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Experimental Analysis and Optimization of Process Parameters on Friction Stir Welding of Aluminium (AA6061 T6) Alloy and ABS Plastic

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Abstract: Friction stir welding is a solid-state joining process which can produce high quality welds of different components with either similar or dissimilar materials which are difficult to weld by conventional fusion welding techniques. Friction stir welding utilizes frictional heating combined with forging pressure to produce high strength bonds virtually free of heat affected defects, even in case of dissimilar metal to polymer sheets. Material joining are gaining a great deal of attention in several industries, in particular where a trade-off between reduced weight, improved performance and cost reduction is required. Combination of ABS plastic and aluminium alloys is an alternative solution to this problem. This project aims to weld plates of aluminium (AA6061 T6) alloy and ABS sheet in the lap joint configuration. Optimize the process parameters using Taguchi method for higher shear strength and shore D hardness and to analyse the effect of process parameters such as tool rotational speed, welding speed and shoulder diameter on the output parameters of friction stir weldment. The feasibility of the process was identified by means of microstructure and mechanical analysis.

Keywords: FSW, ABS plastic, AA6061 T6 Aluminum Alloy, Shore D hardness, Shear strength

I. INTRODUCTION

Recently, especially in automotive industries, widely used metals like steel are being replaced by the new lighter nonferrous materials such as magnesium and aluminium alloys. In addition, polymer technology developments led into modern structures. Modern thermoplastic materials as a specific type of polymer for having reshaped properties, are used in different engineering applications, such as automotive and aerospace industries, due to their lower cost, high toughness and stress ratios compared to their weight. These are one of the most commonly used materials in many industrial applications due to their easy manufacturing process. Even though thermoplastic materials offer wider choice of design or process, manufacturing of bigger and complex parts frequently need joining to different materials and alloys. These materials can be integrated with the polymer metal hybrid technologies in a monadic component. Studies and developments of such hybrid structures which led to the reduction of the weight of structures is increased in recent years. Lower fuel usage and co_2 emission are the main factors that persuade the engineers to produce these lightweight structures.

Joining of polymer-metal hybrid structures is more difficult by traditional welding process due to their big difference in physical and chemical features. Metal polymer joining limitations such as surface treatments and adhesive bonding time, motivated novel joining techniques.

FSW's success is due to a relatively simple concept. The process consists of a non-consumable rotating tool having a pin on a shoulder surface. As a first step, the rotating tool penetrates into the joining surface until the shoulder of the tool touches the top surface of the base metal. Then the tool transverses along the joining line under a load. The combined translation and rotation of the tool results in high frictional heating between tool and workpiece and this will change the weld zone to plastic stage and thus form a strong defect-free weld upon cooling. Since there is significant difference in mechanical as well as thermal properties of AA6061 T6 and Acrylonitrile Butadiene Styrene, the dissimilar FSW of these two materials is difficult due to their variation in material properties.

II. OBJECTIVE

The aim of this thesis to develop the fundamental knowledge on the possibilities to apply friction stir welding techniques to join an ABS plastic to Aluminium alloy sheet by using the conventional FSW method. In order to understand the metal-thermoplastic welding, the effect of welding parameters was investigated.

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III. LITERATURE SURVEY

Hamed Aghajani Derazkolaa et al (2018) The possibility of dissimilar friction stir welding between AA5058 aluminium alloy and polycarbonate (PC) in lap joint design was assessed.
Yongxian Huanga et al. (2018) conveys the material flow patterns highly depended upon the geometry of the tool pin, welding temperature, material flow and axial force.
Surjeet Singh et al. (2017) focuses on the success and strength of these joints mainly depends on the dimension of the joined area, the quality of the penetration of the teeth produced.
Anjal R. Patela et al (2018) studies the effect of relationship among the size of the Al anchor and the tool rotational speed. They have identified that while Increasing welding speed resulted in the increase in the size of the Al anchor.
Francesco Lambiasea et al (2017) investigates the importance of the tool geometry of the tool pin, welding temperature, material flow and axial force. And also identified that the transportation or material flow is highly influenced by welding parameters and peak temperature.

IV. EXPERIMENTAL METHODS

The experimental setup consists of a vertical milling machine (Batliboi FA3V) and a welding fixture which is to be mounted on the work table to carry out friction stir welding. An AA6061 T6 aluminium-magnesium alloys and Acrylonitrile butadiene styrene (ABS) polymer sheets utilized as the raw base materials. These plates were cut in the dimensions of 130×110×3mm. AA6061 T6 alloy is commonly used for automobile sheet panels and ABS is a special thermoplastic which shows good thermal and chemical stability that is usually being used for external and internal parts of automobile body. These initial materials have potential application in automobile body structure. The physical properties of the selected initial materials are presented in Table 1.

Table 1. physical properties of AA6061 T6 alloy and ABS polymer

Base material	AA6061 T6	ABS
Density(kg/m3)	2660	1010
UTS(MPa)	290	50
Elongation (%)	25	75
Shear strength (MPa)	207	101
Microhardness (HV)	50	-
Hardness (shore d)	-	72
Glass transition temp (Tg)	-	105
Melting point (°c)	580	200
Thermal conductivity(w/mk)	151	0.188

Fig. 1. Experimental setup

A. Vertical Milling Machine

The conventional vertical milling machine having spindle speed up to 2000 rpm, feed range of 14-900 mm/min and spindle swivel from -45^0 to 45^0 was used for the present work. Automatic table movement by engaging the lever and manual movement is also possible in this machine. The experimental setup is shown in Fig. 1.

B. Fixture

The fixture consists of mild steel plate of thickness 18 mm having 200 mm X 200 mm size is prepared for fixing the base plates firmly. Two mild steel flat strips are used for holding the work pieces with eight bolts. The plate along with the strip arrest all the degrees of freedom.

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C. FSW Tool

In this present study, an FSW tool with plane shoulder along with a tapered probe or pin is used to increase the contact area of the probe with workpiece. This will lead to an increase in the frictional heat causing more plastic deformation. the tapered probe also promotes a high hydrostatic pressure in the weld zone, which is extremely important for enhancing the material stirring and the joint strength.

1) Tool Material: Tool steel is the most widely used tool material for aluminium alloys which possesses a combination of high temperature strength and stiffness. The selection of tool material is determined by the approximate temperature reached during processing of Al alloy (in the range of 500-600 ^{0}C). Therefore, any tool steel with tempering temperature higher than 600 ^{0}C is ideal for FSW tool. In this study, the tool material was chosen as Hot Die Steel (H13 tool steel), which was heat treated to a hardness of 50 HRC.

2) Tool Geometry: Tool pin profile was selected as tapered cylindrical shape. The selection of pin length is based on workpiece thickness, which is to be approximately 0.70-0.75 times of total workpiece thickness. In this present study three different shoulder diameter of 18,20,22mm and having same taper pin Figure 1 shows the view of FSW tool. It is having 18mm shoulder diameter and a tapered pin. The pin diameter is 6 mm diameter on the top (nearer to shoulder surface) and 4 mm at the bottom surface. Length of the pin used was 4.2 mm in order to avoid full penetration plate. The FSW tool is shown in fig.2.

Fig. 2. FSW tool

D. Workpiece

The weld coupon was prepared for lap joint configuration with 130x110 x 3 mm dimension so as to get a total width of 177 mm in order to tightly fit in the fixture and for readily preparing the workpiece for doing the tensile shear testing according ASTM D5868 standard. the aluminium alloy sheet were placed as bottom plate and the ABS sheet as top plate when arranged in lap joint configuration.

E. Shear and Hardness Testing Machines

Shear test samples were prepared from the welded sheets as per ASTM D5868. Test specimens were carried out on a SHIMADZU AUTOGRAPH testing machine with strain rate of 2 mm/min. The shore D test measures the penetration of a specified indentor in to the material under specified conditions of force and time. In this experiment, the hardness of upper plate or ABS sheet were measured through the joint line and the mean values were recorded. After successful pilot experiment, these upper and lower plate configurations were selected for further investigations, with design of experimentation based on Taguchi L27 design of experiments is listed in table 2.

Table 2. Taguchi L27 orthogonal array

Parametric conditions	Tool Rotational Speed(rpm)	Feed rate (mm/min)	Diameter (mm)
A1	500	14	18
A1	500	14	18
A1	500	14	18
A2	500	28	20
A2	500	28	20
A2	500	28	20
A3	500	40	22
A3	500	40	22
A3	500	40	22
A4	710	14	20
A4	710	14	20
A4	710	14	20
A5	710	28	22
A5	710	28	22
A5	710	28	22
A6	710	40	18

A6	710	40	18
A6	710	40	18
A7	1000	14	22
A7	1000	14	22
A7	1000	14	22
A8	1000	28	18
A8	1000	28	18
A8	1000	28	18
A9	1000	40	20
A9	1000	40	20
A9	1000	40	20

V. RESULT AND DISCUSSIONS

After successful experimental runs for each combination of metal to polymer according to Taguchi L27 orthogonal array, the result for different output parameters like shore D hardness and Shear strength at weld joint have been recorded in table 3.

Table 3. Shore D Hardness and shear strength (MPa) of welded joint

Parametric conditions	Average shore D Hardness	Average shear strength (MPa)
A1	53	11.5508
A1	50	10.6491
A1	48	10.8385
A2	55	10.9880
A2	57	10.9512
A2	53	10.8684
A3	58	10.6531
A3	61	10.6433
A3	60	10.8347
A4	57	12.8038
A4	50	13.0535
A4	54	12.8782
A5	61	10.8125
A5	63	9.7108
A5	58	9.3745
A6	54	11.4588
A6	52	12.0735
A6	53	11.3094
A7	51	9.8943
A7	47	10.9520
A7	49	9.0541
A8	59	11.2856
A8	57	11.2893
A8	54	11.0680
A9	56	11.8071
A9	55	10.5621
A9	50	11.4327

A. Taguchi Parametric Analysis

1. Effect of Process Parameters on Shore D Hardness

The observation of Shore D (Durometer) hardness of the welded joint is recorded in Table 3 as shown above. The output obtained for Shore D hardness of welded specimens were analysed on Minitab software under the condition larger the better is shown in Figure 3. It shows that maximum hardness is obtained at parametric condition of shoulder diameter 22 mm, feed rate 28 mm/min and rotational speed of 710 rpm. It means higher shoulder diameter, medium feed rate and medium tool rotational speed gave the nearest base material hardness, but least shoulder diameter 18 mm, least feed rate 14 mm/min and high rotational speed of 1000 rpm for welding resulted in lowest hardness value. Molecular weight reduction is one of the influencing criteria for the change in hardness value. As the tool rotational speed increases, the heat due to friction increases which results in the reduction of molecular weight. This in turn decreases the hardness value. Maximum value of hardness is obtained at second level of tool rotational speed, second level of feed rate and third level of tool shoulder diameter at 710 rpm, 28 mm/min and 22 mm respectively.

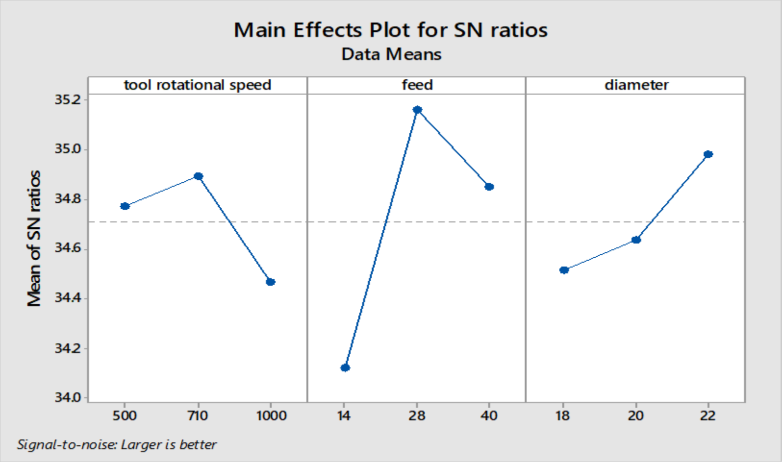

Fig. 3. Main effects plot for SN ratios of shore D hardness.

Table 4. Analysis of variance of S/N Ratio

Source	DF	Adj SS	Adj MS	F	P	Contribution
Tool rotation Speed	2	0.2914	0.1457	0.42	0.707	9.52
Feed Rate	2	1.7177	0.8588	2.45	0.290	56.13
Diameter	2	0.3487	0.1743	0.50	0.668	11.39
Residual	2	0.702	0.351			22.94
Total	8					99.98

Table 5. Response table for signal to noise ratios (larger is better)

Levels	A	B	C
1	34.77	34.12	34.52
2	34.89	35.16	34.64
3	34.47	34.85	34.98
Delta	0.43	1.04	0.46
Rank	3	1	2

2. Effect of Process Parameters on Shear Strength

Shear strength is higher the better type characteristics. Effect of process parameters on shear strength was found out by evaluating mean and S/N ratio in Taguchi method. Fig.4 gives plot for SN ratio main effect of shear strength.

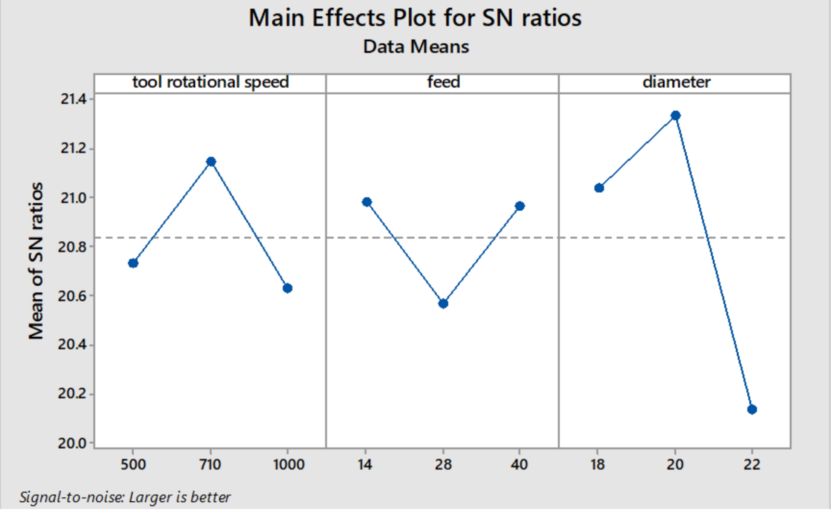

Fig. 4. Main effects plot for SN ratios of shear strength

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Highest shear strength is observed at rotational speed of 710 rpm, feed rate 14 mm/min and tool shoulder diameter 20 mm. This is due to the fact that sufficient heat is generated at medium level of rotational speed and effective intermolecular dispersion at joint interface is occurred with lower feed rate. The shear strength characteristics are quite high for the medium diameter of shoulder, low feed rate and medium tool rotational speed. On the other hand, higher shoulder diameter of 22 mm, medium feed rate 28 mm/min and higher rotational speed of 1000 rpm for welding results in lower shear strength.

Table 6 gives the analysis of variance table for shear strength. Table 7 gives the response table for SN ratios of shear strength. From these tables we can see that shoulder diameter and tool rotational speed are the most influencing factor for shear strength with percentage contribution of 58.88 and 11.17 respectively. Thus the maximum value for shear strength is obtained at tool rotational speed of 710 rpm, feed rate of 14mm/min and tool shoulder diameter of 20mm.

Table 6. Analysis of variance of shear strength

Source	DF	Adj SS	Adj MS	F	P	Contribution
Tool rotation speed	2	0.4422	0.2211	0.52	0.659	11.17
Feed rate	2	0.3304	0.1652	0.39	0.721	8.34
Diameter	2	2.3305	1.1652	2.73	0.268	58.88
Residual	2	0.8544	0.4272			21.58
Total	8					99.97

Table 7. Response table for signal to noise ratios (larger is better)

Levels	A	B	C
1	20.73	20.98	21.04
2	21.14	20.56	21.33
3	20.63	20.96	20.14
Delta	0.51	0.41	1.20
Rank	2	3	1

B. Grey Relational Analysis

In Grey Relational Analysis, experimental data i.e. measured features of quality characteristics of the product are first normalised ranging from zero to one. Next, based on normalised experimental data, grey relational coefficient is calculated to represent the correlation between the desired and actual experimental data. Then overall grey relation grade is determined by averaging the grey relational coefficient corresponding to selected responses. The overall performance characteristics of the multiple response process depends on the calculated grey relational grade. This response converts a multiple response process optimization problem into a single response optimization situation, with the objective function is overall grey relation grade. The optimal parametric combination is then evaluated by maximizing the overall grey relation grade. Based on Grey Relational Grade, rank of different experiments was obtained. With respect to the rank obtained, it is concluded that the optimum level of all parameters are comes on rank 1 and the values of the parameters are Tool rotational speed 710 RPM, feed rate 14 mm/min, Tool shoulder diameter 20 mm.

Table 8. Grey Relational Grade and Rank

A7.1	0.38762	0.4	0.39381	26
A7.2	0.487587	0.333333	0.41046	25
A7.3	0.333333	0.363636	0.348485	27
A8.1	0.530765	0.666667	0.598716	8
A8.2	0.531286	0.571429	0.551357	10
A8.3	0.50178	0.470588	0.486184	18
A9.1	0.616022	0.533333	0.574678	9
A9.2	0.445257	0.5	0.472628	20
A9.3	0.552325	0.380952	0.466639	21

Trial No	GRG Avg. Shear Strength	GRG SHORE D	Avg. GRG	RANK
A1.1	0.570953	0.444444	0.507699	15
A1.2	0.454052	0.380952	0.417502	23
A1.3	0.474453	0.347826	0.41114	24
A2.1	0.491905	0.5	0.495953	16
A2.2	0.487494	0.571429	0.529461	13
A2.3	0.477848	0.444444	0.461146	22
A3.1	0.454465	0.615385	0.534925	12
A3.2	0.453455	0.8	0.626728	6
A3.3	0.474029	0.727273	0.600651	7
A4.1	0.701795	0.571429	0.636612	4
A4.2	1	0.380952	0.690476	2
A4.3	0.919398	0.470588	0.694993	1
A5.1	0.471549	0.8	0.635774	5
A5.2	0.374302	1	0.687151	3
A5.3	0.352139	0.615385	0.483762	19
A6.1	0.556336	0.470588	0.513462	14
A6.2	0.671106	0.421053	0.546079	11
A6.3	0.534135	0.444444	0.48929	17

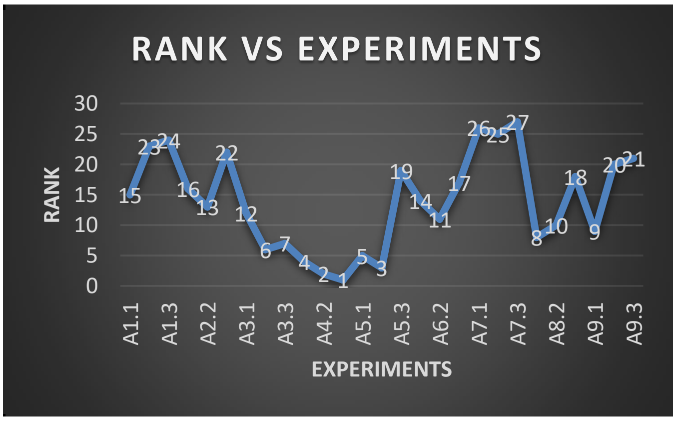

Fig.5. Rank profile for set of experiments

C. Macro and Micro Images

The cross-sectional view of joints that has been shown in figure 6, 7 and 8 indicates that the stir zone (SZ) is formed as polymer-metal composite by mixing the ABS matrix and aluminium particles reinforcement.

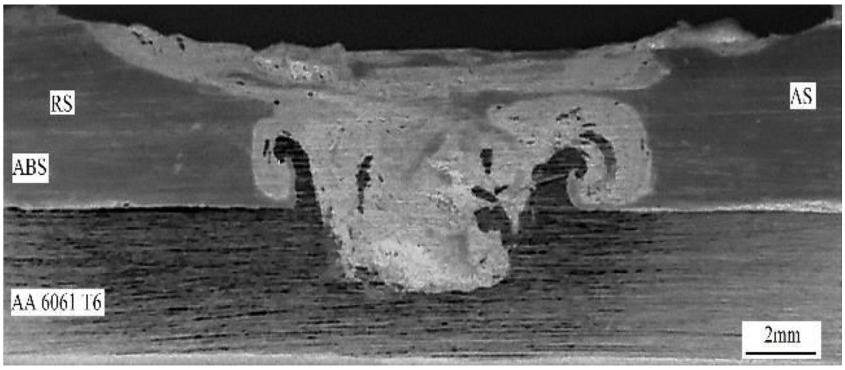

Fig. 6 Cross-sectional view of joint welded at 500 rpm tool rotation , 14 mm/min feed rate and 20 mm shoulder diameter.

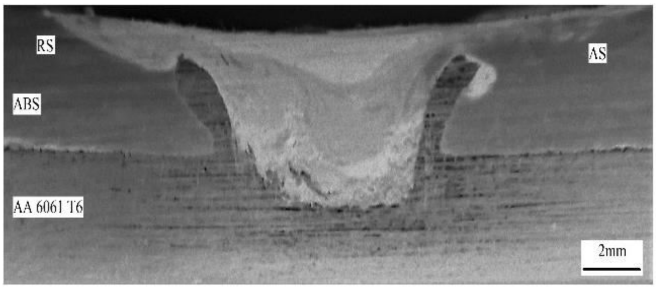

Fig. 7 Cross-sectional view of joint welded at 710 rpm tool rotation, 14 mm/min feed rate and 20 mm shoulder diameter.

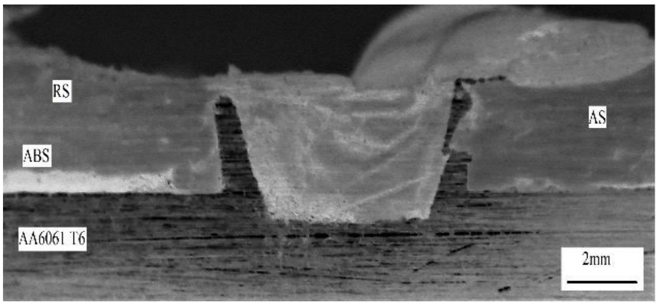

Fig. 8 Cross sectional view of joint welded at 1000 rpm tool rotation, 14 mm/min feed rate and 20 mm shoulder diameter.

During the FSW process, tilted pin, penetration aluminum base metal led to the high mechanical work rate. Subsequently, the AA6061 T6 twisted around the pin and the produced wavy dent in advancing and retreating side along the joint line. The aluminium wavy dent increases mechanical interlock between AA6061 T6 and ABS plastic in the lower area of stir zone. The results showed that by increasing tool rotational speed the length and width of aluminum ramus in advancing and retreating side will increase. Some tiny aluminum particles were spread in ABS matrix that fractured from AA6061 T6 alloy during stirring action.

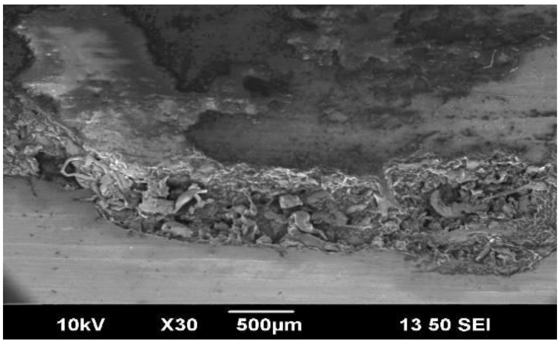

Fig. 9. SEM image of joint welded at 710 rpm, 14mm/min and 20 mm diameter.

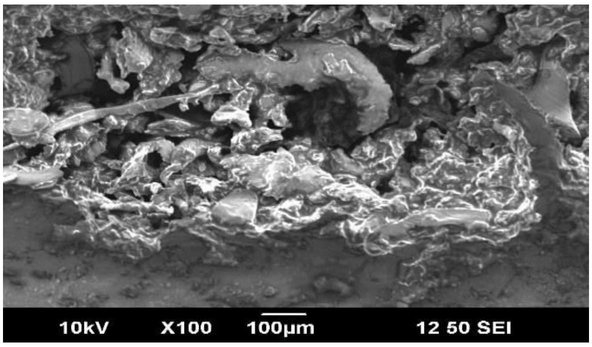

Fig. 10. Magnified SEM image of joint interface welded at 710 rpm, 14mm/min and 20 mm diameter.

The SEM image from cross-sectional view of joint welded at 710 rpm and 14mm/min and 20 mm shoulder diameter is shown in Fig.4.9. As shown figure , the joint interface between aluminum and ABS plastic is well mixed of aluminum and polymer particles . The micrograph under SEM of the Al powder used for the reinforcement is shown in Figure 4.10. The morphology of the Al powder revealed irregular shaped milled powder. In figure 4.10 its shows that, Some voids were formed at the lower end of the stir area, which could reduce the mechanical characteristics of the joint.

VI. CONCLUSION

The possibility of dissimilar friction stir welding between AA6061 T6 aluminum alloy and ABS plastic in lap joint design was established. The following conclusion can be extracted.

- Feasibility of the tapered pin with flat shoulder in the FSLW of ABS and AA6061 T6 alloy was verified. The solid mechanical interlocking by the large aluminum anchor has been accomplished.

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- The aluminum anchor featured by the bended, deformed and elongated grains penetrated into the molten and resoldified polymer. Mechanical interlocking induced by the Al anchor attributed to the main joining mechanism.
- Optimum value for Shore D hardness is obtained at tool rotational speed of 710rpm, feed rate of 28mm/min and tool shoulder diameter of 22mm.
- Welding speed plays a vital role and contributes 56.13 % to the overall contribution and tool shoulder diameter and tool rotational speed have 11.39%, 9.52% influence on shore D hardness of joints respectively.
- The hardness of ABS after FSW decreased for all sample compared to the initial raw ABS sheet, because of the molecular weight reduction of the ABS due to the frictional heat during the process.
- Optimum value for shear strength is obtained at tool rotational speed of 710 rpm, feed rate of 14mm/min and tool shoulder diameter of 20mm. In these parameters, the shear strength reached close to 32% (40.5Mpa) of the raw ABS sheet strength.
- Tool shoulder diameter plays avital role and contributes 58.88 % to the overall contribution and tool rotational speed and welding speed have 11.17%,8.34% influence on shear strength of joint respectively.
- From Analysis of Variance, the percentage contribution of input parameters was found out for each output parameter.
- Based on Grey Relational Grade, rank of different experiments was obtained. With respect to the rank obtained, it is concluded that the optimum level of all parameters are comes on rank 1 and the values of the parameters are tool rotational speed=710 rpm, feed rate= 14 mm/min, Tool shoulder diameter=20 mm.
- The cross-sectional image shown that by increasing tool rotational speed the length and width of aluminum ramus in advancing and retreating side will increase.

VII. FUTURE SCOPE

The present work is to determine the optimal process parameters for Friction stir welding of aluminium alloy (AA6061 T6) and ABS plastic based on a single tool profile, tool geometry, tool material. It would be useful to extend the present work by changing the tool pin profile to check for the improvement in weld quality. The process of FSW can be extended to different combinations of thermo-setting plastics. Thermal analysis can be added to this work to study on the effect of heat effected zones in the weld area. The effect of post heat treatment of FSW joints with different ageing treatments to improve the shear strength can also be of another topic of discussion.

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