Experimental Investigation on Influences of Tool Shoulder Diameter (D) to Plate Thickness (T) ratio on Friction Stir Welding of Dissimilar Aluminium Alloys

Srirangam Adithya Vamshi[1], M. S. Srinivasa Rao[2], S. N. S. Sai Hari [3]

[1]*P. G. Student, Department of Mechanical Engineering, VNR VJIET, Hyderabad, India, 500090*
[2,3]*Assistant Professor, Department of Mechanical Engineering, VNR VJIET, Hyderabad, India, 500090.*

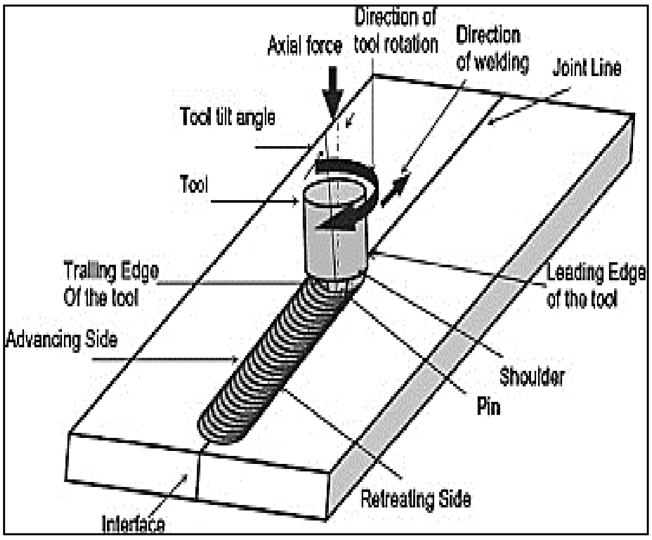
Abstract - *Friction Stir Welding is a novel solid-state welding technique ideal for joining metals in similar and dissimilar joint configurations, that generally yield a low efficient joint, when fabricated with conventional welding techniques. The dissimilar joint configuration welded joint of aluminium alloys of 5xxx series and 6xxx series is of greater importance in many industrial applications. In this present research work, an attempt has been made to identify the influences of tool shoulder diameter to plate thickness ratio on the quality of the weldments fabricated. The fabricated weldments are analyzed by various tests like Liquid Penetrant Test, Bending test, Macro and Micro structures of weldments, Vickers hardness test. Results revealed that the joints fabricated with tool shoulder diameter to plate thickness ratio as 3.5 yielded optimum results, indicating effective plasticizing of the material, better flow of the plasticized material along the length of the joint.*

Key Words: **Friction Stir Welding, Dissimilar butt joint configuration, Liquid Penetrant Test, Bending test, Macro and Micro structure, Vickers hardness test.**

1. INTRODUCTION

Joining of dissimilar metals with a higher joint efficiency is of greater importance in various engineering domains like electrical, electronic, aerospace, petrochemical, defense etc. which generally strive for low weight structures with desired amount of strength. Welding of dissimilar metals is carried over a large basis as benefits from both the materials can be derived from within a single structure. Conventional welding techniques like Gas welding, Arc welding; High energy welding techniques like Laser Beam Welding, Electron Beam Welding, Plasma Arc Welding etc. causes a high heat density in the joint interface. These welding techniques normally use an under matched filler metal during welding, resulting in a lower efficient joint, residual stresses in the weldments, distortion in the welding; making a post processing operation like annealing necessary for the weldments. Moreover, the use of conventional welding techniques results in the evaporation of lower melting point elements in the weldments and formation of Inter Metallic Compounds which tend to lower the strength of the weldments [1,2]. Friction Stir Welding is an emerging solid-state welding technique invented in 1991 at TWI [3] and is proved to be successful for joining metals in both similar and dissimilar joint configurations. This process does not involve in high operating temperature as in case of conventional welding techniques, do not require any use of filler metal, no or little distortion to the welded plates, no emission of harmful gases during welding and is practically possible to weld any metal.

Fig.1 Schematic diagram of Friction Stir Welding [20]



During the process of Friction Stir Welding as in Figure 1, a rotating tool consisting of shoulder and pin is inserted till the surface of the shoulder contacts the surface of the plates to be joined at the joint interface and is traversed along the length of the joint. As the tool traverses along the length of the joint, the frictional heat generated between the tool and workpiece helps in plastically deforming the material. The plasticized material is then travelled from the front face of the tool from the advancing side of the joint and is deposited to the retreating side of the joint by back face of the tool [4]. Local heat generation due to friction [5] between tool and work piece is given by equation 1 as:

$$De_f = \delta\ (\omega r - U\sin\Theta)\ \mu_f\ p\ dA \qquad (1)$$

Where, δ = Extent of slip; δ = 1 when no sticking of the material occurs and all the heat generated is due to friction and δ = 0 indicates complete sticking of the material and heat generation is due to plastic deformation.

ω = Tool rotational speed (*rpm*)

r = radial distance from tool axis (*mm*)

U = welding speed (*mm/min*)

μ_f = Coefficient of Friction

P = Pressure applied (*Pa*)

From the above equation 1, it is very clear that, the dimensions of the tool i.e. shoulder diameter, pin diameter, pin length play a major role in the generation of heat required to plasticize the material and guiding its flow along the length of the joint. R. Palanivel et al. [6] studied the influences of tool rotational speed and pin profile of Friction Stir Welded dissimilar joint of AA5083-H111 and AA6351-T6 and have concluded that above considered process parameters have a significant effect on the material flow pattern in the weld zone and the variations in the properties of weldments are due to loss of cold work in non-heat treatable HAZ of AA5083-H111, dissolution and over aging of precipitates in heat treatable 6351-T6. D.M. Rodrigues et al. [7] studied the effect of variation in process parameters on the FSW of 5083-H111 and 6082-T6 and identified that proper Shoulder diameter to Plate thickness ratio is necessary to yield a defect free joint. Sang-won Park et al. [8] investigated the effects of shoulder diameter and weld pitch on mechanical properties of FSW AA6111 and AA5023 and concluded that the joint interface area increased with an increase in shoulder diameter of the tool and the magnitude of weld pitch determines the amount of heat generated and the quality of the weldment fabricated. M. Koilraj et al. [9] studied the behavior of FSW of AA2219 to AA5083 and identified that AA2219-T87 placed on the advancing side of the joint dominated the nugget zone and the lowest hardness was obtained in the HAZ of AA5083 placed on the Retreating Side of the joint. Aman deep singh et al. [10] studied the tensile behavior of AA6082 and AA5083 under varying process parameters like tool rotational speed, welding speed, shoulder diameter, pin diameter. They have identified that tool rotational speed, welding speed followed by shoulder diameter and pin diameter are the most important process parameters that influence the quality of the weldments. S. Ravi Kumar et al. [11] studied dissimilar FSW of AA6061-T651 and AA7075-T651 by varying rotational speed, welding speed and pin profile. They concluded that the size of grain structure determines the hardness in various zones of Friction Stir Welding. Kush P. Mehta and Vishvesh J. Badheka [12] studied the effect of tool pin design on formation of defects of AA6061 and electrolytic tough pitch copper. They concluded that polygonal pin profiles yielded defects such as voids, tunnel defects, cracks. They added that defects decreased with decrease in the number of sides of tool pin profiles. S. Malarvizhi and V. Balasubramanian [13] studied that influences of tool shoulder diameter to plate thickness ratio on the mechanical properties of FSW of AA6061 and AZ-31B and have concluded that the weldment fabricated with D/T as 3.5 yielded better results when compared with its counter parts. Thumb rule generally employed for Friction Stir Welding of Dissimilar aluminium alloys that the tool shoulder diameter is 3 times the thickness of the plates [14,15] and is proved to be unsuccessful in many cases. Hence in this present research work, an attempt has been made to investigate the influences of D/T ratio for dissimilar aluminium alloys of AA6351-T6 and AA5083-H111.

2. EXPERIMENTAL PROCEDURE

Rolled plates of 6.3 mm thickness of AA 6351 in T6 condition and AA 5083 in H111 condition have been cut into required dimensions of 100 mm x 150 mm by power hack saw as shown in Figure 2 and the mechanical properties of the base materials are shown in Table 1. H13 hardened die tool steel of HRC 55 is used as tool material with square pin profile having a pin side length as 6 mm and pin length as 5.8 mm during this entire research work and made into required dimensions. Initially, dissimilar butt joint configuration between AA6351-T6 on Advancing Side(AS) of the joint and AA 5083-H111 on Retreating Side(RS) of joint is obtained by clamping the plates over the bed of the FSW machine. A total of 6 weldments were fabricated by varying the tool shoulder diameter from 13 mm to 28 mm with an interval of 3 mm as shown in Figure 3. Experiments are performed as shown in Table 2.

Table 1 Mechanical Properties of Base Materials

S.no.	Material	Yield strength (*MPa*)	Ultimate Tensile Strength (*MPa*)	% Elongation
1	AA 6351-T6	255.9	326	15.9
2	AA 5083-H111	242.3	303.6	13.2

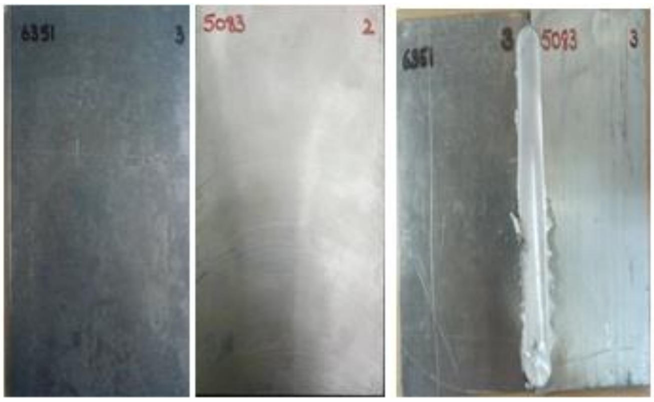


Fig. 2 a) AA 6351-T6 b) AA 5083-H111 c) welded plate

The process parameters considered during this research work are listed in Table 2 and the CAD images of the tools employed in this research work are shown in Fig. 3

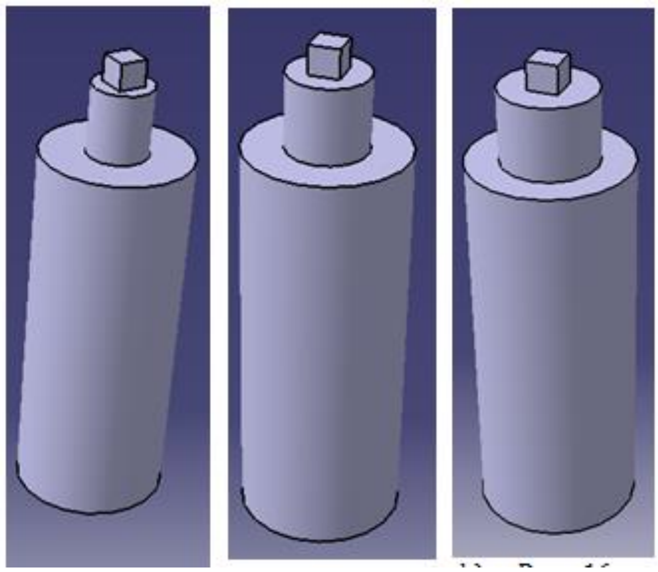
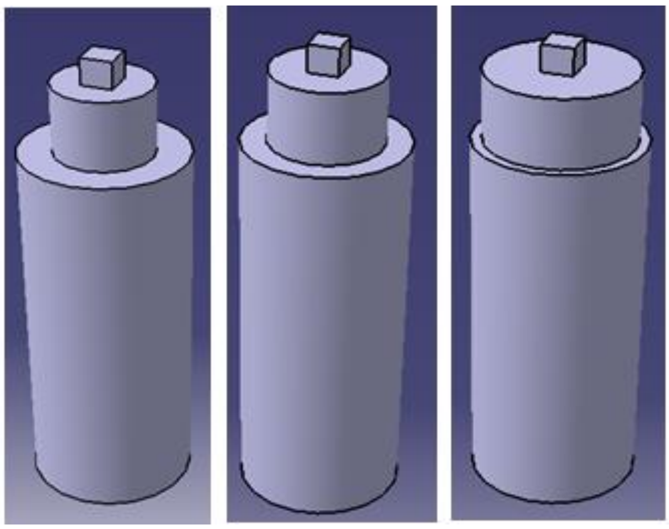


Fig. 3a) D= 13mm b) D= 16mm c) D= 19mm



d) D= 22mm e) D= 25mm f) D= 28mm

Table 2 Design of Experiments

S. No.	Shoulder Diameter (mm)	Plate Thickness (mm)	D/T ratio	Tool Rotational Speed (rpm)	Welding Speed (mm/min)	Axial Load (kN)	Tool Tilt Angle (deg.)
1	13	6.3	2.0	1400	40	8	0
2	16	6.3	2.5	1400	40	8	0
3	19	6.3	3.0	1400	40	8	0
4	22	6.3	3.5	1400	40	8	0
5	25	6.3	4.0	1400	40	8	0
6	28	6.3	4.5	1400	40	8	0

To determine the influence of tool shoulder diameter to plate thickness ratio on the mechanical properties of weldments, Non-Destructive and Destructive Tests like Liquid Penetrant Test (LPT), Bending Test, Macro and Micro structure of the Specimens, Vickers Hardness of the specimens are performed. The specimen for bending test are cut from wire cut EDM according to ASTM- D790 standard. The Specimen cut for macro and micro structure analysis is polished with emery papers of grades 1/0, 2/0, 3/0, 4/0 respectively and etched with a solution of (25ml of HNO_3 + 25 ml of Methanol + 25 ml of HCl + one drop of HF), with an etching time of 45 seconds. Same specimen is used for Vickers hardness test as is used for macro and micro structure analysis.

3. RESULTS AND DISCUSSION

1.Liquid Penetrant Test (LPT): Liquid Penetrant test has been performed on the weldments according to the SAE AMS 2647/ASTM E-165 standard to detect the presence of any surface and subsurface defects of the weldments.

From the results obtained, it is clear that, no surface defects like cracks, porosity are observed over the length of the weldments. This might be due to the optimum axial load is inserted by the tool over the welding plates at the joint interface, preventing any formation of cracks over the surface of the weldments.

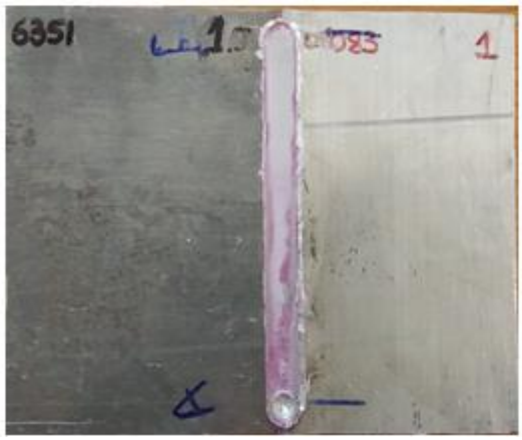


Fig. 4 Dye penetrant applied on weldment

2.Flexural Test: Flexural test has been performed on the weldments to determine the flexural strength of the weldment. The effect of tool shoulder diameter (D) to plate thickness (T) ratio (D/T) on the variation of flexural strength of the weldments is determined. One specimen from each weldment is cut with wire cut EDM according to ASTM D790 standard. Bending test has been carried out to detect defects like root flaw and kissing bond.

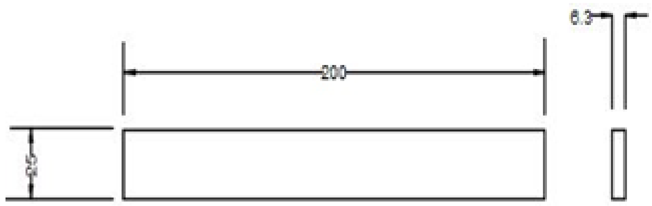


Fig. 5 ASTM D790 standard for Flexural test

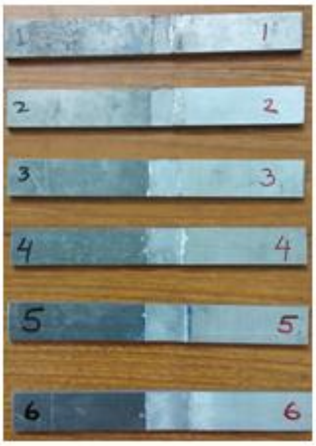


Fig. 6 Flexural specimen before test

Fig. 7 Flexural specimen after test

Flexural test has been performed on the weldments to determine the influence of D/T ratio on quality of the fabricated weldments. The specimens for the test have been cut in such a way that the weld zone is exactly at the center of the specimen. It has been observed from the test such that, the specimen of the welded joints fabricated with tool shoulder diameter to plate thickness ratios as 3.5 and 4.0 have survived the flexural test. No evidences of cracks are observed on these specimens after the test. On the other hand, the weldments fabricated with D/T ratios of 2.0, 2.5, 3.0 and 4.5 have failed the flexural test revealing a poor quality of the fabricated weldment.

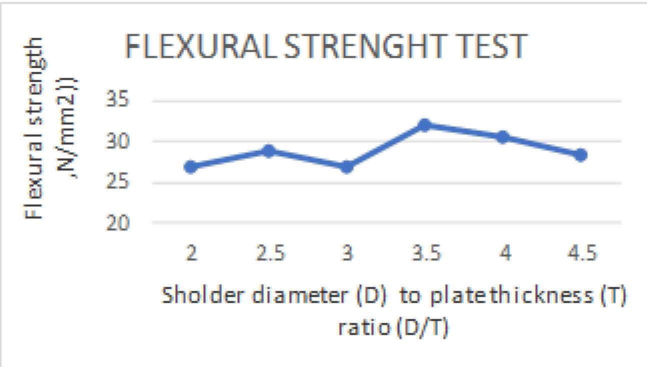


Chart 1 Flexural strength at various D/T ratios

It can be seen from the Chart 1, that the flexural strength of the weldment increased with increase in the tool shoulder diameter(D) to plate thickness (T) ratio and is highest for the D/T ratio of 4.0. With the further increase of D/T ratio from 4.0 to 4.5 results in decrease in flexural strength of weldment. The sudden decrease in the flexural strength of the weldment fabricated with D/T = 3.0 is might be due to presence of any void defect in the specimen cut for test, lowering the strength of the joint. By employing a tool of smaller shoulder diameter results in the improper heat generation in the weld zone. By increasing the shoulder diameter of the tool, thus by providing sufficient heat in the weld zone results in the enough plastic deformation of the material in the weld zone and thus yielding a defect free joint. On the other hand, by employing a tool with larger shoulder diameter results in the excessive heat generation in the weld zone which causes the material to expel from the zone in the form of flash. This in turn results in the formation of defects like tunnel defect, void defect along the length of the joint.

3.Macro structure: Macro structure of the weldments is performed to identify the various zone formation and width of each zone formed and to corelate them with the process parameters considered.

It is evident from Table 3, that the weldments fabricated with D/T as 2.0 and 2.5 yielded joints with voids in the nugget zone. This might be due to, insufficient heat generation in the joint interface during the welding phase resulting in improper mixing of material in the nugget zone. For the weldments fabricated with D/T ratio as 3.0 and 3.5, no such evidence of any defect is found.

Table 3 Macro structure of weldments

S. No.	D/T ratio	Image of Macro structure	Observations
1	2.0		Void observed at the Nugget Zone
2	2.5		Void observed at the Nugget Zone
3	3.0		Defect free joint
4	3.5		Defect free joint
5	4.0		Defect free joint with widened welding zones

6	4.5		Defect free joint with more widened welding zones

This is probably due to sufficient heat generation in the weld zone by employing appropriate geometry of the tool producing sufficient heat generation in the weld zone. The welding zones are increased in terms of width on either side of the weldment. In the case of weldments fabricated with D/T as 4.0 and 4.5, although no macroscopic defects are not present in the weldment, presence of such widened welding zones is not desirable. According to T. Azimzadegan and S. Serajzadegan [16] creation of some of the defects during FSW may be attributed to discontinues in the velocity field around the rotating tool. As the material flows around the advancing side of the pin, it may correspond to high or low rotational speeds, resulting in a typical tunnel or wormhole defect.

4.Micro structure: Micro structure analysis of weldments is carried out to understand the flow of material under the varying operating conditions i.e. under varying D/T ratios resulting in different processing temperatures. The following figure shows the micro structure images of nugget zone for each weldment. According to S. Malarvizhi and V. Balasubramanian [13], the frictional heat is created by the rubbing of the tool shoulder and the mechanical stirring of material by tool probe. The weld zone consists Dynamically recrystallized material from welding plates. Due to this severe plastic deformation, solid state material flow takes place and the mixed pattern of the material can be seen from above micro structural images.

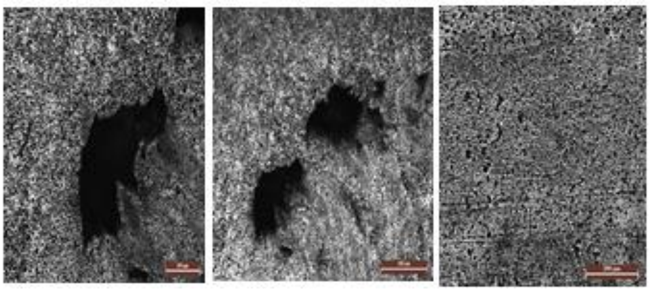
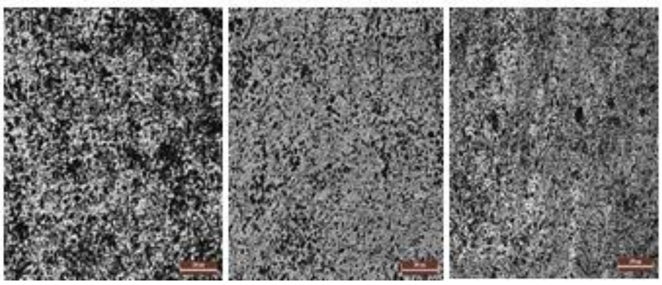


Fig. 8 a) D/T= 2.0 b) D/T= 2.5 c) D/T= 3.0



d) D/T= 3.5 e) D/T= 4.0 f) D/T= 4.5

5.Vickers Hardness test: Vickers Hardness Test has been performed on the cross section of the weldments to understand the hardness variation along the length of the joint fabricated. It is considered as a thumb rule, that the hardness of the weldment depends on the size of the grain. The following figure shows the variation in the hardness across the length of the joint.

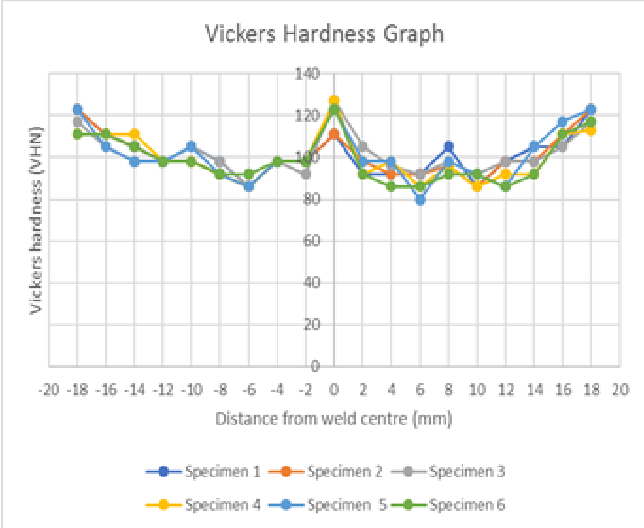


Chart 2 Vickers hardness profile across the weldment

It is observed from Chart 2, that maximum hardness is observed in the nugget zone in of weldment and is might be due to Dynamic Recrystallization in grain structure during the phase of welding. Minimum hardness is observed due to the Heat Affected Zone of the weldments, this might be due to processing temperatures that effect the Heat Affected Zone on both sides of weld zone due to increase in the size of the grains. The precipitate distributions and the consequent hardness profiles are affected mainly by local thermal hysteresis. During welding, the frictional heat is generated at the weld center by the rotating head-pin and on the upper surface of the weld zone by the rotating tool shoulder [6]. During the FSW process the material from the advancing side of the joint is excavated from the front face of the tool and is deposited in the retreating side of the tool and flows from rear of the tool to front of the tool to fill the vacancy formed during the excavation of the material [17]. Stir zone consists of mainly three regions i) Un Mixed Region (UMR) ii) Mechanically Mixed Region (MMR) iii) Stirring induced Plastic Flow Region (SFPR) [18]. The variation in the hardness in the stir zone is mainly due to the presence of these regions and is mainly influenced by the type of tool pin profile employed for the fabrication of the joint.

CONCLUSIONS

In this present research work, an attempt has been made to investigate the influences of tool shoulder diameter to plate thickness ratio (D/T) on properties of FSW of AA 6351-T6 and AA 5083- H111 has been made and following conclusions are drawn:

1. Results of Liquid Penetrant Test revealed that all the weldments fabricated are free from surface defects like cracking, porosity.

2. Weldments fabricated with D/ T as 3.5 and 4.0 survived bending test implying sufficient heat generation in the weld zone during welding phase and better refinement of grains in the weld zone.

3. Macroscopic structures of the weldments revealed that tunnel defects are present in the weldments fabricated with D/T as 2.0 and 2.5 implying poor heat generation in the weld interface obtained due to usage of under matched tool for welding.

4. Microscopic images of the weldments revealed that proper plasticizing of the material at the weld zone was achieved for the weldments fabricated with D/T as 3.0, 3.5, 4.0 and 4.5.

5. A classical "W" hardness profile was achieved during the hardness profile measurement along the length of the weldments fabricated. The results revealed that, dynamic recrystallization of material is achieved for the weldments fabricated with D/ T as 3.5 and 4.0.

ACKNOWLEDGEMENT: I am thankful to my guide Mr. M. S. Srinivasa Rao for his continuous support and guidance throughout this research work and Dr. G. Madhusudan Reddy, Outstanding Scientist, grade "H", Head of Metal Joining Group (MJG), DMRL Hyderabad, M. Suresh Kumar, MJG, DMRL Hyderabad for permitting me to fabricate weldments at their organization.

REFERENCES:

[1]. Lohwasser D, Chen Z, "Friction Stir Welding: From basics to applications". Elsevier 2009.

[2]. Mehta KP, Badheka VJ, "A Review on Dissimilar Friction Stir Welding of coper to aluminium: Process, Properties and variants". Materials and manufacturing processes 2016; 31 (3): 233-254.

[3]. W.M. Thomas, E.D. Nicholas, J.C. Needham, M.G. Murch, P. Temple smith and C.J. Dawes, G.B. Patent Application No. PCT/GB92/02203, GB Patent Application No. 9125978.8, December 1991, and U.S. Patent No. 5,460,317, October, 24, 1995.

[4]. What is friction Stir Welding? Dr. Christian Widener Director, Arbegast Materials Processing and Joining Laboratory, South Dakota School of mines and Technology.

[5]. Heurtier P, Jones MJ, Desrayaud C, Driver JH, Montheillet F, Allehaux D, "Mechanical and thermal modelling of friction stir welding". J Matter Process Technol 2006; 171:348-57.

[6]. R. Palanivel, P. Koshy Mathews, N. Murugan, I. Dinaharan, "Effect of tool rotational speed and pin profile on microstructure and tensile strength of dissimilar friction stir welded AA5083-H111 and AA6351-T6 aluminium alloys." Materials and design 40 s (2012): 7-16.

[7]. D.M. Rodrigues, C. Leitao, R. Louro, H. Gouveia, and A. Loureiro, "High speed friction stir welding of aluminium alloys". Science and Technology of Welding and Joining.

[8]. Sang-Won Park, Tae-Jin Yoon and Chung-Yun Kang, "Effects of the shoulder diameter and weld pitch on the tensile shear load in friction-stir welding of AA6111/AA5023 aluminium alloys", Journal of Materials Processing and Technology 241 (2017) 112-119.

[9]. M. Koilraj, V. Sundareswaran, S. Vijayan and S.R. Koteswara Rao. "Friction stir welding of dissimilar aluminium alloys AA2219 to AA5083 – Optimization of process parameters using taguchi technique." Materials and design 42 (2012) 1-7.

[10]. Aman deep singh, Jasbir singh Ratol and Niraj Bala, "Effect of welding parameters on tensile behavior of friction stir welded joints of AA6082-AA5083 alumium alloys." International journal of surface engineering and materials technology, Vol. 2 No.1 Jan-June 2012, ISSN:2249-7250.

[11]. S. Ravi Kumar, V. Seshagiri Rao and R.V. Pranesh, "Effect of Process Parameters on Mechanical Properties of Friction Stir Welded Dissimilar Materials between AA 6061-T651 and AA7075-T651 Alloys". International Journal of Advanced Mechanical Engineering. ISSN 2250-3234 Volume 4, Number 1 (2014), pp. 101-114.

[12]. Kush P. Mehta and Vishvesh J. Badheka, "Effects of tool pin design on formation of defects in dissimilar friction stir welding". Proceedia Technology 23 (2016) 513-518.

[13]. S. Malarvizhi, V. Balasubramaniyan, "Influences of tool shoulder diameter to plate thickness ratio (D/T) on stir zone formation and mechanical properties of friction stir welded dissimilar joints of AA6061-AZ31B magnesium alloys." Materials and design 40 (2012) 453-460.

[14]. Balamurugan K G, and Mahadevan K J Manuf Process 15 (2013) p 659.

[15]. Santella M L, Engstrom T, Storjohann D, and Pan T Y, Sci Matter 53 (2005) p 201.

[16]. T. Azimzadegan and S. Serajzadegan, "An investigation into Microstructures and Mechanical Properties of AA7075-T6 during Friction Stir Welding at Relatively High Rotational Speeds". JMEPEG (2010) 19:1256–1263.

[17]. Murr LE, Liu G, McClure JC, "A TEM study of precipitation and related microstructures in friction stir welded 6061 aluminum". J Mater Sci 1998; 33:1243–51.

[18]. Mishra RS and Ma ZY,(2005) Friction Stir Welding and Processing Mater Sci and Eng R: Reports 50 (1-2):1-78.

[19]. Onyang JH, Kovaceivic R, "Material flow and microstructure in the friction stir butt welds of the same and dissimilar aluminium alloys", J Mater Eng Perform 2002; 11:51-3.

[20]. https://www.researchgate.net/figure/Schematic-diagram-shows-friction-stir-welding-process-and-terminology5_fig7_261804701.