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Study the Process Parametric Influence on Impact Strength of Friction Stir Welding of Dissimilar Aluminum Alloys (AA5083 and AA6061) using Taguchi Technique

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Abstract: Taguchi philosophy was utilised to calculate the most significant control factors which will yield higher impact strength of the joints of friction stir welded dissimilar AA5083 and AA6061 aluminium alloy. To optimize the process parameters such as tool rotational speed, weld speed and tool tilt angle on impact strength of friction stir welded dissimilar AA5083 and AA6061 aluminium alloy, Taguchi Design of Experiment (DOE) and optimization technique was utilised. The optimum levels of process parameters were fund by utilising the Taguchi parametric design concept. The outcomes indicate that the rotational speed, welding speed and tool tilt angle are the important parameters in deciding the impact strength of the weld joint. The predicted optimal value of Impact strength of friction stir welded dissimilar AA5083 and AA6061aluminium alloy is 30J. The outcomes were confirmed by further experiments.

Keywords: Friction stir welding; AA5083 and AA6061; Taguchi design of experiment (DOE) ; Process parameters; Impact strength.

I. INTRODUCTION

Friction stir welding (FSW) is the most important and innovative process in the field of similar or dissimilar metal joining and most important of which is its ability to weld generally unweldable alloys [1]. Compared with number of the fusion welding processes that are routinely utilised for joining structural alloys, FSW is a solid state joining method in which the material that is being welded less than its melting point[2]. Defect free welds with high mechanical properties have been made in different aluminium alloys, even those beforehand thought to be not weldable. Porosity, hot cracking and alloy segregation defects won't get in the friction stir welding process. FSW generates high surface finish and need not required post weld cleaning [3]. The material flow was not symmetric about the weld centreline, the flow patterns on the advancing & retreating sides were different. There have been many efforts to understand the effect of process parameters on microstructure development, material flow behaviour and mechanical properties of friction stir welded joints. The influence of some parameters such as rotational speed, traverse speed and tool tilt angle on weld properties is important topics for researchers[4–6].Taguchi design of experiment (DOE) is a most important tool to calculate significant factor from many by performing relatively few number of trials, regardless, this design fundamentally does not represent the interaction among processing parameters. In perspective of time and cost saving, once in a while these interactions are not considered. If compulsory, the missing interactions can be obtained by further performing the required trials.

In this research work , applying Taguchi systems on fusion welding processes and casting methods have been told in literatures[7–8], it demonstrates that the optimization of FSW process parameters of AA5083 and AA6061 aluminium alloy utilising Taguchi technique has not been reported properly yet. Considering the above truths, the Taguchi L9 Orthogonal array is utilized to calculate the influence of each processing parameters (i.e. rotational speed, traverse speed and tool tilt angle) for optimum impact strength of friction stir welded joints of AA5083 and AA6061 aluminium alloy.

II. LITERATURE REVIEW

Shige Matsu et. al. (2003) [9] investigated Joining of 5083 and 6061 aluminum alloys by friction stir welding. He observed that in this method, a rotating tool moves down the thickness of contacting metal plates, and generates a highly plastically deformed zone through the related stirring action. The localized heating zone is generated by friction between the plate top surface and the tool shoulder as well as plastic deformation of the material in contact with the tool. T. Kumbharand K. Bhanumurthy et al. (2012)[10] investigated a friction stir welding of Al 5052 with Al 6061 Alloys and observed that the following friction stir welding of dissimilar materials AA5052 and AA6061 was successfully conducted. It was investigated that at higher rotation speeds, the normal load and spindle torque requirement reduced.

Morteza Ghaffarpour, et. al. 2013[11] In his Review of Dissimilar Welds of 5083-H12 and 6061-T6 performed by Friction Stir Welding, describes that as the conventional fusion welding is undesirable for welding aluminum alloys, there are numerous works performed on the aluminum alloys by FSW. These works are considering to the effects of FSW parameters on sheet formability, weld quality after FSW, and optimization of the FSW process.

S. Jannet et. al. 2013[12] managed Comparative research of friction stir welding and fusion welding of 6061-T6 and 5083-O aluminum alloy in view of microstructure and mechanical properties states. In this study, the mechanical properties of welded joints of 6061-T6 and 5083-O aluminum alloy determined utilizing friction stir welding (FSW) with four rotational speeds (450, 560, 710 and 900 rpm) and conventional fusion welding are investigated.

III. MATERIALS AND METHODS

Taguchi Method

The Taguchi technique is an remarkable technique that gives an exact and profitable theory for process optimization and this is a powerful device for the design of high quality systems [13]. Taguchi strategy to design of experiments in easy to adopt and apply for users with limited information of statistics, thus increased wide popularity in the engineering and scientific community. This is an engineering technique for getting product and process condition, which are insignificantly sensitive to the different reasons for variety, and which produce high-quality products with low manufacturing costs. Signal to noise ratio and orthogonal array are two main tools used in robust design. Further, this technique finds the most influential parameters in the whole execution. The optimum weld parameters found from the Taguchi idea are insensitive to the change in ecological condition and other noise factors[14]. In DOE number of trials increments when the number of process parameters increment.

To solve this trouble, the Taguchi technique utilizes a special design of orthogonal array to find the whole process parameter space with a few number of experiments only. Taguchi has defined three important signals to noise ratios (S/N) (i.e. the nominal-the-better, lower-the-better and the larger-the-better) depending on the of the quality characteristics. The S/N ratio for each of process parameter is computed based on S/N analysis. Regardless of the classification of the quality characteristics, a higher S/N ratio relates to better quality characteristics. Therefore, the highest S/N ratio indicates to the optimal level of process parameter. Statistical analysis of variance (ANOVA) can be performed to find the significant process parameter. A confirmation test is performed to validate the predicted optimal levels found out from the analysis.

Impact Strength

Impact is a most important factor in calculating the life of a structure or machine. e.g , in an aircraft, impact can take place by a bird during landing and takeoff the aircraft might be struck by debris that is available on the runway, and also different causes. Thus the impact strength must be computed for the safety and to design a component of high factor of safety. Impact tests are used to find the toughness of materials.

Toughness is a factor of its capacity to absorb energy during deformation. Brittle materials have lower toughness as a result of the small amount of plastic deformation that they can endure. The impact strength of a material can also change with temperature. Generally ,at lower temperatures the impact strength of a material is reduced. The specimen size may also influence the value of the impact test because it may permit a different number of imperfections in the material, which can act as stress risers and lower the impact strength.

Charpy Impact Test

Charpy impact testing includes striking a standard notched sample with a controlled weight pendulum swung from a set height. The standard Charpy-V notch sample is 55mm long, 10mm square and has a 2mm deep notch with a tip radius of 0.025mm machined on one face. The specimen is supported at its two ends on an anvil and struck on the opposite face to the notch by the pendulum. The quantity of energy absorbed in fracturing the test-piece is measured and this gives a sign of the notch toughness of the test material.

The pendulum swings through amid the test, the height of the swing being a measure of the quantity of energy absorbed in breaking the test-piece. Routinely, two specimens are tested at room temperature and the results averaged. Charpy tests show whether a metal can be classified as being either brittle or ductile. A brittle metal will absorb a little amount of energy when impact tested, a tough ductile metal absorbs a huge amount of energy.

The appearance of a fracture surface also gives information about the kind of fracture that has happened; a brittle fracture is bright and crystalline, a ductile fracture is dull and fibrous. At the point when a ductile metal is broken, the specimen deforms before breaking, and material is squeezed out on the sides of the compression face. The quantity by which the specimen deforms in this way is calculated and communicated as millimetres of lateral expansion. Charpy tests show whether a metal can be named being either fragile or malleable.

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FSW process parameters

An Ishikawa figure (cause and effect diagram)[15] was developed as shown in Fig.1 to identify the FSW process parameters that may impact the quality of FSW joints. From Fig.1, the welding process parameters such as tool rotational speed, traverse speed, tool tilt angle, play a major part in choosing the weld quality. In the present research, three level process parameters, i.e. rotational speed (RPM), weld travel speed(WS) and tool tilt angle (TTA) were considered. Trail experiments were done using 5 mm thick plates of AA5083 and AA6061 Aluminium alloys to set the working range of FSW process parameters. The chemical composition and mechanical properties of the base metals (AA5083 and AA6061) utilized as a part of this investigation are given in Table 1 and 2 respectively.

Table1: Chemical composition of parent materials (mass fraction, %)

Alloy	Mg	Mn	Cu	Cr	Si	Fe	Al
AA6061-T6	1.046	0.101	0.259	0.195	0.533	0.262	Bal
AA5083-H321	4.0	0.548	0.065	0.10	0.145	0.238	Bal

Table2: Mechanical properties of parent materials

Alloy	Yield strength/Mpa	Ultimate tensile strength/Mpa	% Elongation Mm	Average hardness at 0.5kg load (VHN)	Impact strength (J)
AA6061-T6	283	353	18	120	8
AA5083-H321	238	311	20	96	16

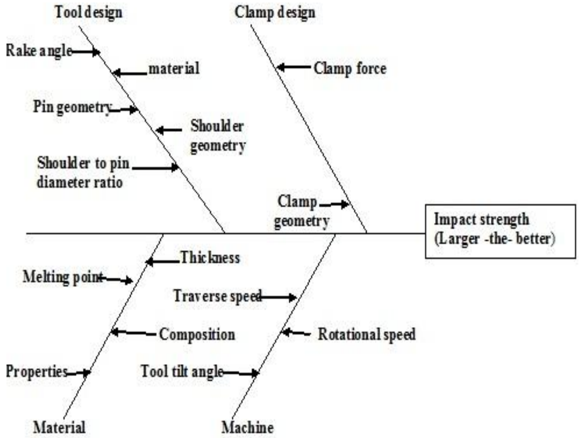

Figure 1. Cause and effect diagram

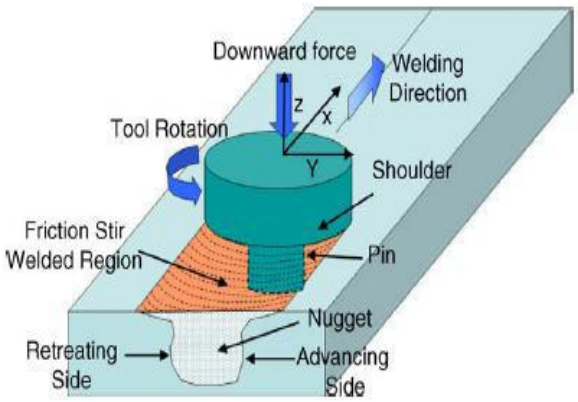

Figure 2. Frictions stir welding set up

When the tool rotational speed is lower than 560 rpm, worm hole defect is discovered it might be due to insufficient heat generation and inadequate metal depositing whereas a tunnel defect was discovered due to excessive heat generation when the rotational speed is higher than 1800 rpm.

At the point when the traverse speed is lower than 40 mm/min, pin holes are discovered because of excessive heat generation and a tunnel defect is observed due to deficient heat input caused by insufficient metal flow, when the traverse speed is more than 100 mm/min.

Defect free surface was found, for a tool tilt angle of 0 to 2^o. Based on the above trials, the range of process parameters was selected as 560-1800 rpm for rotational speed, 40-100 mm/min for weld travel speed and 0-2^o for tool tilt angle. The FSW process parameters along with their ranges are given in Table 3.

Table 3 Process parameters with their range and values at three levels

Level	Rotational speed RPM (r min^{-1})	Weld travel speed WS (mm min^{-1})	Tool tilt angle TTA(degrees)
Range	560 - 1800	40-100	0 - 2
Level 1	560	40	0
Level 2	1120	70	1
Level 3	1800	100	2

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Selection of Orthogonal Array(OA)

The number of degrees of freedom requires to be computed to choose an appropriate orthogonal array for the experiments. Taguchi develops number of standard orthogonal arrays and corresponding linear graphs were developed by Taguchi for this purpose. In this research three factors were selected, i.e., Friction stir welding process parameters for the three factors and three levels Taguchi recommended some standard array. Hence an L9 OA (3^3) was selected for this research. This array requires nine trial runs and has three columns.

IV. EXPERIMENTAL WORK

In this research for base material utilized for the friction stir welding experiments were cut into 5 X 75 X 200 mm size from rolled AA5083 and AA6061 aluminium alloys plates. Two plates of base metal (AA5083 and AA6061) were friction stir welded (FSW) in the butt configuration by using the vertical milling machine. The two plates located side by side and clamped rigidly to stop abutting joint faces from being forced apart. The length of the tool pin is slightly lesser then work piece thickness. In this process single pass welding method was used to produce the joints. The frictional heat developed between the tool shoulder surface and the base material of work piece surfaces because of rotating of weld tool. The heat developed by mechanical mixing method due to the stirred materials to soften below the melting point. As tool pin is travelled in the direction of welding the front face of the tool pin, with the help of special tool pin profile, forces plasticized material to the back of the pin while applying a sufficient forging force to solidify the weld metal. The weld metal was facilitated by intense plastic deformation in solid state involving dynamic recrystallization of base material.

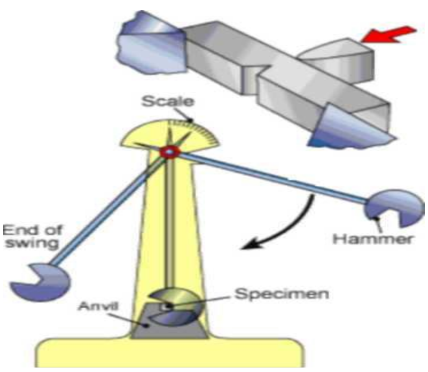


Figure 3 (a) : Charpy Test Apparatus

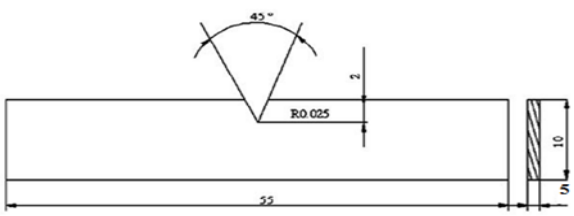


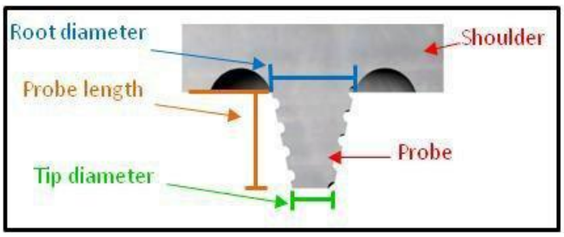
Figure3 (b) Charpy Impact specimen ASTM A370 standards.

The welded joints sliced transverse to the weld direction by using with an EDM wire cutting machine to required dimensions, according to ASTM A370 standards should be followed for preparing test samples. The impact samples were prepared to evaluate impact strength. At each experimental level two samples were prepared to reduce the noise factor. Impact test was conducted in this welded plate of 55 mm x 10 mm x 5 mm is utilised for experimentation.

The charpy "V" notch impact test was conducted at room temperature utilizing pendulum type impact testing machine. The amount of energy absorbed in fracture was recorded and the absorbed energy is defined as the impact toughness of the material. The schematic sketch of charpy impact specimen were shown in Fig.3(a, b).

Tool Design: Tool geometry assumes an important part in material flow in the joint. FSW tool has two fundamental functions localized heating and material flow. The tool ought to play out the accompanying capacities [Mishra RS et.al (2005)] are decrease the welding force, empower simpler stream of plasticized material, encourage the downward force impact, and expand the interface between the pin and the plasticized material, thereby increase the frictional heat production. In this work Concave shoulder with scrolling on shoulder surface and cylindrical taper treaded pin /probe was used. Shoulder diameter = 18mm, Root diameter = 6mm, Probe diameter = 4mm, Probe length= 4.7mm. Tool material = H13 tool steel is used. The tool shown in figure 4.

(a) (b)



(c)

Figure 4: (a) &b weld tool, (c) Probe Dimensions

V. EXPERIMENTAL RESULTS AND DISCUSSION

SIGNAL TO NOISE RATIO

Impact strength is the main characteristic considered in this research describing the quality of FSW joints. So as to evaluate the impact of factors on the response, the Signal-to-Noise ratios (S/N) and means for

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every control factor can be calculated. The signals are indicators of the impact on average responses and the noises measures of the impact on the deviations from the affectability of the experiment output to the noise factors. The suitable S/N ratio must be selected using past learning, skill, and understanding of the process.

At the point when the objective is settled and there is minor or missing signal factor (static design), it is possible to select the signal-to-noise (S/N) ratio depending on the target of the design [16]. In this research, the S/N ratio was selected corresponding to the criterion of the larger- the-better, in order to maximize the response. In the Taguchi technique, the signal to noise ratio is utilized to compute the deviation of the quality characteristics from the required value. The S/N ratio η_j (larger-the-better) in the j_{th} experiment can be communicated as

$$\eta_j = -10 \log_{10}((1/n)\sum(Y_{ijk})^2) \qquad 1$$

where n is the number of tests and Y_{ijk} is the experimental value of the ith quality characteristics in the jth experiment at the kth test.

In the present study, the impact strength data were analyzed to find the effect of FSW weld parameters. The trial results were then converted into means and signal-to-noise (S/N) ratio. In this research, 9 means and 9 S/N ratios were computed and the estimated impact strength, means and signal-to-noise (S/N) ratio are given in Table 4. Every experiment will give the analysis of mean for better combination of parameters levels that guarantees a high level of impact strength according to the experimental set of data. The mean response indicates to the average value of execution characteristics for every parameter at various levels. The mean for one level was computed as the average of all responses that were fund with that level. The mean response of crude information and S/N ratio of impact strength for every parameter at level 1, 2 and 3 were computed and are shown in Table 5. The means and S/N ratio of the different process parameters when they converted from the lower to higher levels are also shown in Table 5. It is clear that a larger S/N ratio with respect to better quality characteristics. Therefore, the optimal level of weld parameter is the level of highest S/N ratio[17]. The mean effect and S/N ratio for impact strength were calculated by statistical software [18], showing that the impact strength was at highest when rotational speed, welding speed and tool tilt angle are at level 2, 2 and 3 i.e. rotational speed at 1120 r/min, welding speed at 70 mm/min and tool tilt angle at 20 degrees . The comparison of mean effect and S/N ratio are given in Fig.5.

Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) test was conducted to find the weld parameters that are statistically significant. The purpose of the ANOVA test is to research the importance of the process parameters which influence the tensile strength of FSW joints. The ANOVA results for tensile strength of means and S/N ratio are given in Tables 6 and 7 separately. Also, the F-test named after Fisher can also be utilized to find which process has a significantly affects on tensile strength. Generally, the change of the process parameter significantly affects the quality characteristics, when F is high. The results of ANOVA show that the considered weld parameters are highly significant factors affecting the impact strength of FSW joints in the order of rotational speed, tool tilt angle weld travel speed.

Interpretation of Experimental Results

Percentage of contribution

The percentage of contribution is the part of the total variation observed in the experiment attributed to every significant factors and/or interaction which is shown. The percentage of contribution is a function of the sum of squares for each significant item; it shows the relative power of a factor to minimise the variation. If the factor levels are controlled definitely, then the total variation could be minimise by the amount represented by the percentage of contribution.

Table 4 Orthogonal array for L9 with response (raw data and S/N ratio)

No	Input parameters			Response		Mean value	S/N ratio
	RPM	WS	TTA	I1	I2		
1	560	40	0	20	18	19.0	25.54
2	560	70	1	22	26	24.0	27.51
3	560	100	2	26	20	23.0	27.01
4	1120	40	1	28	27	27.5	28.78
5	1120	70	2	32	31	31.5	29.96
6	1120	100	0	19	22	20.5	26.17
7	1800	40	2	18	21	19.5	25.72
8	1800	70	0	14	18	16.0	23.88
9	1800	100	1	18	22	20.0	25.89

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Table 5 Main effects of impact strength (means and S/N ratio)

		for Means			for S/N Ratios		
	Level	RPM	WS	TTA	RPM	WS	TTA
	1	22.00	22 .00	18.50	26.69	26.68	25. 19
	2	26.50	23.83	23.83	28.30	27.12	27. 40
	3	18.50	21.17	24.67	25.16	26.36	27. 57
	Delta	8.00	2.67	6.17	3.14	0.76	2.37
Rank	1	3	2	1	3	2	

(RPM,WS, TTA are process parameters)

Table 6 ANOVA for Impact Strength (for mean)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% of contribution
RPM	2	96.500	48.250	13.47	0.069	53.02
WS	2	11.167	5.583	1.56	0.391	06.14
TTA	2	67.167	33.583	9.37	0.096	36.91
Error	2	7.167	3.583		3.93	
Total	8	182.000				100.00

DF- Degrees of freedom, Adj SS-Adjusted of square, Adj MS-Adjusted mean square,
F- Feisher ratio, P- Probability that exceeds the 95% confidence level.

Table 7 ANOVA for Impact Strength (S/N ratio)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	%of contribution
RPM	2	13.7542	6.8771	20.51	0.046	53.7
WS	2	0.8167	0.4083	1.22	0.451	03.2
TTA	2	10.3757	5.1878	15.47	0.061	40.5
Error	2	0.6706	0.3353			02.6
Total	8	25.6171				100.0

DF- Degrees of freedom, Adj SS-Adjusted of square, Adj MS-Adjusted mean square,
F- Feisher ratio, P- Probability that exceeds the 95% confidence level.

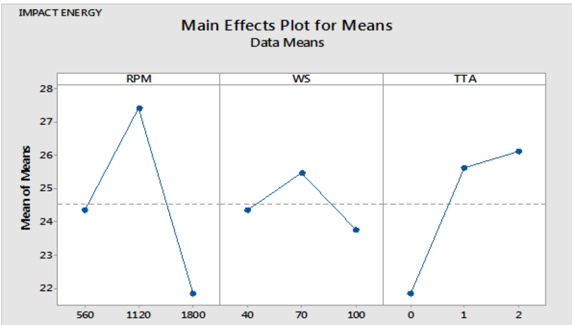

Fig:5 (a) F Main Effects Plot for Means of IE

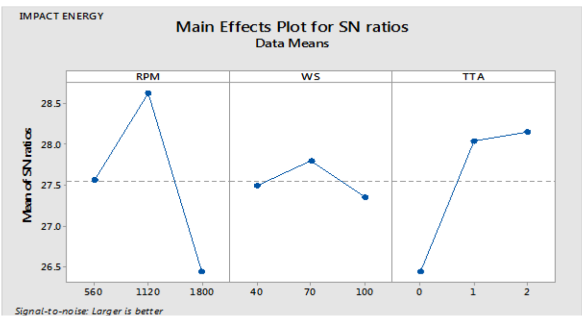

Fig:5 (b) Main Effects Plot for S/N ratio of IE

Estimation of optimum performance characteristics

The methods explained in this process for impact strength prediction and optimization can terminate the need for conducting experiments on the basis of the conventional hit and trial technique which is time consuming and financially not justifiable. The present study is aimed at to recognize the highest influencing significant parameter and percentage contribution of every parameter on impact strength of friction stir welded dissimilar AA5083 and AA6061 aluminium joints by conducting least number of experiments using Taguchi orthogonal array. Based on the greatest values of the S/N ratio and mean levels (Fig.5) for the significant factors RPM, WS and TTA the entire optimum condition thus obtained were RPM_2, WS_2 and TTA3.

Once an experiment is performed and the optimum process condition within the experiment is fund, one of two conceivable outcomes exists:

1) The recommended combination of factors level is identical to one of those in the experiment,

2) The recommended combination of factors level is excluded in the experiment.

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The optimum value of impact strength is predicted at the chosen levels of significant levels of significant parameters. the predicted impact is taken from the literature (19) The estimated mean of the response characteristics (impact strength) can be calculated as

Impact strength (predicted) = $RPM_2+WS_2+TTA_3-2T$ ....(2)

where T is the overall mean of impact strength in Mpa (Table 2),

RPM2 = The average impact strength second level of rotational speed,1120 r/min;

WS2 = The average impact strength at second level of welding speed 70 mm/min,

TTA3 = The average impact strength at third level of tool tilt angle 2^0derees.Substututing the values of various terms in Eqn (2), then

Impact strength = RPM2 + WS2 + TTA3 - 2*T

= 26.50 + 23.83 + 24.67 - 2*22.33 = 30 J

Confirmation Test:

The confirmation test was conducted for impact strength and it was found that predicted value (30 J) for impact was very close to the values obtained after actual test conditions on optimum levels (31.5 J).

Fractography of Impact Specimens

The fractural morphology of the impact specimens of the fracture surface of the weld joints were studied using the scanning electron microscopy (SEM) to understand the mode of failure. Fractured features of the weld joints are shown in Fig.6 . The dimple pattern is observed in the whole width of the specimen. The joints fabricated at the condition of tool rotation speed at 1120rpm and weld speed at 70 mm/min 2^0exhibited superior ductility as compared with other conditions.

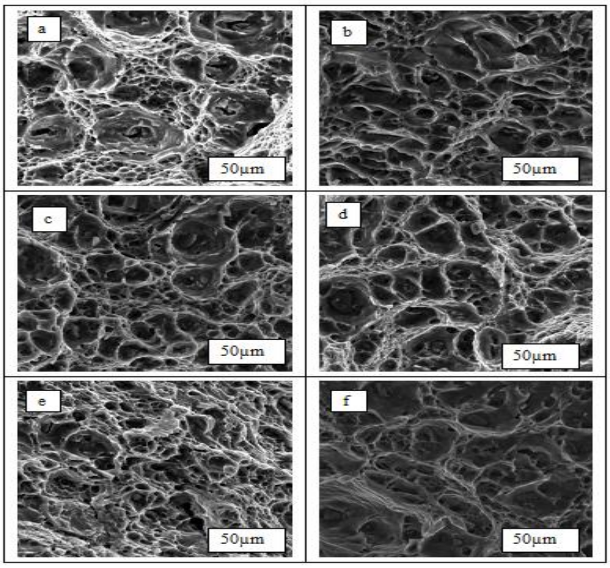

Fig6 : Fracture Surface of Impact Specimens at Various Conditions: (a) base metal AA5083 (b) base metal AA60061 (c) exp1: 560RPM,40mm/min,0^0 (d) exp2: 560rpm,70mm/min,1^0 (e)exp5:1120RPM,70mm/min,2^0 (f)exp6:1120,100mm/min,0^0 (high magnification) (Fracture surface of AA5083&AA6061 after impact testing showing ductile dimple pattern)

This is because of presence of small shallow dimples furthermore some large dimples resulted from micro dimples coalescence. It could be credited to the high plastic deformation which indicates more intense ductile fracture.

The SEM observations of the fracture surfaces of the impact tested specimens revealed the best bonding characteristics of the FSW joints. The fracture behaviour of alloy is due to the reduction of undissolved coarser phase and the increase of precipitated phase (the increase of impact strength).

VI. CONCLUSION

1) AA5083 and AA6061 alloys were successfully friction stir welded under the following range of process Parameters: tool rotational speed of 560 -1800 rpm, weld travel speed of 40-100 mm/min, and the tool tilt angle of 0-2^o.

2) The percentage contribution of FSW process parameters was assessed. It is observed that the tool Rotational speed has 53.02% contribution, tool tilt angle36.91% and traverse speed has 6.14 % contribution to impact strength of welded joints.

3) The optimum value of process parameters like rotational speed, traverse speed and tool tilt angle are determined to be 1120 r/min, 70 mm/min and 2^0 degrees respectively.

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