Effect of Tool Shoulder Diameter (D) to Plate Thickness (T) Ratio (D/T) on Quality of Friction Stir Welding of Dissimilar Aluminium Alloys

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Abstract - *Aluminium and its corresponding alloys offers a wide range of advantages over conventionally used metals in terms of high strength to weight ratio, excellent corrosion resistance, good thermal and electrical conductivity, good machinability etc. making them as a prior choice in fields of aerospace, defense, automobile, marine industries which strive for high strength materials at relatively lower weight. Friction Stir Welding is relatively new entrant in the domain of solid state welding technique and is ideal for the welding of Aluminium and Magnesium alloys which yield inefficient weldments when fabricated with conventional welding techniques. In this present research work, the effect of D/T ratio on quality of Friction Stir Welded dissimilar joints of AA6351-T6 and AA5083-H111 is investigated by keeping all the other process parameters as constants. The quality of the weldments fabricated is evaluated by conducting tests like X-Ray Radiography, Tensile test and Izod Impact test. Results revealed that the joint fabricated with Tool shoulder diameter to Plate Thickness ratio as 3.5 yielded defect free joint and has good mechanical properties when compared with its counterparts.*

Key Words: AA6351-T6, AA5083-H111, Dissimilar butt joint configuration, Friction Stir Welding, Izod impact test. Plate thickness (T), Tensile test, Tool shoulder Diameter (D), X-ray Radiography.

1. INTRODUCTION

Joining of dissimilar metals is of greater importance in different sectors of electrical, chemical, nuclear, aerospace, petrochemical etc. as the benefits from both the metals can be achieved. Dissimilar welding of AA6351 and AA5083 is of greater importance in aerospace and structural applications. Dissimilar welding of these two alloys is generally completed in the industries by using conventional welding techniques like LBW, EBW and GTAW [1]. Even though the use of LBW, EBW for welding dissimilar materials results in narrow weld region but the high reflectivity of the Aluminium causes the LBW process as low efficient. The use of conventional welding techniques of dissimilar metals causes enormous difficulties due to vast differences in physical, chemical, mechanical and metallurgical properties between the joining materials. It further creates problems like porosity, use of under matched filler metal, lack of penetration, solidification cracking and results in the formation of larger amounts of Inter Metallic Compounds (IMCs). The presence of these IMCs in the weld zone seriously deteriorate the quality of the weldments [2,3]. Thus, solid state welding techniques, which generally overcome these difficulties and are preferred over conventional welding techniques. Friction Stir Welding is a relatively new solid-state welding technique invented at TWI, in the year of 1991[4]. It uses a non-consumable rotating tool of having hardness greater than the hardness of the materials to be joined is plunged at the faying surfaces of the joint and is traversed over the length of the joint. The frictional heat generated between the tool and workpiece is sufficient to plasticize the material in the joint interface. This plasticize material is stirred by the pin of the tool and the degree of material mixing and the quality of weldments fabricated depends on the pin profile. The process of Friction Stir Welding can be considered as a combination of forging and extrusion processes [5].

As the tool traverses along the length of the joint, the plasticized material in the advancing side of the weldment is drag by the front face of the tool and is deposited at the retreating side of the weldment by the back face of the tool [5]. Even though the tool consists of shank, shoulder and pin; the quality of the weldment fabricated mainly depends on the tool geometry implying shoulder diameter, pin diameter, pin profile and length of pin besides other process parameters like tool rotational speed (rpm), transverse speed (mm/min), Axial load (kN), Tool tilt angle (deg.). The shoulder of the tool acts as "lid over pot" to prevent the escape of plasticized material from the weld zone during the process of welding and it even it acts as major source of friction heat generation for the accomplishment of welding.

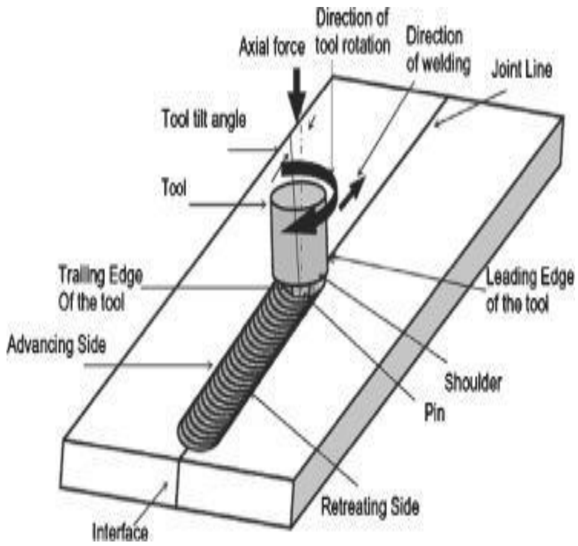

Fig.1 Schematic diagram of Friction Stir Welding [21].

R. Palanivel et al. [6] studied the effect of tool rotational speed and pin profile on microstructure and tensile properties of the weldments of AA5083-H111 and AA6351-T6 and concluded that Tool rotational speed of 950 rpm and square pin profile has yielded better tensile strength. R. Palanivel et al. [7] studied the mechanical and metallurgical properties of Friction Stir Welding of AA5083-H111 and AA6351-T6 and concluded that welding speed of 63mm/min, by keeping all other process parameters as constant yielded defect free weldments and most of the tensile specimens followed ductile fibrous mode of failure during testing. M. Koilraj et al. [8] studied the Friction Stir Welding of AA2219 and AA5083 and concluded that rotational speed, tool geometry and D/d ratio have a major influence on the quality of the weldments fabricated and ANOVA results of their study demonstrated that the D/d ratio is the most influencing process parameter and the material on the advancing side of the joint dominates the weld zone. M. Elangovan et al. [9] studied the effect of tool pin profile on microstructure and tensile properties of Friction Stir Welded dissimilar joints of AA6061-AA5086 aluminium alloy joints and have concluded that the use of threaded pin profile tool contributes to better flow of material between two alloys and results in formation of defect free weldments. They corelated the hardness of weldments in terms of with grain size and finer grains in weld zone yielded high hardness values. Aman deep singh et al. [10] studied the effect of welding parameters on tensile behavior of FSW joints of AA6082 and AA5083 and concluded that quality of weldments fabricated mainly depends on the process parameters like Tool rotational speed, feed, shoulder diameter and pin depth. N. Shanmuga Sundaram and N. Murugan [11] have studied the effect of process parameters and tool pin profile on tensile strength and tensile elongation of dissimilar FSW of AA2024-T6 and AA5083-H321and have concluded that joint fabricated with hexagonal tool pin profile have yielded highest tensile strength and tensile elongation when compared with it counterparts. D.M. Rodrigues et al. [12] have studied the FSW of AA5083-H111 and AA6082-T6 and developed a methodology for determining suitable levels of process parameters. S. Malarzhvi and V. Balasubramanian [13] investigated the effect of shoulder diameter to plate thickness ratio on AA6061 and AZ31B Magnesium alloy and have concluded that D/T ratio of 3.5 yielded superior tensile properties. P. Sevvel and V. Jaiganesh [14] have studied the influences of D/T ratio on mechanical properties and nugget zone characteristics on FSW of dissimilar Magnesium alloys and have concluded that D/T = 3.5 yielded sound welds and having superior mechanical properties. Generally, the thumb rule employed during FSW for either similar or dissimilar metals as "3" but it is proved to be unsuccessful in most of the cases. Moreover, the available literature on the characterization on FSW of AA6351-T6 and AA5083-T6 is relatively low. Hence in this present research work, an attempt has been made to investigate the influences of tool shoulder diameter to plate thickness ratio on the quality of the weldments.

2. EXPERIMENTAL PROCEDURE:

6.3 mm thick plates of AA6351-T6 and AA5083-H111 were cut in required dimensions as 150 mm x 100 mm with power hacksaw. The plates are initially secured in dissimilar butt joint configuration by keeping AA6351-T6 on advancing side and AA5083-H111 on retreating side by employing mechanical clamps over the bed of FSW machine. The tool employed for the present work is made of H13 hardened tool steel having hardness of 55HRC. The tools are then made into required dimensions by varying shoulder diameter from 13 mm to 28 mm with an interval of 3 mm. Square pin profile of 6mm side with pin length of 5.8mm have been selected for welding. As such a total of 6 weldments are fabricated with D/T ratio varying from 2.0 to 4.5 with an interval of 0.5mm. All the weldments are fabricated at DMRL Hyderabad, by keeping tool rotational speed as1400 rpm, welding speed as 40mm/min, Axial load as 8 kN, Tool tilt angle as 0 degrees as constants for the entire work.

Table 1 Chemical Composition of AA6351-T6

Cu	Mg	Si	Fe	Mn	Zn	Ti	Al
0.038	0.786	1.252	0.326	0.598	0.018	0.020	Remaining

Table 2 Chemical composition of AA5083-H111

Cu	Mg	Si	Fe	Mn	Zn	Ti	Cr	Al
0.043	4.430	0.173	0.302	0.580	0.136	0.015	0.080	Remaining

Table 3 Chemical composition of H13

C	Mn	Si	P	S	Cr	Mo	Ni	V	Fe
0.331	0.321	10183	0.014	0.011	5.127	10176	0.049	0.989	Remaining

Fig. 2 H13 tools fabricated with shoulder diameters increasing from 13 mm to 28 mm with an interval of 3 mm (from left to right).

In this present research work, tool rotational speed is taken as 1400 rpm, welding speed as 40 mm/min, axial load as 8kN, tool tilt angle as 0 degrees. All these process parameters are kept as constant. X-Ray radiography a Non-Destructive test has been performed on the weldments to identify the internal defects in the weldments. The mechanical properties of the weldments fabricated are evaluated by Tensile test and Izod Impact test. Two specimens from each of the weldment for tensile test and one specimen from each weldment for Izod impact test have been cut with wire cut EDM.

2. RESULTS AND DISCUSSION:

1. X- Ray Radiography test: The test has been performed according to ASME Section IX Acceptance Standard Code and the specifications of the apparatus used for the test can be tabulated as follows:

Table 4 Specifications of X-Ray Test apparatus

Source	X-Ray
Current	0.3mA
Voltage	100kV
Experiment time	0.8 min
Film used	MX-125
Density of the film	1.8 to 3
Sensitivity of the test	2%
Technique used	SWSI

Table 5 Results of X-Ray Radiography test

S.no.	D/T ratio	X-Ray film	Observations
1	2.0		Tunnel defect in the overall length of weldment
2	2.5		Voids present at beginning and end of the length of weldment
3	3.0		Voids present at beginning and end of the length of weldment
4	3.5		Defect free joint
5	4.0		Defect free joint
6	4.5		Defect free joint

According to Saravanan et al. [15] optimal heat energy produced in the weld joint interface results in a defect free joint. They also noted that at constant travel speed, as tool rotational speed increases, energy input increases and results in the decrease of axial force and torque required to deform the material in the joint interface. Thus, the material was more softened with increasing energy input, forming a more sticking condition of plasticized material to surface of the tool. Under such conditions, material reaches to a state of abnormal stirring with a very low downward force and torque which may lead to formation of cavity. When the heat input is low, the amount of heat in the weld interface is insufficient to plasticize the weld zone, resulting in the formation of a cold weld as shown in case of D/T of 2.0. A grove defect [16] is observed in advancing side of the joint. This can seriously degrade the mechanical properties of weldments. Previous studies [17,18] revealed that groove like defects are primarily formed when the heat input during FSW is insufficient. In this case, the material could not flow to fill up the gap generated by the tool pin as in case of D/T 2.5 and 3.0. Defect free joints are obtained for weldments fabricated with D/T as 3.5, 4.0, 4.5.

2. **Tensile Testing:** Tensile test has been performed on the weldment to determine yield strength, ultimate tensile strength, % elongation of the weldment. Two tensile specimens from each of the weldment have been cut with wire cut EDM according to ASTM E8/E8-M-16a standard and the average of two of the readings is considered. The tensile test has been performed on the specimen with Universal Testing Machine of 400kN and with unidirectional tensile loading. A gauge length of 50 mm has been marked on the specimen to determine % elongation that a specimen undergo after the test.

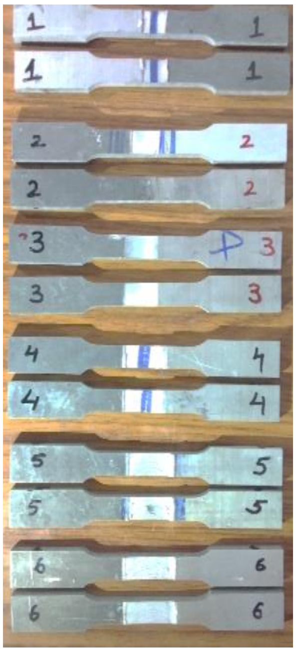

Fig. 3 Tensile specimen before test

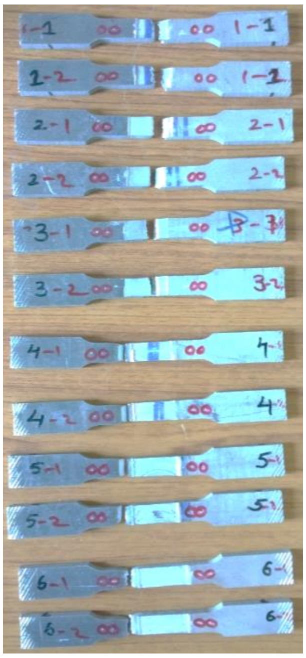

Fig. 4 Tensile specimen after test

According to R.Palanivel et al. [6] factors that contribute the tensile strength of the dissimilar aluminium FSW joints are : a) Presence of macroscopic defects in weld zone b) amount of mixing of plasticized material at the joint interface and degree of plastic flow c) Size of grains in Heat Affected Zone (HAZ) d) degree of dissolution and over aging of precipitates. The maximum ultimate tensile strength obtained in case of weldment fabricated with D/T =3.5 is about 66% of ultimate tensile strength of AA5083-H111. It can be seen from the above Figure [4] that most of the specimens that are fabricated with D/T = 2.0, 2.5, 3.0 failed in the nugget zone representing the inefficient weld formed between the joining materials. This might be due to improper heat generation in the weld zone due to the use of smaller shoulder diameter tool. On the other hand, in case of weldments fabricated with D/T = 3.5, 4.0, 4.5 all the specimens failed in the Heat Affected Zone (HAZ) of AA6351-T6. During the process of welding, the heat generated in the weld region due to the friction between tool and work pieces causes in dissolution of precipitates in the HAZ region of AA6351-T6 (heat treatable aluminium alloy) and making it as a lower strength region in the entire weld section. The failure of tensile specimens near TMAZ of 6351-T6 may be attributed to the dissolution and over aging of the precipitates [6].

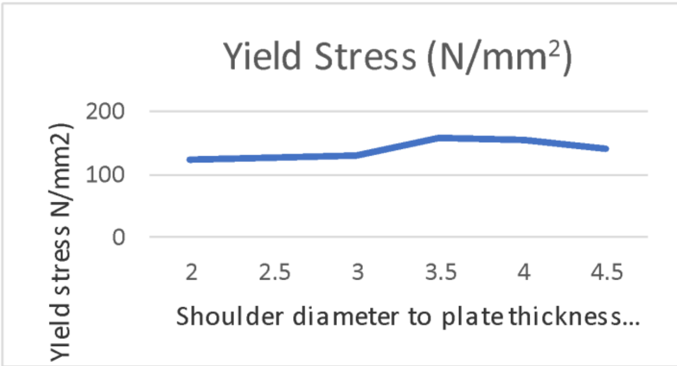

Fig. 5 Yield Stress of AA6351- T6 and AA5083-H111

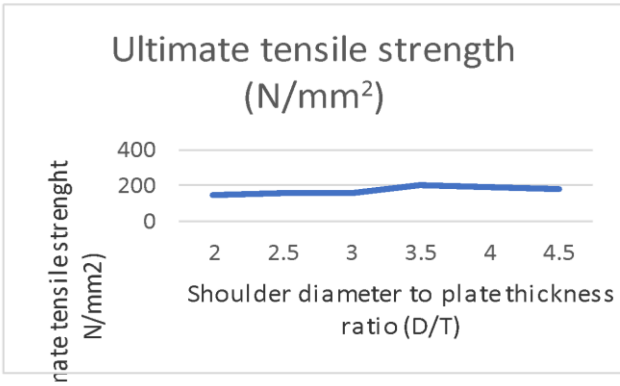

Fig. 6 Ultimate tensile Stress of AA6351- T6 and AA5083-H111

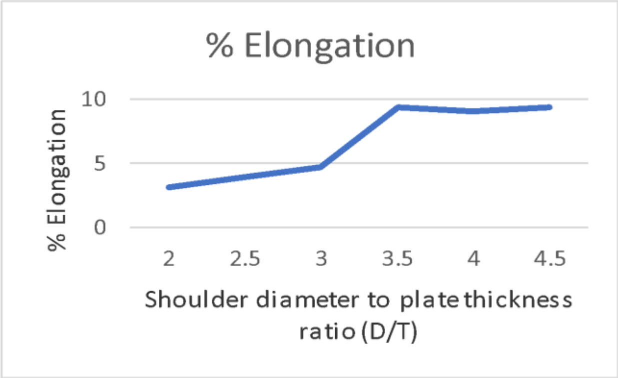

Fig. 7 % Elongation of AA6351- T6 and AA5083-H111

It can be seen from the above graphs that a similar pattern is followed in case of plots for yield stress, ultimate tensile strength, % elongation. It can be observed that the tensile strength of the weldments increased with an increase in D/T ratio from 2.0 to 3.5. Further increase in the D/T ratio from 3.5 to 4.5 results in decrease in the tensile strength, representing excessive formation of heat in the weld zone causing excessive deformation of plasticized molten material from the weld zone resulting in the loss of material and formation of a relatively weaker joint.

3. Izod impact test: Izod impact test has been performed on the weldments to determine the impact strength of the weldments. One specimen from each of the weldment has been cut with wire cut EDM according to ASTM E23-16b.

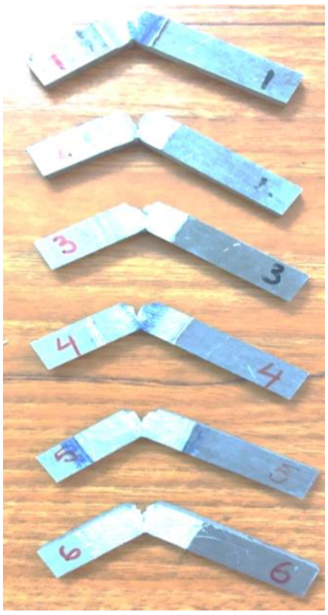

Fig. 8 Impact specimen before test Fig. 9 Impact specimen after test

It can be seen from the figure [9] that all the specimens are failed in a fibrous ductile fracture fashion indicating good ductility of the fabricated weldments. Even the plot of impact energy of the specimens with D/T followed a same pattern as that of in case of tensile strength graph.

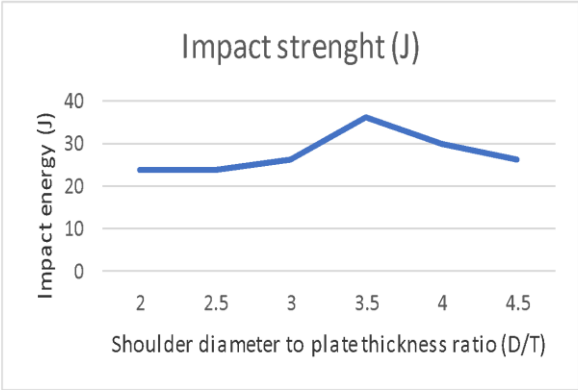

Fig. 10 Impact strength of AA6351-T6 and AA5083-H111

The optimum values of tool rotational speed and welding speed determines the frictional heat per unit length along the joint interface and will lead to proper material mixing and flow of the plasticized material in the weld zone resulting in finer grains, thus improving the mechanical properties of the joint (which is the case in the weldment fabricated with D/t as 3.5). On the other hand, by employing un suitable process parameters, causes higher hat conditions as in case of joins fabricated with D/T as 4.0 and 4.5 resulting a slower cooling rate and forming coarser grains, which seriously deteriorate the properties of weldments [19, 20]. It can be observed from the fig.10 that the impact energy of the specimens increased with the increase with D/T from 2.0 to 3.5. The reason for this increase in impact energy might be due to as the shoulder diameter increased from 2.0 to 3.5, resulting in the proper heat generation in the weld zone causing proper material flow in the joint interface and better mechanical mixing of the plasticized material yielding sound weldments. As the tool shoulder diameter further increased from 3.5 to 4.5, there is an increased amount of heat generation in the weld zone causing excessive deformation of the plasticized material in the weldment resulting in lower strength weldments.

CONCLUSIONS: The influence of tool shoulder diameter to plate thickness ratio (D/T) on the quality of the weldments fabricated has been evaluated. The conclusions drawn from this research work can be listed as follows:

1. X-ray radiography test revealed that weldments fabricated with D/T ratio as 3.5, 4.0, 4.5 yielded defect free joints representing proper plasticizing and flow of material in the weld zone.

2. Better tensile properties of the weldments like highest yield strength, tensile strength, elongation of the specimen was observed for the weldment fabricated with D/T ratio as 3.5.

3. The weldment fabricated with D/T ratio as 3.5 has yielded better Impact strength when compared with its counterparts.

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