Microstructure and Percentage Elongation Analysis for Friction Stir Welding of Joining A6061 and A6082 Alloys

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ABSTRACT

The Friction Stir Welding (FSW) is a modern solid phase joining technique of aluminium alloys for producing high quality joints. In this paper, the effect of process parameters of friction stir welded joint of A6061 and A6082 Alloys on microstructures and percentage elongations have been investigated. Joints are fabricated according to L_9 orthogonal array of Taguchi approach. ANOVA is implemented for analyzing the responses with respect to input process parameters (tool rotational speed, tool tilt angle and types of tool pin profile) as the raw data and S/N ratio analysis. The observation revealed minimum variation of microstructure in base metals and dissimilar welded region. The result indicates that the most significant process parameter is rotational speed of tool with percentage contribution of 78.87 % followed by tool pin profile with 15.12 % and tool tilt angle with 5.90 %. The optimum combination of process parameters was found by conducting confirmation test. The predicted and experimental values of percentage elongation of joints are 6.347 % and 6.286 % respectively.

KEY WORDS: Friction Stir Welding, Taguchi Approach, Aluminium alloy, Elongation

1.0 INTRODUCTION

Friction Stir Welding (FSW) is an innovative solid-state material joining technology invented by The Welding Institute (TWI) in 1991. It has been one of the most significant joining methods for aluminium alloys. The FSW process combines heat flow, produced mainly by friction between the tool shoulder and the top of the plates, and plastic strain resulting from the rotation of the pin tool. These thermo-mechanical conditions vary within the joint and create a heterogeneous microstructure across the weld [1].

The main applications of friction stir welding are the joining of long lengths of materials in the aerospace, shipbuilding, and railway industries. This process has the advantages over conventional fusion-welding processes such as good mechanical properties, safety and no consumable materials are used. It can operate in all positions.

Santella M.L. et al. [2005] performed experiments to produce surfaces of A319 and A356 castings, treated by friction stir processing to reduce porosity and to create more uniform distributions of second-phase particles. With the help of experimental data, authors eliminated dendritic micro-structures in stir zones. The ultimate tensile strength, ductility and fatigue life of both alloys were increased by the friction stir processing [2].

Genevois C. et al. [2006] investigated the effect of the microstructure heterogeneity on the global and local tensile properties of friction stir welded joints of AA5251 (O temper) and AA2024 (T351 and T6 tempers) aluminium alloys. Results revealed that tensile properties for various regions of 2024 (T351) and 2024 (T6) welds were very heterogeneous and essentially controlled by the state of precipitation. The thermo-mechanicaly affected zone is the weakest region where the strain localizes during a transverse tensile test [3].

Cavaliere P. et al. [2006] analyzed the effect of process parameters on mechanical and microstructural properties of AA6056 joints produced by Friction Stir Welding. Different samples obtained by employing rotating speeds of 500, 800 and 1000 rpm and welding speeds of 40, 56 and 80 mm/min. Mechanical properties like microhardness (HV) and tensile tests were evaluated at room temperature. Maximum tensile strength was obtained at higher rotating speeds (800 and 1000 rpm) and at the maximum welding speed (80 mm/min) [4].

Cavaliere P. et al. [2006] investigated the mechanical and microstructural properties of dissimilar 2024 and 7075 aluminium sheets joined by FSW. Authors achieved fatigue endurance (S–N) curves of the welded joints, since the fatigue behavior of light welded sheets was the best performance indicator for a large part of industrial applications. It is observed that the resulted microstructure due to the FSW process by employing optical and scanning electron microscopy either on 'as welded' specimens and on tested specimen after rupture occurred [5].

Ahmed and Toshiya [2008] studied about the microstructure and mechanical properties of dissimilar joints of 2024-T3 Al alloy to 7075-T6 Al alloy produced by friction stir welding. The effects of welding speed and fixed location of base metals on microstructures, hardness distributions, and tensile properties of the welded joints were investigated. SEM-EDS analysis revealed that the stir zone containes a mixed structure and onion ring pattern with a periodic change of grain size as well as a heterogeneous distribution of alloying elements [6].

Amancio-Filho S.T. et al. [2008] welded the dissimilar Al alloys (AA2024-T351 and AA6056-T4) by friction stir welding. Welded joints obtained by varying process parameters, namely the rotational speed (500–1200 rpm) and the welding speed (150–400 mm/min), while axial force and tool geometry were kept constant. Process parameters optimized on the basis of macrographic analysis and microhardness testing. It indicated that sound joints can be obtained at 800 rpm rotational speed and welding speed of 150 mm/min [7].

Cavaliere P. et al. [2009] analyzed the effect of process parameters on the mechanical and microstructural properties of dissimilar AA6082–AA2024 joints produced by FSW. The welded joints were produced by varying the advancing speeds of the tool as 80 and 115 mm/min and by varying the alloy positioned on the advancing side of the tool. Microhardness (HV), tensile strength and microstructural behavior were evaluated [8].

Aval H. Jamshidi et al. [2011] investigated the thermo-mechanical behavior and microstructural evolution in similar and dissimilar friction stir welding of AA6061-T6 and AA5086-O alloys. The thermo-mechanical behavior of materials during similar and dissimilar operations have been predicted using three dimensional finite element software, ABAQUS. Also, the mechanical properties and microstructures of welded samples have been studied with the aid of experimental observations and model predictions. Results showed different strengthening mechanisms in AA5086 and AA6061[9].

In the present experimental work, the effect of process parameters on microstructure and percentage elongation of different welded joints fabricated based on Taguchi L_9 orthogonal array were investigated. The effects of process parameters (rotational speed, tool tilt and types of tool pin profile) on percentage elongation was analyzed on the basis of ANOVA raw data and S/N data analysis. From this analysis, the optimum value of process parameters for optimal percentage elongation was estimated. Three-confirmation test were conducted to verify these optimum process parameters.

2.0 METHODOLOGY

2.1. Taguchi Approach

In this experimental study, Taguchi method is used for optimization of process parameters of friction stir welding of dissimilar aluminium alloys. The Taguchi Approach for quality engineering is intended as a guide and reference source for industrial practitioners involved in product or process experimentation and development.

By using and understanding the Taguchi method, managers and engineers realize the importance to design quality into the products. The Taguchi method for quality engineering will bridge the gap between customer's requirements and availability of quality products, eventually making companies more competitive with their products in the world market. Taguchi addresses quality in two main areas: [11]

Off line quality control
On line quality control

Taguchi Approach is a robust design method that uses experimental design called Orthogonal Arrays to study a large number of decision variables with a small number of experiments. It also uses a new measure of quality called signal to noise (S/N) ratio to predict the quality from the customers perspective. Thus, the most economical product and process design from both manufacturing and customer's viewpoint can be achieved at the smallest, affordable development cost [11].

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2.2 Analysis of Variance (ANOVA)

The purpose of product or process development is to improve the performance characteristics of the product or process relative to customer needs and expectations. The purpose of the experimentation should be to reduce and control variation of a product or process; subsequently decisions must be made concerning which parameters affect the performance of a product or process. ANOVA is the statistical method used to interpret experimental data and to take the necessary decision. The method was developed by Sir Ronald Fisher in the 1930's as a way to interpret the results from agricultural experiments. ANOVA is a statistics based decision tool for detecting any differences in average performance of groups of items tested [11].

2.3 Orthogonal Array

Taguchi recommends Orthogonal Arrays (OA) for conducting the experiments. The orthogonal arrays are generalized Graeco-Latin squares. To design an experiment is to select the most suitable OA and to assign the parameters and interactions of interest to the appropriate columns. The use of linear graphs and triangular tables suggested by Taguchi makes the assignment of parameters and interactions simple. The array forces the experimenters to design almost identical experiments. In the Taguchi method, the results of the experiment are analyzed to achieve one or more of the following objectives:

- To establish the best condition for a product or process
- To estimate the contribution of individual parameters and interactions
- To predict optimal response at the best setting of factors

Studying the main effects of each of the parameters identifies the optimum condition. The main effects indicate the general trend of influence of each parameter. The knowledge of contribution of individual parameters in affecting the response is a key in deciding the nature of control to be done on a production process. The analysis of variance (ANOVA) is the statistical tool commonly applied to the results of the experiments in determining the percentage contribution of each parameter against a stated level of confidence. Study of ANOVA table helps to determine the parameters needed to be controlled [11].

Taguchi suggests two different routes to carry out the complete analysis. First is the standard approach, where the results of a single run or the averages of the repetitive runs are processed through main effects and ANOVA analysis. The second approach, which Taguchi strongly recommends for multiple runs, is to use S/N Ratio for the same steps in the analysis [11].

Each of the three level parameters has 2 degrees of freedom (DOF = no. of levels -1); the total DOF required for three parameters, each at three levels is 6 [3 X (3-1)].

As per Taguchi's method, the total DOF of selected OA must be greater than or equal to the total DOF required for the experiment. So, an L_9 OA (a standard three level OA) having eight DOF were selected for the analysis as given in **Table 1**.

Table 1 : Standard L_9 Orthogonal Array

Experimental Run	Control factors and levels		
	1	2	3
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

All process parameters have three levels and hence, column 1 is assigned for the rotational speed, column 2 for the tool tilt and column 3 for the types of tool pin profiles. The nine rows of L_9 orthogonal array represent the nine experiments to be conducted during experimentation.

3.0 EXPERIMENTAL DESIGN

3.1 Selection of Materials

For this work, aluminium alloys 6061 and 6082 have been selected for FSW. In present days, both materials are widely used in aircraft and automobile industries for structural applications. These have good formability, corrosion resistance and good weldability. The specimens are prepared to the size of 100 mm x 35 mm x 7.5 mm. Chemical composition of aluminium alloy 6061 and 6082 are shown in **Tables 2**.

Table 2 : Chemical composition of 6061 and 6082 aluminum alloy

Chemical Composition %	Material	Al	Si	Cu	Mg	Zn	Fe	Ti	Cr	Mn
	6061	Balance	0.40-0.80	0.15-0.40	0.60-1.20	0.20	0.70	0.10	0.25	0.40-1.00
	6062	Balance	0.70-1.30	0.10	0.80-1.20	0.25	0.50	0.15	0.40-0.35	0.15

3.2 Selection of Friction Stir Welding Parameters and Their Levels

Based on review of literature and some preliminary experiments, the following process parameters were selected for the present work along with their notations and ranges which are shown in **Table 3**.

Table 3 : Process parameters and their levels

Parameters	Notation	Levels of factors		
		1	2	3
Rotational speed (rpm)	RPM	900	1550	2200
Tool tilt (degree)	TLT	0	2	4
Types of tool pin profile	TTP	TC	OC	THC

TC- Tapered Cylindrical, OC- Octagonal, THC- Threaded Cylindrical

3.3 Fabrication of Tool Pin Profiles

High speed steel alloy (M42) tool is used for tool pin profile. It has superior red-hardness and wear resistance with high toughness. The three types of tool pin profile along with their specification are shown in **Table 4**. Pictorial views of all tool pin profiles are shown in **Fig. 1 (a, b and c)**. These tools are fabricated with the help of surface grinder and lathe.

3.4 Experimental Procedure

The level of each process parameter during each trial is expressed by means of experimentation log sheet as shown in **Table 5**.

The experiments were performed on vertical milling machine with a milling tool dynamometer and thermocouple. The pre-machined aluminum plates of 6061 and 6082 aluminium alloys were fixed rigidly. Two thermocouples are placed on the work piece at 25 mm distance from each other and 15 mm apart from weld line.

Table 4 : Types of Tool Pin Profile and Specifications

S. No.	Type of Tool Pin Profile	Specifications
A.	Threaded cylinder (THC)	Diameter of shoulder- 16 mm, Pin length- 7.4 mm, Diameter of pin- 6 mm, Thread- M6X0.80
B.	Tapered cylinder (TC)	Diameter of shoulder- 16 mm, Pin length- 7.4 mm, Diameter of pin- 7 mm- 5mm
C.	Octagonal (OC)	Diameter of shoulder- 16 mm, Pin length- 7.4 mm Diameter of pin- 6 mm

(a) Threaded Cylinder (b) Tapered Cylinder (c) Octagonol

Fig. 1 (a, b, & c) : Different types of tool pin profile

Table 5 : Experimentation control log using OA L_9

Experimental Run	Rotational speed (rpm)	Tool tilt (degree)	Types of tool pin profile
	RPM	TLT	TPP
1	900	0	TC
2	900	2	OC
3	900	4	THC
4	1550	0	OC
5	1550	4	THC
6	1550	4	TC
7	2200	0	THC
8	2200	2	TC
9	2200	4	OC

Experiments were performed according to L_9 OA as shown in **Table 6**. When the milling machine is turned on, the rotational motion of the spindle is started and the tool comes in to contact with the surface of the work-pieces. Now the tool pin is penetrated in between work-pieces to be welded. The tool is given some time as it rotates in contact with the surfaces to soften the material due to the frictional heating. This time is called as pre-heat time or dwell period. After dwell period, the milling table is given forward motion resulting formation of weld. The tool is withdrawn after the weld is fabricated. The experimental setup is shown in **Fig. 2**.

Fig. 3 and **Fig. 4** show the welded joints which are fabricated by friction stir welding and the top surface of welded joints, respectively. The experimental results of testing data of elongations and heat inputs are tabulated in **Table 6**.

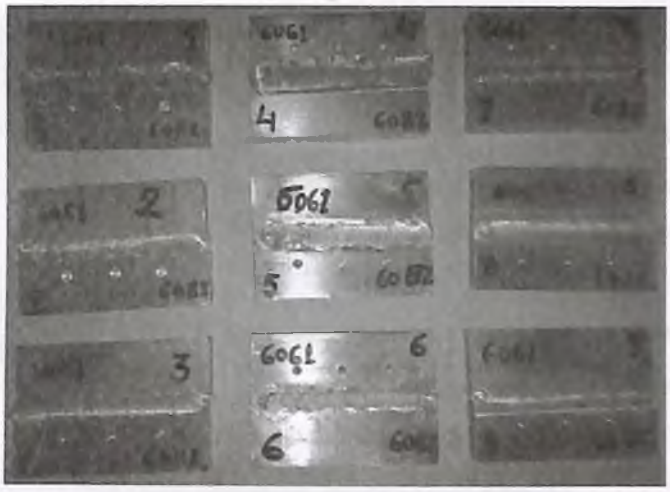


Fig. 3 : Friction Stir Welded work pieces.

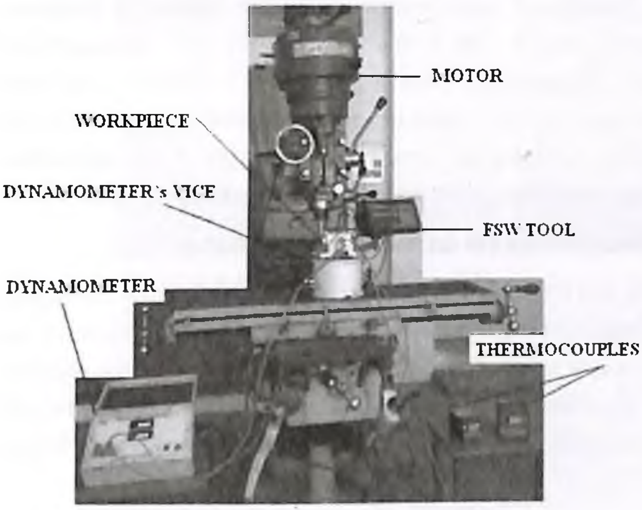


Fig. 2 : Experimental Setup of FSW.

Tensile strength, elongation and hardness of 6061 aluminium alloy are 286.08 MPa, 9% and 80 HRB, respectively. For the 6082 aluminium alloy, tensile strength, elongation and hardness are 318.27 MPa, 8% and 93 HRB, respectively.

For analyzing the data, mean and signal-to-noise ratios (S/N) of each control factor are calculated by using Minitab 15. Signals represent the effect on average responses. Noises are the measure of deviations from experimental outputs. In this experimental work, S/N ratio must be chosen according to criterion, 'Larger is better', in order to maximize the response.

Fig. 4 : Top surface images of the weld zone.

Table 6 : Experimental Results for the Elongation

Experimental Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Elongation (%)	5.10	5.60	5.40	6.13	6.06	5.97	5.10	5.20	5.60
Heat Input (J/s)	746.35	842.78	794.56	1507.98	1441.78	1331.44	2008.80	1875.58	2131.80

$$\left(\frac{S}{N}\right)_{HB} = -10 \log \left[\frac{1}{R}\sum_{j=1}^{R} 1/y_j^2\right] \quad \text{......(Eq. Larger is better)}$$

Where,

y = value of characteristic in an observation, j

R = number of repetition in a trial

4.0 RESULTS AND DISCUSSION

4.1 Microstructural Analysis

In fusion welding of aluminium alloys, the defects such as porosity, slag inclusion, solidification cracks, etc. deteriorates the weld quality and joint properties. Usually, friction stir welded joints are free from these defects since there is no melting takes place during welding and the metals are joined in the solid state itself due to the heat generated by the friction, and flow of metal by the stirring action. However, FSW joints are prone to other defects like pin hole, tunnel defect, piping defect, kissing bond and cracks due to improper flow of metal and insufficient consolidation of metal in the stir region [9]. In this experimental investigation, all the friction stir welded joints are analyzed at high magnification (400 X) using Trinocular Metallurgical Microscope with CCD camera to reveal the quality of joints. **Fig. 5 (a, b)** shows the microstructure of base material before welding. It is observed that the AA6082 has fine grains as compared to AA6061, which shows that the AA6082 has high tensile strength and elongation.

4.2 Influence of Process Parameters on Microstructure

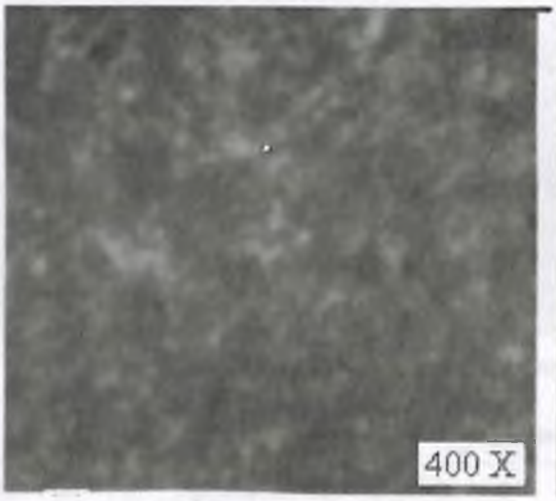
The microstructures of welded joints as per L_9 OA are shown in **Fig. 6 (a to i). Fig. 7 (d)** represents the microstructure of two dissimilar welds that gives highest mechanical properties. It is the combination of larger grains and fine grains of AA6061 and AA6082 alloys, respectively. It also shows the proper mixing of plasticized dissimilar metals.

Effect of Rotational Speed on the Microstructures

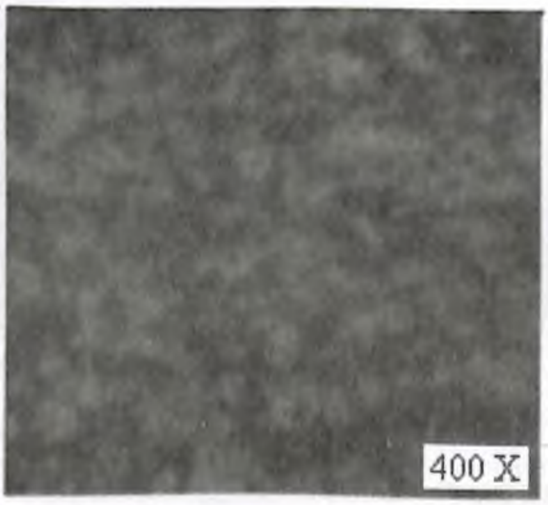
It is fact that the rotational speed is directly proportional to heat generation in FSW up to a certain extent. The frictional heat produced facilitates recrystalization of plasticized material that causes grain refinement in stir zone. At low rotational speed, tunnel defects occurred in middle of retreading side due to insufficient heat generated in joint region. At moderate speed, defect free joints formed with fine, equiaxed and recrystallized Si particles in the aluminium matrix of stir zone. At higher speed, turbulence in the plasticized metal produces broken Si particles, which are clustered in the aluminium matrix and forms non- homogeneous coarse grain structure.

Effect of Tool Tilt on the Microstructures:

The tool tilts significantly affect the appearance of the welded joints. When the tool tilt increases, the heat-affected zone deceases due to reduction in contact between tool shoulder and metal surface to be welded. The higher tool tilt produces appropriate forging action at trailing edge and forms defect-



(a) AA6061



(b) AA6082

Fig. 5 (a, b) : Optical microstructure of base materials

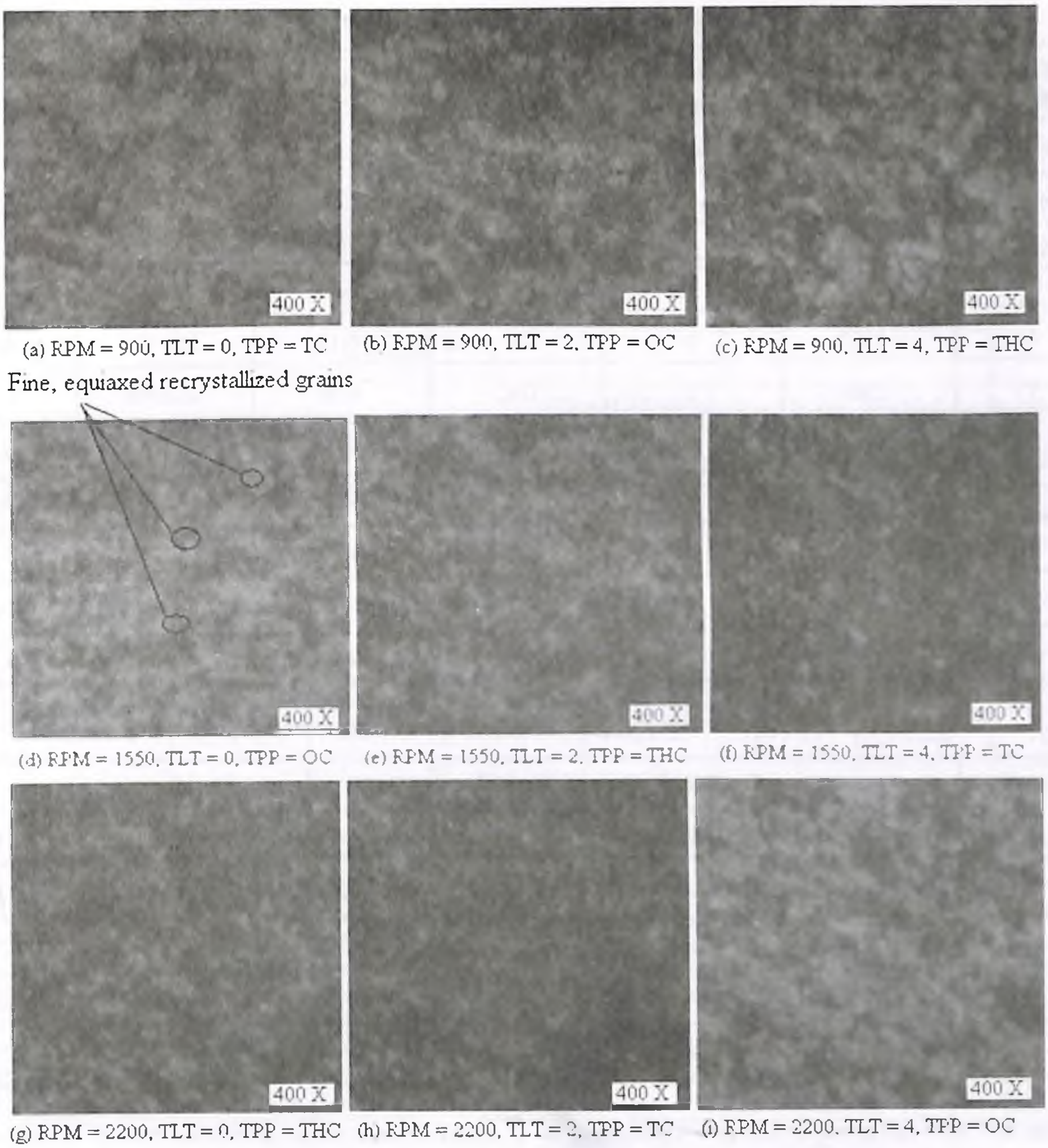


Fig. 6 (a to I) : Optical microstructure of the joints of L9 OA

free welded surface. At lower tool tilt, the contact between tool shoulder and workpiece surface are more that causes large heat affected zone. In the heat-affected zone, the grains are slightly dense due to heat generated in joint region.

Effect of Tool Pin Profiles on the Microstructures

The types of tool pin profile appreciably affect the micro-structures of welded joint. Tool pin profile is responsible for appropriate heat generation and stirring of plasticized metal. Due to proper mixing of plasticized metals, fine-equiaxed re-crystallized grain structures produced in weld nugget zone. The welded joints formed by octagonal type tool pin profile (OC) shows good microstructure characteristics instead of THC and TC tool pin profiles.

4.3 Analysis of Elongation

The mean responses of raw data and S/N ratios of elongation for each parameter at all levels are calculated by Minitab 15 and are shown in **Table 7**.

Table 7 : Test data summary for Elongation

Exp. Run	Rotational speed (RPM)	Tool Tilt (degree)	Types of tool pin profile	Elongation (%)	S/N Ratio (dB)	Elongation MEAN Value
1	900	0	TC	5.10	14.1514	5.10
2	900	2	OC	5.60	14.9638	5.60
3	900	4	THC	5.40	14.6479	5.40
4	1550	0	OC	6.13	15.7492	6.13
5	1550	2	THC	6.06	15.6495	6.06
6	1550	4	TC	5.97	15.5195	5.97
7	2200	0	THC	5.10	14.1514	5.10
8	2200	2	TC	5.20	14.3201	5.20
9	2200	4	OC	5.60	14.9638	5.60
				Average	**14.9018**	**5.57**

Table 8 : Factor effect on S/N data and average response (response table for S/N ratios and mean)

Level	For S/N Ratio			For Mean		
	RPM	**TLT**	**TTP**	**RPM**	**TLT**	**TTP**
1	14.59	14.68	14.66	5.367	5.443	5.423
2	15.64	14.98	15.23	6.053	5.620	5.777
3	14.48	15.04	14.82	5.300	5.657	5.520
Delta	1.16	0.36	0.56	0.753	0.213	0.353

The average S/N ratios and average mean values of elongation for each parameter at all three levels are given in **Table 8**. These values are plotted in **Fig. 7 (a, b, c)** and **Fig. 8 (a, b, c)** for mean and S/N ratio, respectively. Elongation is maximum at second level of rotational speed (RPM_2 i.e. 1550 rpm), third level of tool tilt (TLT_3 i.e. 40) and second level of tool pin profile (TPP_2 i.e. octagonal type). The S/N ratio also proposes the same levels as the best level for maximum elongation of the friction stir welded joints.

Table 9 and **Table 10** show the ANOVA result for S/N data and mean, respectively. The rotational speed, tool tilt and types of tool pin profile are significant parameters for elongation. Out of these parameters, rotational speed has maximum percentage contribution of 78.87 %, and tool tilt and types of tool pin profile have percentage contribution of 5.9 % and 15.12 % respectively. The value of R-Sq is nearest to one. R-Sq (0.999) shows good agreement with R-Sq (adj) (0.996).

Effect of Process Parameters on Elongation

Fig. 7 (a, b, c) shows the effect of process parameters on the Elongation.

Effect of rotational speed on Elongation

The **Fig. 7 (a)** shows the effect of rotational speed on elongation. Elongation increases with increase in rotational speed up to 1550 rpm, after that it decreases. This is due to increase in heat input. At 1550-rpm rotational speed, sufficient

Table 9 : Analysis of Variance for S/N ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% PC
RPM	2	2.46588	2.46588	1.23294	855.20	0.001	77.17
TLT	2	0.22003	0.22003	0.11001	76.31	0.013	6.89
TTP	2	0.50660	0.50660	0.25330	175.70	0.006	15.85
Residual Error	2	0.00288	0.00288	0.00144			
Total	8	3.19538					
S = 0.03797 R-Sq = 99.9% R-Sq(adj) = 99.6%							
Order of significance: 1. RPM, 2. TLT, 3. TPP							
*Significance at 95% level							

Table 10 : Analysis of Variance for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% PC
RPM	2	1.04347	1.04347	0.521733	745.33	0.001	78.87
TLT	2	0.07807	0.07807	0.039033	55.76	0.018	5.90
TTP	2	0.20007	0.20007	0.100033	142.90	0.007	15.12
Residual Error	20	0.00140	0.00140	0.00007			
Total	26	1.32300					
S = 0.03797 R-Sq = 99.9% R-Sq(adj) = 99.6%							
Order of significance: 1. RPM, 2. TLT, 3. TPP							
*Significance at 95% level							

heat input produces fine, equiaxed recrystallized grain structure leading to better elongation. At 900 rpm rotational speed, improper mixing of plasticized metal, due to insufficient heat input produced defective welded joints, which results lowering the elongation. Excess heat generated at higher rotational speed (2200 rpm) produces turbulence in plasticized metal zone. It results that formation of heterogeneous, broken Si particles, which gives lower elongation.

Effect of tool tilt on Elongation

Fig. 7 (b) shows that the elongation increases with increases the tool tilt. Tool tilt is responsible for surface contact between workpiece and tool shoulder. This contact leads to heat generation and flow of plasticized metal in weld zone. It also offered forging action at the trailing side of weld line which produces good surface appearance. High tool tilt angle, appropriate heat input and good forging action in weld zone, which produces fine, equiaxed, and recrystallized grain structure in welded joint, results in high elongation. At lower tool tilt angle, the large contact between tool shoulder and workpiece produce excess heat and heat affected zone (HAZ). This results is to produce coarse and non- homogeneous grain structures in weld region that causes lowering the elongation.

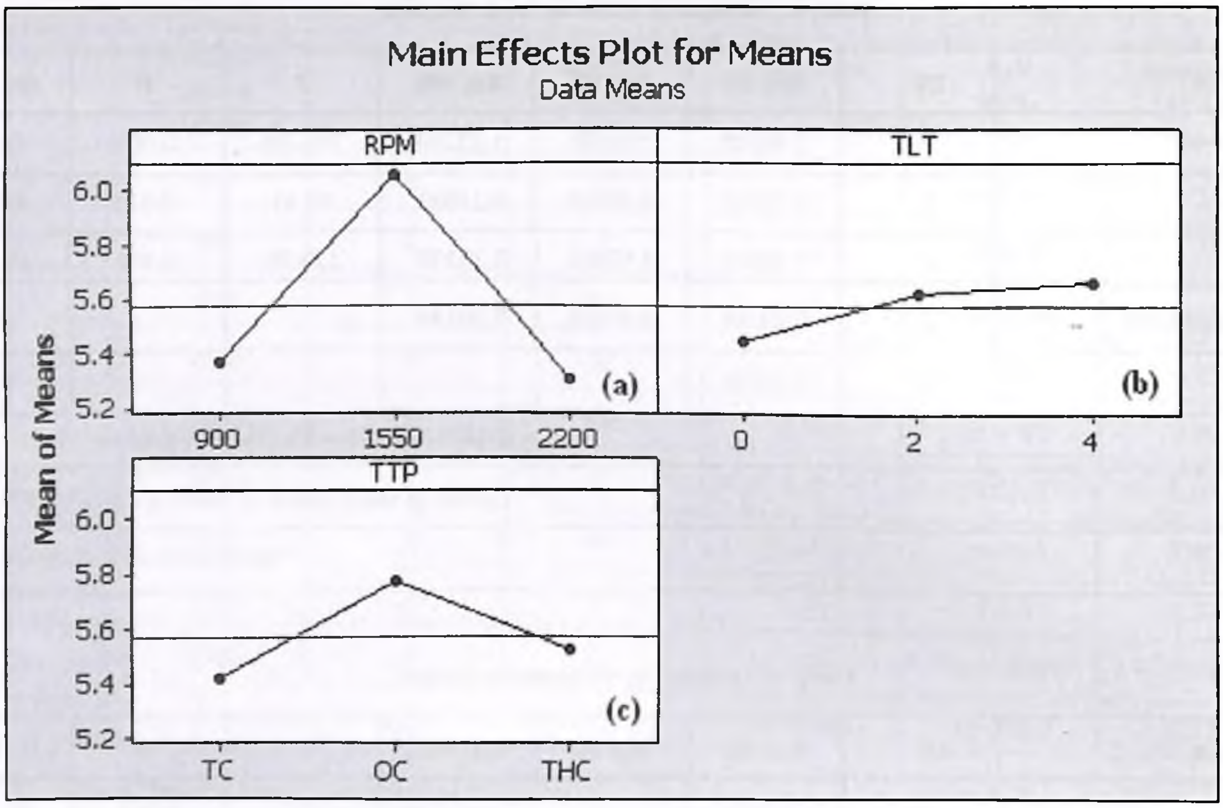


Fig. 7 (a, b, c) : Effects of process parameters on elongation (Main effects)

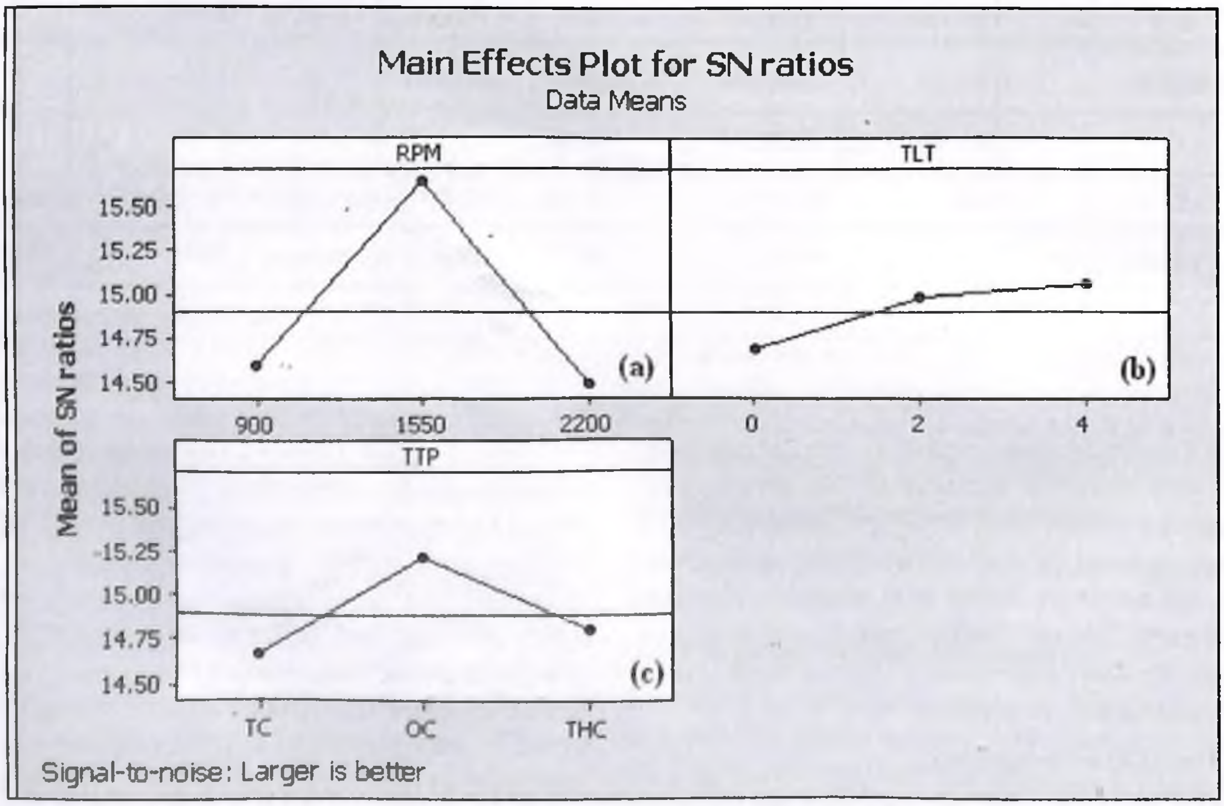


Fig. 8 (a, b, c) : Effects of process parameters on elongation (S/N effects)

Effect of tool pin profile on Elongation

The joints fabricated using the octagonal pin profile has higher elongation compared to tapered and threaded cylindrical pin profile. The behavior of these three types of tool pin profile with respect to mean elongations shown in **Fig. 7 (c)**. The octagonal type of tool pin profile produces good material stir quality and mixing of dissimilar plasticized metals during welding. This leads to high elongation welded joints. Threaded cylindrical and tapered cylindrical type tool pin profile produce insufficient mixing of dissimilar plasticized metals because tool pin is incapable of deforming appropriate metal during rotation. As a result, welding defects like pin holes, cracks and tunnel defects are formed.

Optimum Performance characteristics for Elongation

The optimum value of elongation is predicted based on the selected levels of significant process parameters. The significant process parameters and their optimum levels have already been chosen as rotational speed, at level 2 as RPM_2 (1550 rpm), tool tilt at level 3 as TLT_3 (4^0) and tool pin profile, at level 2 as TPP_2 (octagonal type). The estimated mean of response characteristic can be computed as [11] :

$$\mu_{EL} = \overline{T}_{EL} + (\overline{RPM}_2 - \overline{T}_{EL}) + (\overline{TLT}_3 - \overline{T}_{EL}) + (\overline{TPP}_2 = \overline{T}_{EL})$$

$$\mu_{EL} = [(\overline{RPM}_2) + (\overline{TLT}_3) + (\overline{TPP}_2)] - 2\overline{T}_{EL}$$

Where,

$\overline{T}_{EL}$ = Overall mean of elongation = 5.57 % (Table- 7)

$\overline{RPM}_2$ = Average value of elongation at level 2 of factor RPM = 6.053 % (Table- 8)

$\overline{TLT}_3$ = Average value of elongation at level 3 of factor TLT = 5.657 % (Table- 8)

$\overline{TPP}_2$ = Average value of elongation at level 2 of factor TPP = 5.777 % (Table- 8)

Hence,

μ_{EL} = 6.347

The confidence interval for the predicted mean for the confirmation experiment can be calculated by following equation-

$$C1_{CE} = \sqrt{F_\alpha(1,f_e)V_e\left[\frac{1}{\eta_{eff}} + \frac{1}{R}\right]}$$

Using the value V_e = 0.0000700 and f_e = 20 from **Table 10**, the confidence interval was calculated. Total degree of freedom (DOF) associated with the estimation of mean (μ_{TF}) = 2+2+2 = 6, Total number of experiments (N) = 3x9 = 27. Effective number of replications (η_{eff}) is calculated using equation

$$\eta_{eff} = \frac{N}{1+\text{Total DOF involved in estimation of mean}}$$

Therefore,

η_{eff} = 27/7= 3.857

Sample size for confirmation experiments R= 3

Tabulated F ratio at 95% confidence level

(α = 0.05): $F_{0.05;(1,20)}$ = 4.35

So,

CI_{CE} = ± 0.0134

The predicted mean of tensile strength is: μ_{EL} = 6.347

The 95% confidence interval of the predicted optimal elongation is:

$$(\mu_{EL} - CI_{CE}) < \mu_{EL} < (\mu_{EL} + CI_{CE})$$

$$6.3336 < \mu_{EL} < 6.3604$$

4.5 **Confirmation Test**

Three confirmation experiments are conducted at the optimum level of process parameters (RPM=1550, TLT= 4^0 and TPP= Octagonal type pin profile). The average mean value of the elongation of welded joints is found within the confidence interval as reported in **Table 11**.

Table 11 : Responses at optimum levels of process parameters

Responses	Predicted mean values	Experi-mental values (avg.)	Confidence Interval
Elongation	6.347	6.286	$6.336 < \mu_{EL} < 6.3604$

In this investigation, the estimated error between predicted mean value and experimental average value of elongation are 0.96 %.

5.0 CONCLUSIONS

The following conclusions derived from above experimental analysis:

(i) Minimum variation examined in microstructures of parents metals and friction stir welded joints of A6061 - A6082 alloys.

(ii) The rotational speed, tool tilt angle and types of tool pin profile parameters used in this investigation are significant for elongation. The elongation increases with increase in the tool rotational speed, up to certain limit and elongation decreases with further increase in the tool rotational speed.

(iii) The tool rotational speed has most significant process parameter with percentage contribution of 78.87% followed by tool pin profile with 15.12% and tool tilt angle with 5.90 % contribution.

(iv) Welded joint formed by octagonal tool pin profile has good weld qualities. It highly affects both the microstructure and elongation.

(v) The range of optimum values of elongation is in between $6.3336 < \mu EL < 6.3604$.

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