

Effect of Process Parameters on Mechanical Properties of Friction Stir Welded Dissimilar Materials between AA6061-T651 and AA7075-T651 Alloys

S. Ravikumar¹, V. Seshagiri Rao² and R.V. Pranesh³

¹*Department of Mechanical & Production Engineering, Sathyabama University, Rajiv Gandhi Road, Chennai, India*

²*Department of Mechanical Engineering, St Joseph College of Engineering, Rajiv Gandhi Road, Chennai, India*

³*Department of Mechanical & Production Engineering, Sathyabama University, Rajiv Gandhi Road, Chennai, India*

Abstract

Aluminium alloys have gathered wide acceptance in the fabrication of light weight structures requiring a high strength-to weight ratio and good corrosion resistance. Compared to the fusion welding processes that are routinely used for joining structural aluminium alloys, friction stir welding (FSW) process is an emerging solid state joining process was invented in 1991 by TWI, in which the material that is being welded does not melt and recast. Dissimilar AA6061-T651 and AA7075-T651 alloy have been friction stir welded with various process parameters like tool rotational, tool welding speed and tool pin profiles. The effects of rotational and welding speeds with the pin profiles on micro hardness distribution and tensile property of the joints were investigated keeping AA6061-T651 plate on the advancing side. It was found that the tensile strength of the dissimilar joints increases with decreasing heat input. All the obtained joints fractured in the heat-affected zone on the AA6061-T651 side during tensile testing, where micro hardness value is less. The good mixing of both the materials joined was obtained at lower welding and higher rotational speed.

Keywords: Dissimilar materials joining, Friction stir welding, Micro hardness, Tensile strength.

1. Introduction

Friction stir welding (FSW) process is a solid state joining technique considered to be the significant development over the past two decades which was invented and validated at the welding institute (TWI), United Kingdom in the year 1991[1]. In this process a non consumable tool is to be plunged into the faying surfaces of the plates with rotation and also it moves along the joint line for weld consolidation. The joint integrity depends upon the tool geometry nature used in this process. The tool pin and shoulder are helpful for heat generation, and material mixing by stirring producing the joint. In this process no melting occurs and the heat is generated internally by means of friction between the material-tool interface and the plastic deformation takes place without pre or post heating. Materials with different aluminum alloys can be welded together with a least alteration in mechanical properties due to no melting [2-5]. Tensile behavior of friction-stir-welded Al 6061-T651 was largely related to the clustering of coarse Mg_2Si precipitates, due to the whirling and hurling action by severe plastic flow in the weld zone [6]. Joints between dissimilar materials of 6061-T6 and 7075-T6 in aerospace structures mostly made by riveting which causes stress concentration and increase the weight of the final joints. FSW can be used in order to improve weldability without great loss of strength and corrosion properties [9]. Many researchers have been performed a numbers of successful experiments on the FSW of various dissimilar aluminium alloys. Muhamad Tehyo et al [7] investigated the influence of process parameters on metallurgical and mechanical properties of dissimilar FS welded joint between semi-solid metal 356-T6 and aluminum alloy 6061-T651; and reported that an increase in the welding speed apparently leads to an increase in the tensile strength of the specimen. In fact, the tensile strength approached a maximum value close to the lesser of the parent base materials then decreased with increasing welding speed on the dissimilar FS welded specimens. Thus, neither a too low welding speed nor a too high welding speed is desirable. Sang-Woo Song et al [8] investigated and reported; lowest hardness value was measured in the HAZ/ TMAZ of 5052 and the highest value was measured in the 5J32 region. However, these values did not deviate largely from those of base materials. P Bahemmat et al [9] investigated the mechanical, micro and macro structural characteristics of dissimilar friction stir welding of AA6061-T6 and AA7075-T6; and reported that because of the higher strength of the SZ compared with the HAZ and the TMAZ, the specimen was not fractured in the SZ and the fracture occurred in the TMAZ–HAZ interface on the AA6061 side, which has lower hardness and strength in the weld cross-section. A.A.M. da Silva et al [10] investigated Material flow and mechanical behaviour of dissimilar AA2024-T3 and AA7075-T6; and reported the threaded profile of the pin tool plays an important role in the material flow and mixing pattern of dissimilar FSW of AA2024-T3 and AA7075-T6 high-strength Al alloys. An excessive movement of bulk material from the advancing to the retreating side and vice versa underneath the shoulder seems to be the key reason that explains the lack of mixing. P.M.G.P. Moreira et al [11] investigated the Mechanical and metallurgical characterization of friction stir welding joints of AA6061-T6 with AA6082-T6; and reports that the hardness profile

of the dissimilar joint presents the lowest values of all joints in the AA6082-T6 alloy plate side; this corresponds to the location of rupture when tensile testing the dissimilar joints. C. Leitao et al [12] investigated the Mechanical behaviour of similar and dissimilar AA5182-H111 and AA6016-T4; and reported that both alloys exhibit a hardness variation consistent with the microstructure evolution across the TMAZ. N. Shanmuga Sundaram et al [13] investigated the tensile behavior of dissimilar friction stir welded joints of aluminium alloys 2024-T6 and 5083-H321; reported that the increase in the tool rotational speed or welding speed leads to the increase in the tensile strength; and it reaches a maximum value and then decreases. The increase in the tool axial force leads to the increase in the tensile strength of the dissimilar FS welded joints. Tensile strength decreases after it attains a maximum value. The increase in tool rotational speed results in the decrease in the tensile elongation, whereas tensile elongation increases with increase in the welding speed. The tensile elongation decreases with increase in tool axial force. It is observed that very few experimental works are carried out in dissimilar FSW of aluminium alloys [14-22]. Dissimilar welding of aluminium alloys is a core demand of the Aircraft industries to substitute the traditional joining technologies with low costs and high efficiency ones such as friction stir welding in the future advanced design. However, in the very few studies performed on dissimilar FSW, researchers have not yet been drawn to study about dissimilar FSW of AA6061-T651 and AA7075-T651. The present research work reports the effects of process parameters (rotational speed, welding speed and types of tool pin profile) on tensile strength were analyzed on the basis mechanical and micro structural properties of dissimilar friction stir welds.

2. Experimental Procedure

Aluminium alloys of AA6061-T651 and AA7075-T651 are selected for to fabricate dissimilar joints using the FSW process; where T651 heat treatment consists of solution heat treated, stretched and artificially aged. The FSW machine (Hydraulic power pack motor of 2.2kW /440V with 3000 rpm maximum rotational speed; 5000 mm/min as X axis rapid traverse speed and maximum axial thrust as 50kN) used for the dissimilar welding of the above aluminium alloy plates is shown in Fig.1.(a) the welding setup and the typical welded plates are shown in the Fig.1.(b) & (c)

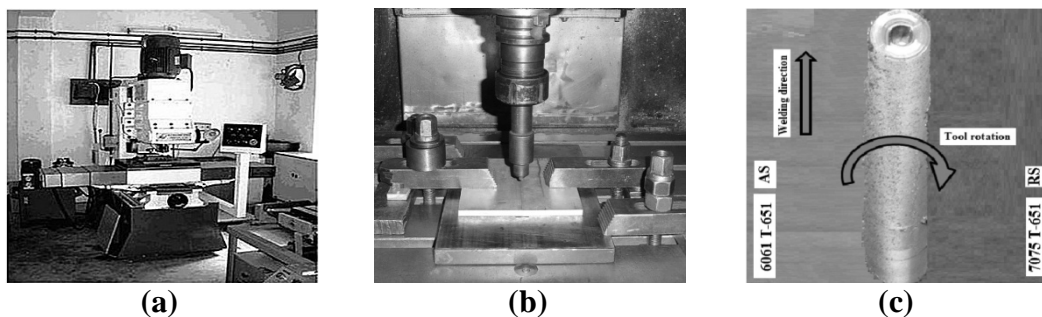


Fig. 1: (a) FSW Machine (b) FSW Welding Setup (c) Typical Welded Plates used in FSW process.

The thickness of the both aluminium alloy plates are 6.35 mm. Chemical compositions and the mechanical properties of AA6061-T651 and AA7075-T651 are given in Tables I and II respectively. The plates are placed in a butt configuration of 100 mm length; 50 mm width and the FSW process is carried out normal to the direction of the plates. The side where the tool rotation is in the same direction of translation of the tool referred to as advancing side whereas when this two tool motion counters referred as retreating side. Dissimilar friction stir welding process is carried out by placing the high strength aluminium alloy AA7075-T651 at the retreating side (RS), and by placing the aluminium alloy AA6061-T651 at the advancing side (AS); since if the weaker alloy is located at the RS, the fabricated weld will become weaker than when the weaker alloy is at the RS [8]. The process parameters which have the greater influence on the tensile strength of dissimilar FSW joints are identified as rotational speed (RS), welding speed (WS) and tool pin profile (PP). Three different tools made of H13 tool steel having different pin profiles are used to fabricate the joints. They are represented in Fig.2 viz.

Table 1: Chemical composition of base aluminium alloys.

Base alloys	Al	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Pb	Sn
6061-T651	97.16	0.8	0.4	0.27	0.09	0.96	0.21	0.01	0.06	0.02	0.01	0.01
7075-T651	89.76	0.05	0.1	1.3	0.03	2.69	0.2	0.01	5.78	0.06	0.01	0.01

Table 2: Mechanical properties of base aluminium alloys.

Aluminium alloys	Yield strength, (MPa)	Ultimate tensile strength, (MPa)	Tensile elongation, (%)	Micro hardness (VHN)
6061-T651	287.0	303.0	17.2	102.0
7075-T651	526.0	583.0	11.3	171.0

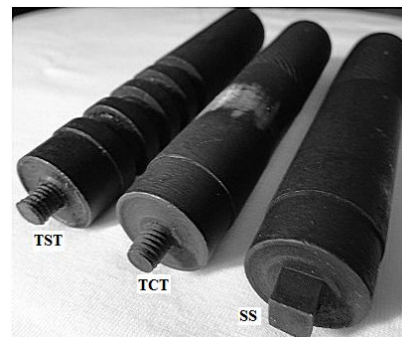


Fig. 2: Pin Profiles used for experiments-TST,TCT,SS.

Simple Square (SS), Taper cylindrical threaded (TCT) and Taper square threaded (TST). Trial experiments are conducted to determine the working and feasible range of process parameters. The influenced process parameters and their working range for the dissimilar FSW of AA6061-T651 and AA7075-T651 are presented in Table III.

Table 3: Dissimilar friction stir welding parameters and the selected levels.

S. No	Operating parameter	Symbol	Unit	Levels		
				Low (-1)	Middle (0)	High (1)
1	Tool rotational speed	R	rpm	800	900	1000
2	Welding speed	W	mm/min	90	100	110
3	Tool pin profile	P	-	SS	TCT	TST

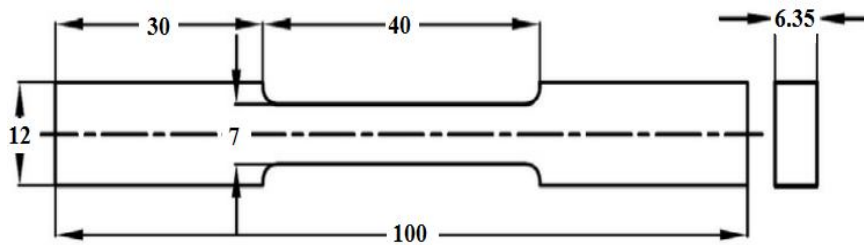


Fig. 3: Tensile Specimen with ASTM E8M-04.

After the welding, the transverse tensile specimens are prepared with reference to ASTM E8M-04 standard and whose geometry and dimensions are shown in Fig.3. The room temperature tensile test was carried out with reference to ASTM D 557 M- 94 at a crosshead speed of 1.5 mm/min using a computer-controlled testing machine (Associated Scientific Engg. Works, New Delhi) and their ultimate tensile strength are measured from the averages of the three specimens. Vickers microhardness distribution conducted under the load of 500g.f. for 10s at 1mm neighbouring distances. The welds were characterized using DE-WINTOR inverted trinocular metallurgical microscope and Hardness was measured by Wilson Wolpert Micro hardness tester, Germany make with a load testing range 10gms to 1Kg and least count 0.01 microns.

3. Results and Discussions

3.1 Macro and micro structural observations

Fig. 4 (a) shows the microstructure of AA 6061 where the particles of Mg_2Si that are evenly precipitated in aluminium solid solution. Some inter metallic's which are undissolved like $Al_6(Fe, Mn)$ also present in the matrix. The matrix is well solutionized and precipitation hardened. The particles of Mg_2Al which are present can be resolved at higher magnification whereas Fig. 4(b) shows the microstructure of AA7075 where the precipitation hardened matrix with the fine precipitation of $Cu-Al_2$

along with Mg Zn₂ and complex precipitates of Cr₂Mg₃Al₁₈ complete dissolution of Cu-Al₂ and reprecipitation leads to finer particles after solutionising and Age hardening. The high hardness measured shows the precipitation of the strengthening agents are complete.

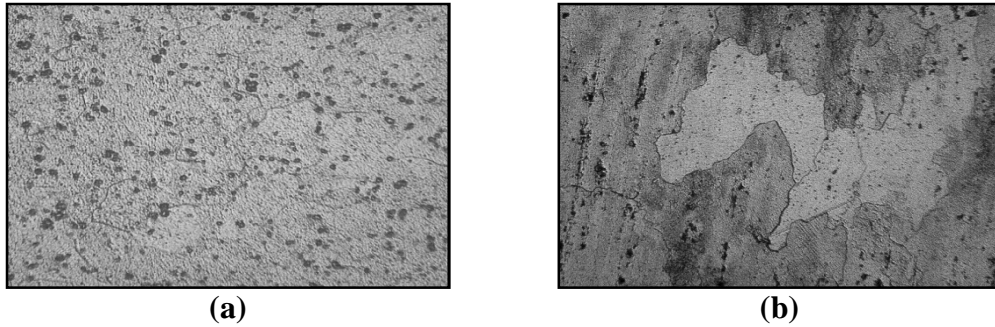


Fig. 4 (a): Micro Structure of AA6061 **(b)** AA7075.

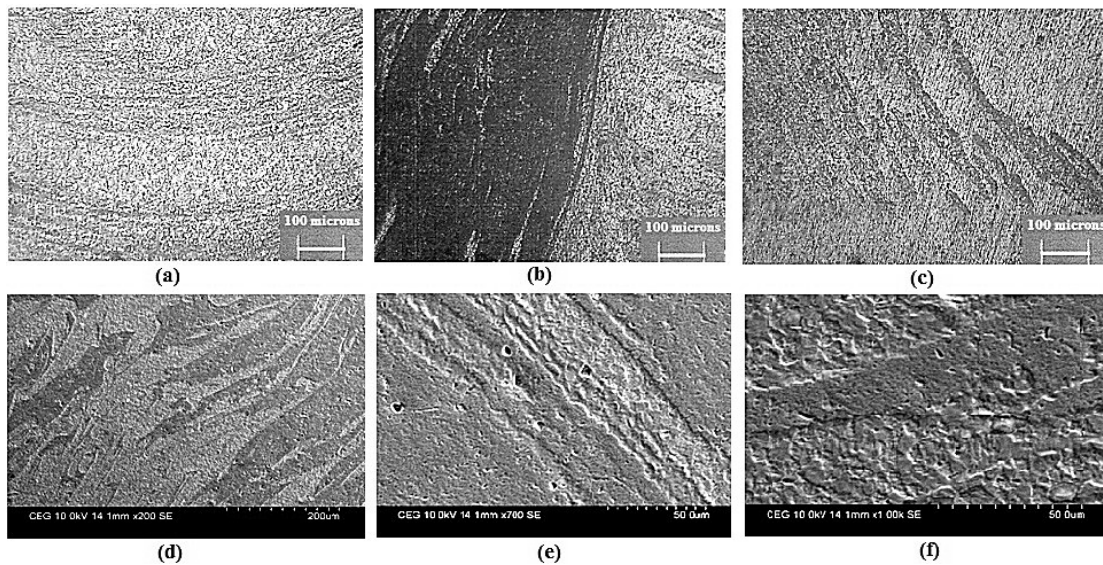


Fig. 5 (a) (b) (c): Micro Graphs at 900 rpm and 100 mm/min, **(d) (e) (f)** SEM images at 900 rpm and 100 mm/min

Fig.5 (a-f) shows the micrographs and SEM images of the produced weld after thoroughly etched with the keller's reagent at 900 rpm, 100 mm/min with TCT tool. Fig 5 (a) represents FSW zone where alternate layers of 7075 alloy and 6061 alloys are have undergone fusion. The precipitated particles in both have become larger due to heat and stress. Fig 5 (b) shows the interface zone of the parent 7075 with the fusion zone (FSW). Fig 5 (c) shows zone of 6061 parent metal with TMT zone of alternate layers of 6061 and 7075 alloys. The Sem images at fig 5 (d) & (e) are the regions from the center of the nugget Zones. The zones indicated that a good fusion of the 7075 and 6061 has produced alternate layers with fine grains. The broad band is from 7075 and

the light dull areas are from 6061 alloy. The SEM image at fig 5 (f) shows the dominant 7075 alloy fusion at the nugget zone. The Stirred zone has higher hardness compared with the HAZ and TMAZ because of the smaller grain size at this zone. The higher hardness is observed when the fracture location is at the body of the base metal or at the HAZ, which has lower hardness in comparison with the stirred zone. The fracture location of joints was in the HAZ of AA6061 side due to lower hardness value.

3.2 Micro hardness variation for the dissimilar joint

The Hardness of the material after welding was tested according to the sketch given below in Fig.6. The hardness test conducted as per ASTM E92-82(2003)e2 standard at the center of the FSW zone was marked and hardness was measured towards left and from center to right.

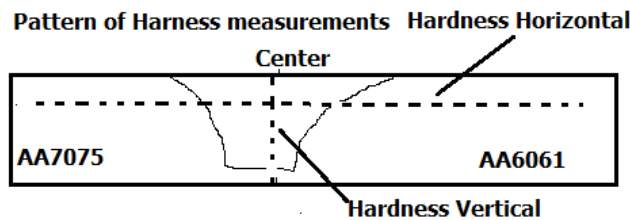


Fig. 6: Pattern of hardness measurements.

The micro hardness profiles for different process parameters with three different pin profiles Taper cylindrical threaded (TCT), Taper square threaded (TST) and Simple Square (SS) versus distance from the weld centre are depicted in Figs 7-9. For all the cases, the hardness decreases by increasing the distance from the weld centre. According to Fig7, 8 & 9; the micro hardness studies reveals that the change of micro hardness at the TMAZ-HAZ interface on the AA6061-T651 side is smoother than for AA7075-T651.

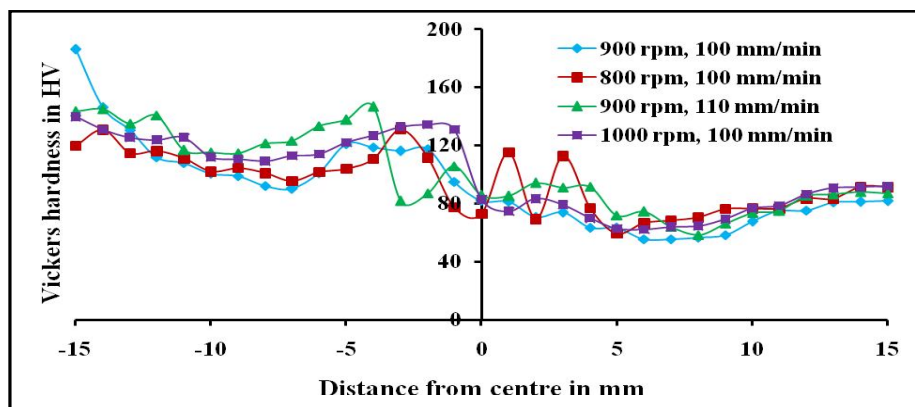


Fig. 7: Micro hardness variations in the weld cross section TCT tool.

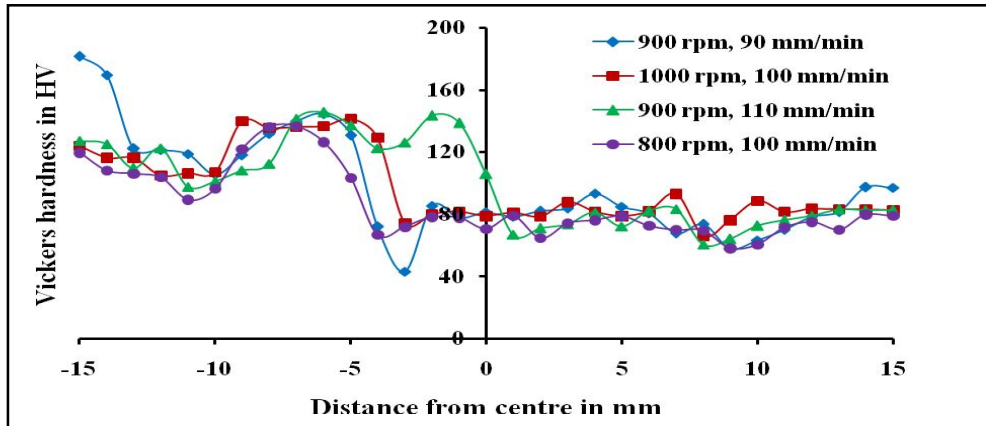


Fig. 8: Micro hardness variations in the weld cross section TST tool.

Also it was observed the hardness distribution in the HAZ and TMAZ in the 6061-T651 side for all the welding speeds is same irrespective of rotational speeds; whereas this variation was much higher in the 7075-T651 side. This may be due to the thermal cycle in the HAZ of the weld which is more influenced due to over-aging of strengthening precipitations of AA7075-T651 than in AA6061-T651. The slope of the hardness variations curve, goes down by decreasing the distance from the weld centre. The micro hardness curve becomes smoother after a certain point and it is closer to the weld centre as the weld speed decreased and also the size of HAZ decreases when the welding speed increases.

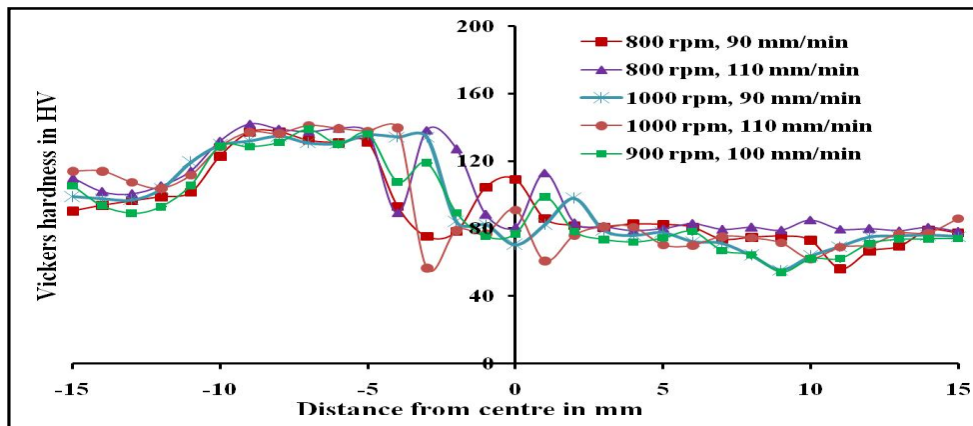


Fig. 9: Micro hardness variations in the weld cross section SS tool.

3.3 Tensile strength observations

Fig.10 (a) shows the typical tensile specimen used for experiments and Fig.10 (b) represents the tensile tested specimens according to standards ASTM D 557 M-94. Table IV shows the micro hardness values in SZ in addition to the tensile test results of all the dissimilar friction stir welded specimens including the tensile failure position. It

is observed that of all the welded plates, the plate welded with 900rpm tool rotational speed, 100mm/min welding speed and TCT tool shows better micro hardness value at the SZ and higher tensile strength. It is observed that most of the specimens failed in the HAZ region of the AA6061 side and a few of them failed in SZ region. The joints fabricated with 900rpm tool rotational speed, 90mm/min welding speed and TST tool showed low tensile strength. Tensile strength increases with increase in rotational speed up to 900rpm, after that it decreases. The tensile strength first increases to a maximum value and afterwards show a decrease with increasing the rotational speed at a given welding speed or tool pin profile of the friction stir welded joints. Generally the tensile strength is poor at lower rotational speeds due to inadequate tool stirring action. At rotational speed (800 rpm) the lowest frictional heat which is generated induce poor material flow results in lower tensile strength. With the increase of rotational speed for a certain range the strain hardening effect induced by tool stirring action increases tensile strength but the tensile strength lowers significantly with an increase of rotational speed to a rather high value due to excess heat input results in re-precipitation, reduction in dislocation density and coarsening of strengthening precipitates.

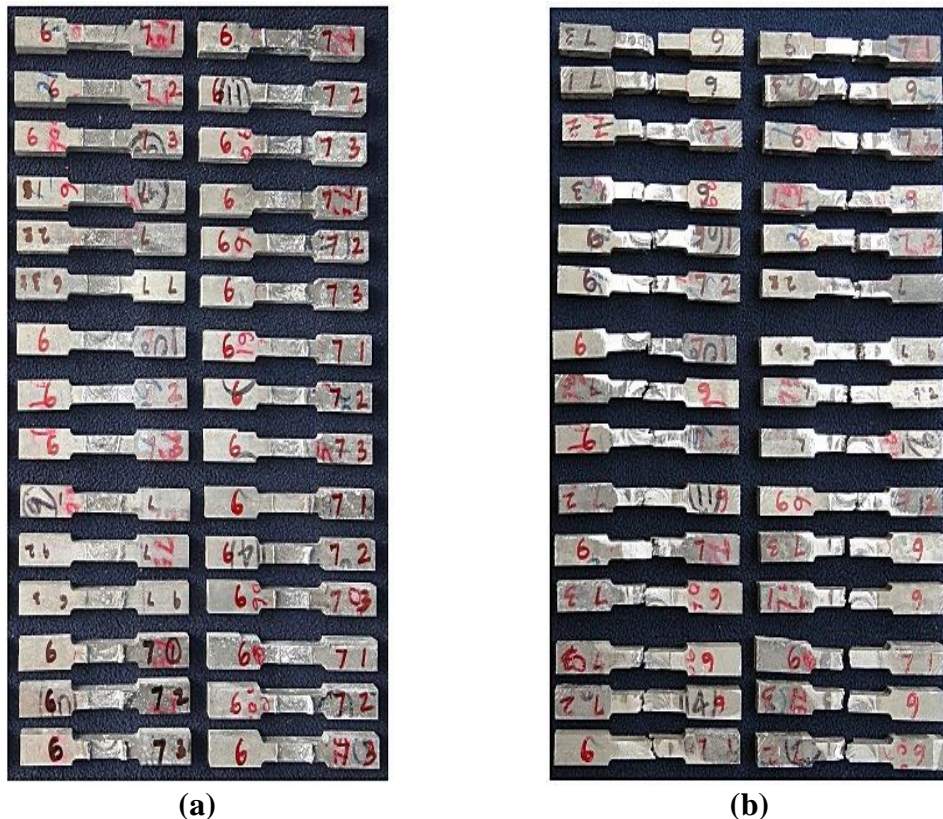


Fig. 10 (a): Typical Tensile Specimen, (b) Typical Tensile Tested Specimen

Table 4: Mechanical properties of dissimilar friction stir welded specimens.

S. No	Rotational speed (rpm)	Welding speed(mm/min)	Pin profile	Axial force (kN)	UTS (Mpa)	Vicker's Hardness	Failure position
1	800	90	SS	12	154	111.65	SZ
2	800	100	SS	12	170	111.11	HAZ of 6061
3	800	110	SS	12	170	111.32	HAZ of 6061
4	800	90	TCT	12	174	112.98	HAZ of 6061
5	800	100	TCT	12	186	112.34	HAZ of 6061
6	800	110	TCT	12	183	111.49	HAZ of 6061
7	800	90	TST	12	150	98.26	SZ
8	800	100	TST	12	160	96.35	SZ
9	800	110	TST	12	153	95.18	SZ
10	900	90	SS	12	170	111.54	HAZ of 6061
11	900	100	SS	12	182	112.23	HAZ of 6061
12	900	110	SS	12	179	111.34	HAZ of 6061
13	900	90	TCT	12	195	113.81	HAZ of 6061
14	900	100	TCT	12	205	114.22	HAZ of 6061
15	900	110	TCT	12	198	113.13	HAZ of 6061
16	900	90	TST	12	178	107.12	HAZ of 6061
17	900	100	TST	12	184	108.12	HAZ of 6061
18	900	110	TST	12	175	109.56	HAZ of 6061
19	1000	90	SS	12	151	94.25	SZ
20	1000	100	SS	12	160	98.26	SZ
21	1000	110	SS	12	152	96.23	SZ
22	1000	90	TCT	12	184	112.46	HAZ of 6061

23	1000	100	TCT	12	188	111.95	HAZ of 6061
24	1000	110	TCT	12	178	110.84	HAZ of 6061
25	1000	90	TST	12	172	106.85	HAZ of 6061
26	1000	100	TST	12	175	104.23	HAZ of 6061
27	1000	110	TST	12	161	98.26	SZ

The variation in tensile strength value at different rotational speed for a tool pin profile is due to the variation of material flow and frictional heat generated. For a given rotational speed or tool pin profiles, the increase of welding speed increases the tensile strength to a certain value, and further increase of welding speed results in the decrease in the tensile strength of the friction stir welded joints. At lowest welding speed (90 mm/min) and highest welding speed (110 mm/min) lower tensile strengths are observed. The lower welding speed, which significantly deteriorates the mechanical properties of joints due to larger heat input into the weld samples, however as the welding speed increases, the thermal cycles effect is minimized which leads to an increase in tensile strength. The lower tensile strength at 110 mm/min is due to insufficient frictional heat generated. Joints made by the taper cylindrical threaded (TCT) tool have the highest tensile strength irrespective of the welding speed used to fabricate the joints. All the three different tools yield lower tensile strength at the lowest welding speed of 90 mm/min. The dissimilar joints fabricated using the taper cylindrical threaded (TCT) tool has maximum tensile strength compared to the joints made using other two tools. The TCT type of tool pin profile produces good material stirring quality and mixing of dissimilar plasticized metals during welding. SS and TST type of tool pin profile produce insufficient mixing of dissimilar plasticized metals because tool pin is incapable of deforming appropriate metal during rotation leads to low tensile strength.

The Stirred zone has higher hardness compared with the HAZ and TMAZ because of the smaller grain size at this zone. The higher hardness is observed when the fracture location is at the body of the base metal or at the HAZ, which has lower hardness in comparison with the stirred zone. The fracture location of all the above three joints was in the HAZ of AA6061 side due to lower hardness value. The fracture mechanism of these two alloys is dimple fracture. From the Fig.11 (a) (b) & (c) it is found that dimple fracture mechanism was occurred with some degree of ductility in mixing these two alloys.

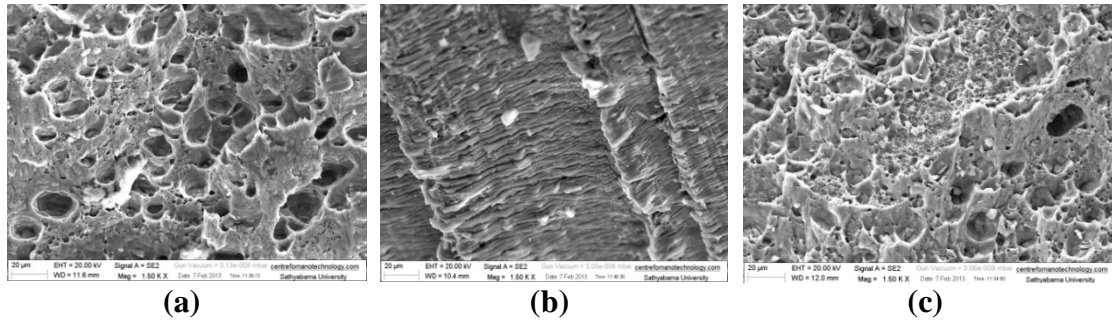


Fig. 11 (a): Fractograph at 900 rpm, 100 mm/min with TCT tool, **(b)** Fractograph at 900 rpm, 110 mm/min with SS tool, **(c)** Fractograph at 900 rpm, 90 mm/min with TST tool.

4. Conclusions

1. The friction stir welding process used successfully to join dissimilar aluminium alloys (AA6061 and AA7075).
2. Better mechanical properties (hardness and tensile strength) were obtained with the FSW plate fabricated with 900 rpm tool rotational speed, 100 mm/min welding speed with TCT tool compared to all other conditions.
3. The Stirred zone has higher strength compared with the HAZ and TMAZ because of the smaller grain size at this zone. The higher hardness values are observed when the fracture location is at the body of the base metal or at the HAZ, which has lower hardness value in comparison with the stirred zone. The fracture location of the joints was in the HAZ of AA6061 side due to lower hardness value. The reason for the lower value can be attributed to the poor fusion of the two plates.
4. The slope of the hardness variation curve goes down by decreasing the distance from the weld centre. The microhardness curve becomes smoother after a certain point and it is closer to the weld centre as the weld speed decreased and also the size of HAZ decreases when the welding speed increases. The HAZ zone experienced thermal cycle without plastic deformation, the over-ageing and coarsening of strengthening precipitates reduced the hardness in HAZ. The over-ageing of precipitates in the HAZ depends on the heat exposure time and temperature, and it is controlled by rotational and welding speeds and also the deciding factors for the hardness distribution in HAZ.

5. Acknowledgement

Friction Stir Welding of the work pieces were performed at Welding Research Cell, Department of Mechanical Engineering, Coimbatore Institute of Technology, Coimbatore, India. The authors are grateful to all the staff members Of Welding Research Cell. Authors are personally indebted to Dr N. Murugan, Coimbatore

Institute of Technology, Coimbatore, India for being a constant source of support and encouragement for the completion of experiments.

References

- [1] W.M. Thomas, E.D. Nicholas, J.C. Needham, M.G. Murch, S.P. Temple, and C.J. Dawes, "Friction stir butt welding", International Patent Application No PCT/GB92/ 02203, 1991.
- [2] M.W. Mahoney, C.G. Rhodes, J.G. Flintoff, R.A Spurling and W.H. Bingel, "Properties of friction-stir-welded 7075-T651 aluminum, Metall Mater Trans A, 29A, pp.1955–1964, 1998.
- [3] C.J. Dawes and W.M. Thomas, "Friction stir process welds aluminum alloys" Weld J ,75,pp. 41-44,1996.
- [4] J.H. Ouyang and R. Kovacevic, "Material flow and microstructure in the friction stir butt welds of the same and dissimilar aluminum alloys" J Mater Eng Perform, 11(1),pp.51-63,2002.
- [5] R.S.Mishra and J.Y. Ma, "Friction stir welding and processing" Mate Sci Eng R, 50, pp.1–78, 2005.
- [6] R.Nandan, T. Debroy and H.K.D.H. Bhadeshia, "Recent advances in friction stir welding process, Weldment structure and properties", Prog Mater Sci, 53, pp.980-1023, 2008.
- [7] M.Tehyo, P. Muangjunburee, A. Binraheem, S. Chuchom and N. Utamarat, "Influence of friction stir welding parameters on metallurgical and mechanical properties of dissimilar joint between semi-solid metal 356-T6 and aluminum alloys 6061-T651", Songklanakarin J Sci Technol ,34(4),pp. 415-421, 2012.
- [8] S.W.Song, B.C.Kim, T.J.Yoon, N.K.Kim, I.B.Kim and C.Y.Kang, "Effect of welding parameters on weld formation and mechanical properties in dissimilar alloy joints by FSW", Mater Trans, 51(7), pp.1319-1325, 2010.
- [9] P.Bahemmat, M.Haghpanahi, M.K.Besharati, S.Ahsanizadeh and H.Rezaei, "Study on mechanical, micro and macrostructural characteristics of dissimilar friction stir welding of AA6061-T6 and AA7075-T6", Proc IMechE Part B: J. Eng Manuf , 224, pp.1854-1865,2010.
- [10] A.A.M.D. Silva, E.Arruti, G.Janeiro, E.Aldanondo, P.Alvarez and A.Echeverria, "Material flow and mechanical behaviour of dissimilar AA2024-T3 and AA7075-T6 aluminium alloys friction stir welds", Mater Des, 32, pp.2021–2027, 2011.
- [11] P.M.G.P.Moreira, T.Santos, S.M.O.Tavares, V.R. Trummer, P. Vilaça and P.M.S.T.D.Castro, "Mechanical and metallurgical characterization of friction stir welding joints of AA6061-T6 with AA6082-T6", Mater Des, 30, pp.180–187, 2009.
- [12] C.Leitao , R.M.Leal , D.M.Rodrigues , A.Loureiro and P.Vilaca , "Mechanical behaviour of similar and dissimilar AA5182-H111 and AA6016-T4 thin friction stir welds", Mater Des,30,pp.101–108,2009.

- [13] N.S.Sundaram and N. Murugan, “Tensile behavior of dissimilar friction stir welded joints of aluminium alloys”, *Mater Des*, 31, pp.4184–4193, 2010.
- [14] Y.J.Chao , Y.Wang and K.W.Miller, “Effect of friction stir welding on dynamic properties of AA2024-T3 and AA7075-T7351”, *Weld J* ,80,pp.196–200,2001.
- [15] P.Cavaliere, E.Cerri and A. Squillace, “Mechanical response of 2024–7075 aluminium alloys joined by friction stir welding”, *J Mater Sci*, 40, pp.3669–3676, 2005.
- [16] P.Cavaliere, R.Nobile , F.W.Pannela and A.Squillace , “Mechanical and microstructural behaviour of 2024–7075 aluminium alloy sheets joined by friction stir welding”, *Int J Mach Tools Manuf* , 46,pp.588–594,2006.
- [17] Y.S.Sato, Y. Kurihara and H. Kokawa, “Microstructural characteristics of dissimilar butt friction stir welds of AA7075 and AA2024”, 6th Int symposium on FSW, Toronto, Canada, pp.10–13,2006.
- [18] S.A. Khodir and T.Shibayanagi, “Friction stir welding of dissimilar AA2004 and AA7075 aluminum alloys”, *Mater Sci Eng B*, 148, pp.82–87.
- [19] S.T.A. Filho, S.Sheikhi , J.F.D.Santos and C.Balfarini, “Preliminary study on the microstructure and mechanical properties of dissimilar friction stir welds in aircraft aluminium alloys 2024-T351 and 6056-T4”, *J Mater Process Technol*, 206,pp.132–42,2008.
- [20] E.Aldanondo, A.A.M.D.Silva, P.Alvarez, A.Lizarralde and A.Echeverria, “Dissimilar friction stir welding of AA2024-T3 and AA7075-T6 aluminium alloys”, “138th Annual meeting and exhibition TMS2009, Friction stir welding and processing V”, San Francisco, USA ,pp.15–19,2009.
- [21] A.A.M.D.Silva, E.Aldanondo , P.Alvarez , A.Lizarralde and A.Echeverria , “Mechanical and microstructural characterisation of dissimilar friction stir welded AA2024-T3 and AA7075-T6 aluminium alloys”, *Mater Sci Forum*, 1221(6),pp.638–42,2010.
- [22] E.T.Akinlabi , R.D.Reddy and S.A Akinlabi , “Microstructural characterizations of dissimilar friction stir welds”, *Proc World Congress Eng 2012 Vol III, WCE 2012, July 4-6, 2012, London, U.K.*, ISBN: 978-988-19252-2-0, ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online).