Ramesha *et. al.* [**24**] suggested that increases welding speed also lead heat input but constant speed has given higher amount of heat above 800 J on weld joint which makes harder joint or required very slow rate of cooling. Most of the researchers have suggested the tool has become red hot during welding which damage the tool geometry [**15,26**]. In order to understand the depth of this phenomenon it was necessary to understand the effect on tool profile.

Effect on FSW tool rotation

Few researchers analysed affect of tool profile, and maximum temperature attained by tool at 2000 Rpm [**33**]. Sekhon *et. al.* [**31**] has scrutinized on tool pin profiles elongation effect on FSW tool, they had taken three type of tool profile. Marzbanrad *et. al.* [**16**] explored effect of rotation speed on pin and tool shoulder geometries [**15 & 36**]. Also, tool pin geometry and shoulder geometry was further cause in weld properties. Deepati *et. al.* [**10**] studied on FSW tool plunging force affect heat production by using finite element (FE) transient thermal analysis. Rajakumar *et. al.* [**23**] focused on the tool speed rotational and material of tool has increase the tool temperature which affects the FSW tool, high temperature production during welding process with variation of parameter and tool geometry [**11**]. Thimmaraju *et. al.* [**34**] evaluate tool geometry on the flow material characteristics around the rotating tool was considered as a viscous flow, exhibiting laminar flow characteristics exhibiting non-Newtonian properties also weld nugget zone revealed the tool pin geometry. Sato [**29**] investigates microstructure behaviour on fracture under static and cyclic loading. Also mentioned FSW parameters affect the interface microstructure and fracture behaviour on dissimilar materials weld by FSW process. Darwins & Satheesh [**9**] has also investigated microstructures and thermo gravimetric on ZE42 magnesium alloy was joined without defects. The previous researches also suggest that workpiece temperature condition would give the better result in FSW process. On other side it was necessary to understand the problems of fabricators also.

The scientific technological significance is to increase the welding joint strength for dissimilar material. By reviewing literature the FSW tool is affected by high speed rotation which increases the temperature of FSW tool. If pre heat treatment has been done on the job piece, it can reduce the speed of rotation of tool. Minimizing the speed of rotation will reduce the temperature of FSW tool. Some parameters are found from the past literature which raises tool temperature in different condition of Rotation and welding speed. All the researches have tried to conduct their experiment near the result expectation and the result has not been found to be a theoretical framework, researchers need to develop a guidance framework with some theoretical expectation that is meaningful to pursue any experiment.

Experimental design and procedure

The representation diagram of the FSW machine is shown in **Fig. 2** Experimental setup is done on the CNC vertical milling machine at GEC Bilaspur. It is clear from the review analysis that the FSW tool rotation varies from 1100 rpm to 1500 rpm but fixed rotation speed 800 rpm is taken for this work and two mode of preheating temperature are apply on work-piece that is 250ºC & 300ºC due to best resultant found in literature review, lowest temperature is taken in this work and then cooling with two different type of material have been apply on pre heated work-piece which decrease the size of grain structure. Prepared work-piece via preheating and cooling process it is passed through friction stir welding process. Current research having workpiece material for this welding is 5 mm thick Al4018 for fabrication of FSW. Non-consumable tool is used for FSW welding which is made by H13 material, due to cheap and easy availability in market or made in workshop with our required dimension. Pin length and Shoulder diameter are 4.5 mm and 20 mm respectively. Pin is threaded conical shape have five steps with maximum and minimum diameter vary from 5 mm to 2.5 mm respectively. Zero tilt angle was applied to FSW tool. Conducting some trail experiments to know the working process parameters of welding. The appropriate FSW parameters were selected in such a way that the working parameters could be efficiently incorporated into the work-piece.

Fig. 2. Experimental setup.

Hardened material gives high friction between workpiece material, workpiece passing through heat treatment up to 200°C and 250°C and hold for two varied time at respective temperature then cool with any of one medium from water and air. In this case four conditions are following for FSW process, out of which two are water cooled and other two are air cooled, mode of temperature holding time is 25 min and 50 min. thermally treated workpiece parameters and machining process parameters of each specimen are shown in **Table 1**. Cooling medium of water is representing as 'W' and Air is representing as 'A'.

Table 1. Design of performance.

Speed of Welding mm/min	Speed of Tool Rotation Rpm	Temperature (T) in oC	Hold Time (Ht) in min	Cooling Medium (M)
15	800	200	25	W
			25	A
			50	W
			50	A
		250	25	W
			25	A
			50	W
			50	A

Preparing tensile test specimens from each welding joint is twice as per ASTM E8M-04. Tensile test performed on universal test machine (UTM) thrice of each experiment and average of measured tensile test shown in **Table 2**. Tool rotational speed is lower than 800 rpm causes inadequate heat production leads to worm holes defects observed in joint surface but when hardness increases this defect is not found because of sufficient heat production between job and work-piece. So, work-piece is treated with heat and cooled by their respective medium to increase hardness. This heat treatment changes the grain structure of material and allows generating friction heat in low speed. Sufficient heat production provide better joint between materials which can be analyze by strength test performance. Defect free joint was obtained by use of tool material H13. Analyzing welding joint strength by tensile test apply on specimens were made as per ASTM E8 as shown in **Fig. 3**.

Fig. 3. Welded joint & ASTM E8M-04 specimens.

Tensile test

Couple of tensile specimens was made from each experiment run. The tensile tests were performed on UTM under 40KN load, applied to the specimens until their breakage and their results were studied. The tensile strength was the approval that seventh experiment run had the highest tensile strength and second experiment run had the lowest tensile strength. Tensile strength increases when the temperature holding time of the parameters increases. Its main reason is the tensile strength of the joint varies with the cooling rate of the sample preparation. It has also been observed that water cooled specimens have higher tensile strength than air cooled specimen at each stage of temperature over holding time. Breaking load under given parameters of UTM were exhibited as tensile strength for seventh specimen is 15.6 KN as shown in **Table 2**.

Table 2. Response of Strength Test

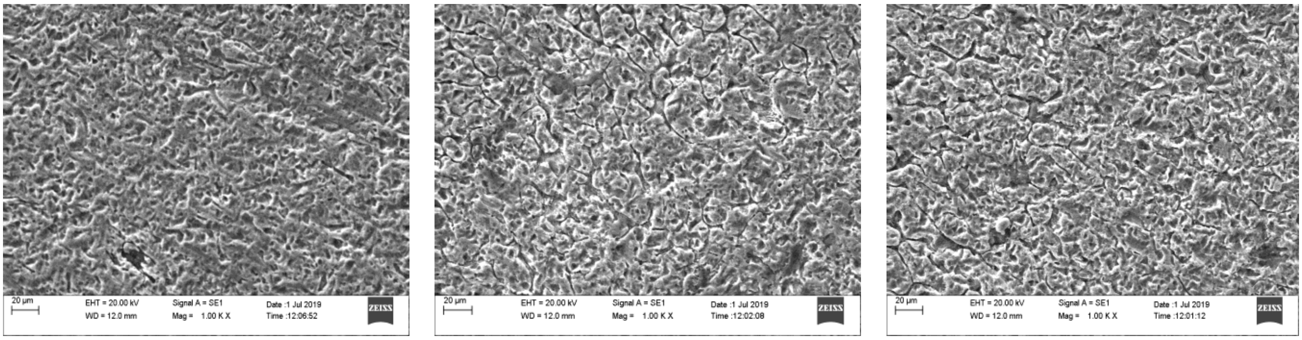
S. No.	T oC	Ht min	M	Tensile test (Tt) KN
1	200	25	Water	11.4
2		25	Air	10.4
3		50	Water	14.1
4		50	Air	13.8
5	250	25	Water	12.6
6		25	Air	12.2
7		50	Water	15.6
8		50	Air	14.3

Micro structure study

In order to understand the effect of friction heat on welded joint, micro structural study was analyzed in cross section of welding joint and studied grain growth of aluminium material properties in base metal welding zone and HAZ (Heat Affected Zone). The welded zone is the zone where the stirring process occurred between the metal and where the frictional heat affected the base metal is considered the HAZ zone. The emission scanning electron microscope ZEISS SIGMA with a magnification is 20X used for observed grain size in welded area. Delta ferrite found in dark microstructure shows crack in welding. Three specimen from all the above were selected for microstructure, one of which was broken under high load and one which was broken under low load of tensile test are experiment run seventh and experiment second respectively. One of these specimens was broken by neck this result was observed in fourth run experiment. The properties of the welding joint at base metal, welded zone and HAZ shows in **Table 3** by microstructure analysis.

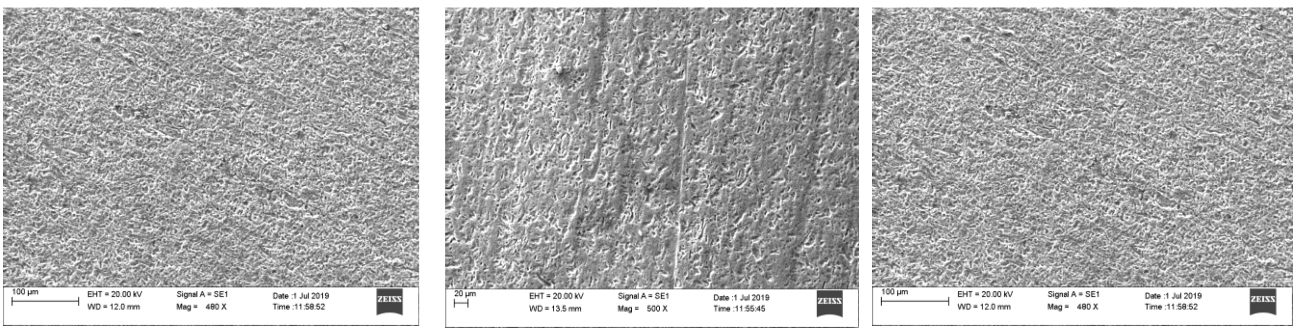
Table 3. Micro structure analysis.

Zone	Seventh	Fourth	Second
Base metal	Austenite light structure	Austenite light structure	Austenite light structure
Welding Zone	dendrites structure	dendrites+ ferrite structure	austenite + ferrite
HAZ	Dark austenite/ferrite	Dark austenite/ferrite	Coarse austenite + second phase



(A) (B) (C)

Fig. 4. Welded zone Micro structures, (A) Specimen Breaking at high Load, (B) Specimen Breaking at Neck, (C) Specimen Breaking at high Load.

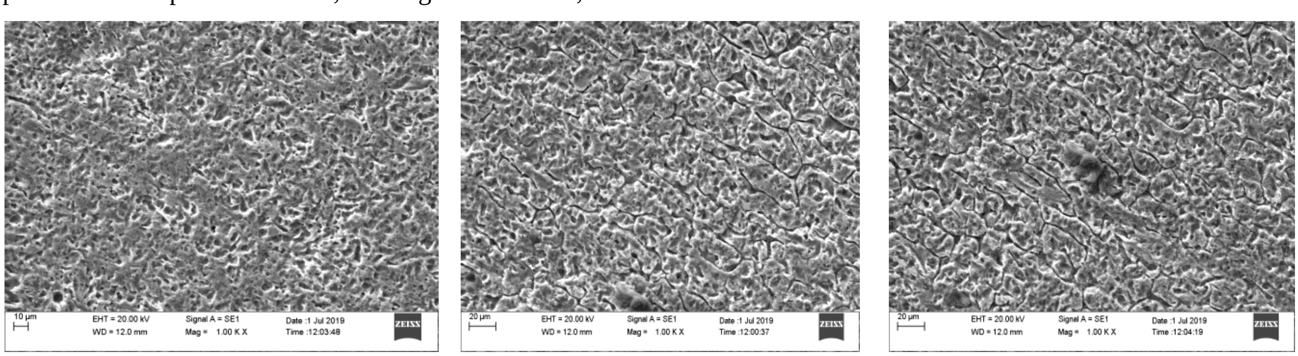


(A) (B) (C)

Fig. 5. Base metal Micro structures, (A) Specimen Breaking at high Load, (B) Specimen Breaking at Neck, (C) Specimen Breaking at high Load.

Results

The effect of welding preparation by Friction heat treatable aluminum alloy are studied which perceived in microstructures. The microstructures at the base metal, welded zone and HAZ region are shown in **Fig. 4** to **Fig. 6** respectively. Dendrites microstructures observed in seventh experiment run and found equal spacing in grain size. The absence of cracks shows that the high strength of the welded joint. On inspection of all the welding zones by microstructure study, it was found that no cracks were found in any of the welding zones (Welding Zone, HAZ) created by the seventh experiment and this specimen were prepared under parameters include 50 minutes of time with a temperature of 250°C and water used as a cooling medium. Experiment run fourth is prepared under running parameters temperature 200 C, holding time 50 min, and cooling medium is air. Experiment run second is prepared under running parameters temperature 200 C, holding time 25 min, and cooling medium is air. Some cracks were observed in microstructure of HAZ in fourth experiment run and second experiment run microstructure shows long cracks in both regions that is welded zone and HAZ region. This can be confirmed after inspecting the microstructure of all experiment run that experiment run seven is higher power than all other experiments and from the observation of weld microstructure it is clear that the grain size in this experiment is presented in small form which is a close to the other also indicating here that there may have been a low in temperature produce in this process. The temperature is 250°C and cooling medium water with time 50 minutes as a result of the fine grain structure is found in seventh experiment run.



(A) (B) (C)

Fig. 6. HAZ Micro structures, (A) Specimen Breaking at high Load, (B) Specimen Breaking at Neck, (C) Specimen Breaking at high Load.

Conclusion

In present research same grade of aluminium material would be welded by friction stir welding on low speed of rotation by using H13 tool. The Low-speed rotation of tool reduces the installation cost of heavy motor machine which saves high power. Minimized rotational speed of FSW tool will give the optimum welding strength under preheated water-cooled work piece. From the tabulated result it is clear that increasing the Temperature of work-piece with water cooled medium increases the strength. Micro structure study shows change in grain sizes and cracks found in welding joint verify the strength.

Keywords

Stir welding, welding strength, temperature, pre-heating, aluminium alloy, cooling medium.

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References

1. Ananthapadmanaban, D.; Rao, V.S.; Abraham, N.; Rao, K.P.; *Elsevier Materials & Design*, **2009**, *30*, 2642.
2. Asadi P.; Givi MKB.; Akbar M.; *International Journal of Mechanical and Materials Engineering*, **2015**, *10*, 1.
3. Azevedo J.; Quintino L.; Infante V.; Miranda R.M.; Santos J.D.; *Soldagem & Inspecao*, **2016**, *21*, 16.
4. Avila J.A., Ruchert C., Mei P.R., Marinho R.R., Paes MTP, Ramirez A.J.; *Engineering Fracture Mechanics*, **2015**, *147*, 176.
5. Bilgin M.B., Meran C.; *Mater. Des.*, **2012**, *33*, 376.
6. Camilleri D., Micallef D., Mollicone P.; *J. Therm. Stresses*, **2015**, *38*, 485.
7. Chauhan A., Kumar S.; *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)*, **2018**, *8*, 615.
8. Chen C.M.; Kovacevic R.; *International Journal of Machine Tools & Manufacture*, **2003**, *43*, 1319.
9. Darwins A.K.; Satheesh M.; *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)*, **2017**, *7*, 429.
10. Deepati A.K.; Kadian A.K.; Biswas P.; *International Journal of Manufacturing Research*, **2015**, *10*, 64.
11. Elangovan K.; Balasubramanian V.; Valliappan M.; *International Journal of Microstructure and Materials Properties*, **2009**, *4*, 455.
12. Fujii H.; Cui L.; Maeda M.; Nogi K.; *Mater. Sci. Eng. A.*, **2006**, 419, 25.
13. Lee W.B.; Yeon Y.M.; Jung S.B.; *Mater. Sci. Technol.*, **2003**, *19*, 1513.
14. Li LX.; He FY.; Liu X.; Lou Y.; Zhou J.; Duczczyk J.; *Key Engineering and Materials*, **2012**, *491*, 264.
15. Liu X.; Li LX.; He FY.; Zhou J.; Zhu B.; Zhang L.; *Transactions of Nonferrous Metals Society of China*, **2013**, *23*, 2692.
16. Marzbanrad J.; Akbari M.; Asadi P.; Safaee S.; *Metallurgical and Materials Transactions B*, **2014**, *45*, 1887.
17. McPherson NA; Galloway AM; Cater SR; Hambling SJ.; *Sci. Technol. Weld. Join.*, **2013**, *18*, 441.
18. Mendes N.; Neto P.; Loureiro A.; Moreira AP.; *Materials and Design*, **2016**, *90*, 256.
19. Motalleb-nejad P.; Saeid T.; Heidarzadeh A.; Darzi K.; Ashjari M.; *Materials & Design*, **2014**, *59*, 221.
20. Nathan SR.; Balasubramanian V.; Malarvizhi S.; Rao AG.; *Int. J. Refract. Met. Hard Mater.*, **2016**, *56*, 18.
21. Nathan SR.; Malarvizhi S.; Balasubramanian V.; Rao AG.; *Eng. Fail. Anal.*, **2016**, *66*, 88.
22. Prasanthi T.N.; Sudha C.; Ravikirana S.S.; Kumar NN.; Janaki Ram G.D.; *Elsevier Materials & Design*, **2015**, *88*, 58.
23. Rajakumar S.; Muralidharan C.; Balasubramanian V.; *International Journal of Microstructure and Materials Properties*, **2011**, *6*, 132.
24. Ramesha R.; Dinaharanb I.; Kumarc R.; Akinlabi ET.; *Materials Science & Engineering A.*, **2017**, *687*, 39.
25. Ramachandran K.K.; Murugan N.; Shashikumar S.; *Mater. Sci. Eng. A.*, **2015**, *639*, 219.
26. Rashidi A.; Mostafapour A.; *Int. J. Adv. Manuf. Technol*, **2015**, *80*, 1087.
27. Rashidi A.; Mostafapour A.; Rezazadeh V.; Salahi S.; *Appl. Mech. Mater.*, **2013**, *302*, 371.
28. Santillana Begon, A.; Boom R.; Eskin D.; Mizukami H.; Hanao M.; *Metallurgical and Materials Transactions*, **2012**, *43*, 5048.
29. Sato Y.S.; Urata M.; Kokawa H.; *Metall. Mater. Trans. A.*, **2002**, *33*, 625.
30. Scialpi A.; LAC D.F.; Cavaliere P.; *Mater. Design*, **2007**, *28*, 1124.
31. Sekhon S.; Kumar H.; Sehgal S.; *International Journal of Materials Engineering Innovation*, **2016**, *7*, 236.
32. Singarapu U.; Kumar A.; Arumalle S.M.; *Journal of Magnesium and Alloys*, **2015**, *3*, 335.
33. Suna Y.; Fujii H.; Takadaa Y.; Tsuji N.; Nakataa K.; Nogi K.; *Materials Science and Engineering A.*, **2009**, *527*, 317.
34. Thimmaraju P.K.; Arakanti K.; Chandra GRM.; *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)*, **2017**, *7*, 471.
35. Toumpis A.I.; Gallawi A.; Arbaoui L.; Poletz N.; *Sci. Technol. Weld. Join.*, **2014**, *19*, 653.
36. Toumpis A.; Gallawi A.; Cater S.; McPherson N.; *Mater. Des.*, **2014**, *62*, 64.