OPTIMIZATION OF FRICTION STIR WELDING PARAMETERS FOR AA6061 ALLOY USING A THREADED PROFILE PIN TOOL

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Abstract: FSW process is essential to making consistent and reliable friction stir welds and this requires an understanding of how tool design can influence process parameters, which in turn can provide high joint strength and performance. Tool optimization hinges on a better understanding of the effect of tool parameters on forces during welding, on the tool torque and tool temperature. Important parameters include flute design (e.g. number, depth, and taper angle), the tool pin diameter and taper, and the pitch of any thread form on the pin. These influences were investigated in this study, an experiment has been carried-out and Twenty- seven joints have been made on 6061 Al Alloy factors. The present study deals with the effect of Threaded Profile Pin on Friction Stir Welded Joint. FSW encompasses complex phenomena related with plastic flow deformation resulting from the stirring of the work pieces materials. The development of a process model would significantly contribute towards a better understanding of joint formation and resultant mechanical properties. Tool Rotational Speed, Welding Speed and Axial Force play a significant role in the assessment of Mechanical Properties. Using ANOVA and signal to noise ratio of robust design, effect of FSW process parameters is evaluated and optimum welding condition for maximizing mechanical properties of the joint is determined. In order to correlate process parameters and measured strength, a mathematical model has been developed. An attempt is made to analyze the microstructure of the joint.

Keywords: Aluminum alloy, FSW, Taguchi method, Tensile strength, Impact strength, ANOVA

1. INTRODUCTION

Welding is a process of permanent joining two metals through localized coalescence resulting from a suitable combination of temperature and pressure. Depending upon the combination of temperature and pressure from a high temperature with no pressure to a high pressure with low temperature, a wide range of welding processes has been developed using different energy sources, from a Gas Flame or Electric Arc to a Laser or Ultrasound. Welding is the most important way to join metals. It is the only way to join two or more pieces of metal to make them act as one piece. Welding is widely used to manufacture or repair all products made of metal. E.g.: Tall building structures, Rocket engines, Nuclear reactors, Home appliances and Automobiles.

Friction Stir Welding (FSW) process is used for welding of Aluminum Alloys as heat input during welding can be precisely controlled. Aluminum plates of 6 mm thickness have been used as the base material for preparing single pass butt welded joints. Taguchi techniques have been widely used for product or process on determining parameters and their performance measure with minimum variation optimization in material processing. It appears that optimization of FSW process parameters of Aluminum Alloy 6061 (Al-Mg-Si Alloy) used in the fabrication of Food Processing Equipment, Chemical Containers, Passenger Cars, Road Tankers and Railway Transport Systems has to be optimized by using taguchi method. This paper by using full factorial experimental design (3^3) with taguchi design concept analysis effect tool rotational speed, welding speed, and axial force of tensile strength and impact strength of FSW joints of A6061 Alloy. Fsw fig shown in fig-1.

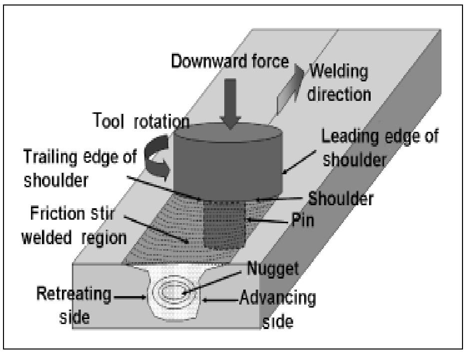

Fig.1. Schematic diagram of FSW

1.1. Microstructure classification:

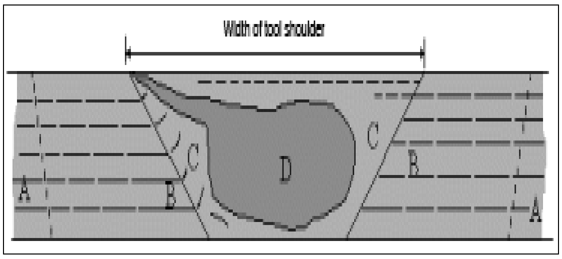

Fig.2. Schematic diagram of microstructure

A. Unaffected Material or Parent Metal:

This is a portion of material remote from the weld which has not been deformed, although it may have experienced a thermal cycle from the weld, is not affected by the heat in terms of micro- structure or mechanical properties.

B. **Heat Affected Zone (HAZ):**

In this region, which lies closer to the weld-center, the material has experienced a thermal cycle that has modified the microstructure and/or the mechanical Properties. However, there is no plastic deformation occurring in this area.

C. Thermo-Mechanically Affected Zone (TMAZ):

In this region, the FSW tool has plastically deformed the material, and the heat from the process will also exert some influence on the material. In the case of aluminium, it is possible to obtain significant plastic strain without recrystallization in this region, and there is generally a distinct boundary between the recrystallized zone (weld nugget) and the deformed zones of the TMAZ.

D. **Weld Nugget (WN)*:***

The fully recrystallized area, sometimes called the stir zone, refers to the zone previously occupied by the tool pin. The term stir zone is commonly used in friction stir processing, where large volumes of mate. microstructure is shown in fig-2.

2. EXPERIMENTAL SETUP

CAMPRO CPV-1100 vertical machining centre is used to fabricate the required joints**.** CPV-1100 is equipped with high precision and heavy loading series linear guide ways on 3 axes. It has automatic lubrication system for all linear guide ways and ball screws. CPV-1100 is constructed with high quality cast iron and heat treated to relieve stress thereby assuring maximum rigidity and accuracy. The base is reinforced by 'A' type rib layout to upgrade absorption capability of vibration and is constructed of a box type structure for excellent rigidity. The machine structure is designed via Finite Element Analysis (FEA) and advanced 3D software. Box ways on Z-axis, X/Y axes are equipped with precision heavy loading linear guide ways, featuring high positioning accuracy. The counter-balance system is equipped with a guide rail for increasing stability, avoiding vibration during high feed rate or rapid traverse and ensuring machining accuracy. The following table shows the specifications of CPV-1100 vertical machining centre

Table-1: Specifications of CAMPRO CPV 1100 VMC

Model cpv 1100	**UNITS**	
X- axis travel	**mm**	**1100**
Y-axis travel	**mm**	**560**
Z-axis travel	**mm**	**560**
Table dimension	**mm**	**550X 1200**
Max. Table load	**kg**	**800**
Spindle speed	**rpm**	**10000**
Spindle motor	**kw**	**11**
Spindle taper	**type**	**7/24 TAPER NO. 40**
Rapid feed rate (x/y/z)	**m/min**	**36/36/24**
Cutting feed rate	**mm/min**	**10000**
Standard power source		**220V 60HZ**
Power capacity	**KVA**	**20**
Machine weight	**kg**	**7000**

Tool dimensions

The friction stir welding technique uses a non consumable rotating tool to make the joint. The tool consists of Shank, body, shoulder, probe (or) pin. The tool used in this process was made of Tungsten carbide which has a tapered cylindrical pin and the dimensions are shown in Figure 3.

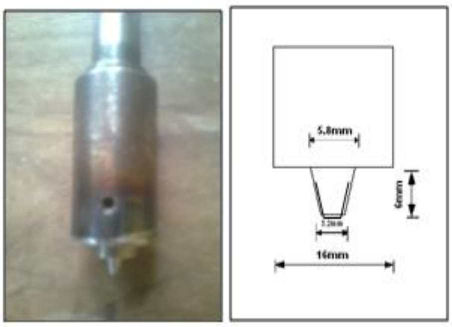

Fig.3. Tool dimensions

2.1. Experimental Procedure:

Process involved:

Friction Stir Welding (FSW) was carried out according to the following sequence. Four work pieces were abutted along a longitudinal section and rigidly on the thick backing plate, which was mechanically fixed on the bed of a Vertical Machining Centre (CAMPRO CPV-1100 series VMC). Tool which is shown in Figure 3.2 rotated anticlockwise and vertically inserted into the work piece. After entry of the pin to almost the thickness of the material and to allow the tool shoulder to just penetrate into the work pieces, the tool is transitioned along the joint line. The rotating tool develops frictional heat to the material, causing the metal to plasticize and produce a high integrity weld. The process parameters like rotational speed, welding speed and axial force play a significant role in assessment of mechanical properties of the joints. Similarly the experiment is repeated to join the remaining pieces by varying the process parameters.

Cutting aluminum strip:
The following procedure was adopted while carrying out the experimentation. Base metal sheets of dimensions 50mm x 150mm x 6.35 mm were cut on shearing machine

Joint fabrication: The methodology for joint considered in GTAW process consists 6061 Al Alloy of 6mm thickness plate (300mm x 50mm).the chemical composition and physical properties of Al 6061 is shown in Table 2.

Table – 2: Chemical composition of AA6061

Mg	Si	Fe	Cu	Cr	Mn	Zn	Ti	Al
0.8	0.6	0.5	0.3	0.25	0.15	0.2	0.15	Bal

Fig.4. Analysis of the joint

2.2. Analysis of the joint:

Specimen for tensile testing:-

The specimens thus prepared are extracted at the mid thickness region to obtain conservative test results. Transverse tensile specimens are machined to test the performance of the joint in tension. The FSW specimens are then machined for dumble shape to evaluate Tensile strength

. The Figure-5 shows the photographs of the FSW tensile test specimen before testing.

Fig.5. specimens for tensile testing

Specimen for impact testing

The specimens thus prepared are extracted at the mid thickness region to obtain conservative test results. The FSW specimens are then machined for rectangular shape to evaluate impact strength. The Figure-6 shows the photographs of the FSW impact test specimen before testing.

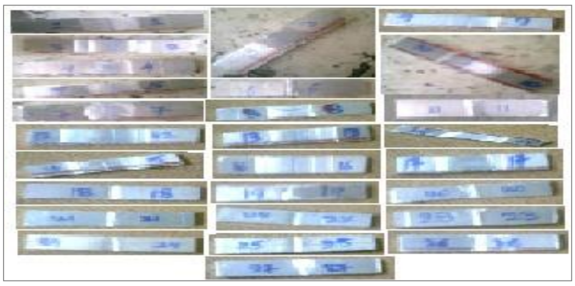

Fig.6. specimens for impact testing

3. RESULTS AND DISCUSSION

3.1 Results from ANOVA

In order to asses influence of factors on response means and s/n for each control factor to be calculated. The Tensile Strength and Impact Strength, of each Specimen is recorded and Presented in the Table-6. Signals are indicators of effect on average responses and noises are measures of deviations from experiment output. Appropriate S/N ratio must be chosen using previous knowledge, expertise and understanding of the process in this study S/N ratio was chosen to criterion larger the better, in order to maximize response. In Taguchi method s/n ratio is used to determine deviation of quality characteristics from desired value. S/N ratio where ‘n’ is the number of tests and y is the experimental value, Impact & Tensile test data was analyzed to determine in order to maintain root gap and alignment shown in fig-4,and the welding machine specifications is shown in table-1.

S/N = -10*log (mean square of the inverse of the response) : $S/N = -10\log_{10}\left(\frac{1}{n}\sum\frac{1}{y^2}\right)$

Analysis of variance (ANOVA) has been performed to identify statistically significant process parameters which affect statistically significant process parameters which affect of FSW joint (table -7).results of ANOVA indicate that selected process parameters are highly significant factors affecting IS&TS of FSW joints.

Optimizing tensile strength:

Analysis of mean for each of experiments gives better combination of parameter levels. Mean responses refers to average value performances characteristics for each parameter at different levels. Mean for one level war s calculated as average of all responses that were obtained with that level. Mean response of raw data S/N ratio of TS for each parameter at level 1, 2, 3 were calculated. it has been observed that the optimum parameters for FSW of Aluminum Alloy 6061 joint strength is maximum at 2000r.p.m tool rotational speed at 72mm/min welding speed with 2kn axial force in comparison to the joints at other process parameters.

Estimation of optimum process parameters

The methods described in this investigation for responses prediction and optimization can eliminate the need for performing experiments on the basis of the conventional trial and error method which is time consuming and economically not justifiable. The present study is aimed at to identify the most influencing significant parameters and percentage contribution of each parameter on responses of FSW 6061 aluminum joints by conducting minimum number of experiments using Taguchi orthogonal array. Based on the highest values of the S/N ratio and mean levels for the significant factors N, S and F the overall optimum condition thus obtained were N3, S3 and F2.

The optimum value of Tensile Strength is predicted at the selected levels of significant levels of significant parameters. The estimated mean of

Estimation Of Optimum Process Parameters

The methods described in this investigation for responses prediction and optimization can eliminate the need for performing experiments on the basis of the conventional trial and error method which is time consuming and economically not justifiable. The present study is aimed at to identify the most influencing significant

the response characteristics (yield strength) can be computed as Tensile Strength

(TS) = N3+S3+F2-2TS ------ equation 1

Where TS is the overall mean of the tensile strength in Mpa, N3 is the average tensile strength at second level of tool rotational speed 2000 rpm, S3 is the average tensile strength at first level of welding speed 72 mm/sec, F1 is the average tensile strength at first level of axial force 2kn. Substituting the values of various terms in equation 1 then

Tensile strength = 140.7233+141.8411+ 135.3755-2(134.30) = 149.33Mpa

Confirmation test for the responses

The final step is verifying the improvement in responses by conducting experiments using optimal conditions. Three confirmation experiments were conducted at the optimum setting of process parameters.

Table-3: confirmation experiment for tensile strength

	Optimal tensile parameters	
	Predicted	Experimental
Setting level	N3,S3,F2(2000,72,2)	N3,S3,F2(2000,72,2)
Tensile Strength (Mpa)	149.33	152.81

Optimizing impact strength:

Analysis of mean for each of experiments gives better combination of parameter levels. Mean responses refers to average value performances characteristics for each parameter at different levels. Mean for one level war s calculated as average of all responses that were obtained with that level. Mean response of raw data S/N ratio of TS for each parameter at level 1, 2, 3 were calculated. it has been observed that the optimum parameters for FSW of Aluminum Alloy 6061 joint strength is maximum at 1600r.p.m tool rotational speed at 60mm/min welding speed with 1.5kn axial force in comparison to the joints at other process parameters.

parameters and percentage contribution of each parameter on responses of FSW 6061 aluminum joints by conducting minimum number of experiments using Taguchi orthogonal array. Based on the highest values of the S/N ratio and mean levels for the significant factors N, S and F the overall optimum condition thus obtained were N2, S2 and F1

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The optimum value of Impact Strength is predicted at the selected levels of significant levels of significant parameters. The estimated mean of the response characteristics (yield strength) can be computed as Impact Strength

(IS) = N2+S2+F1-2IS --------- equation 2

Where IS is the overall mean of the impact strength in Mpa, N2 is the average impact strength at second level of tool rotational speed 1600 rpm, S2 is the average impact strength at second level of welding speed 62 mm/sec, F1 is the average impact strength at first level of axial force 1.5kn. Substituting the values of various terms in equation 2 then

Impact strength = 597.1522+740.5944+ 544.3277 - 2(751.2255) = 379.67

Confirmation Test for the Responses

The final step is verifying the improvement in responses by conducting experiments using optimal conditions. Three confirmation experiments were conducted at the optimum setting of process parameters.

Table-4: confirmation experiment for impact strength

	Optimal impact parameters	
	Predicted	Experimental
Setting level	N2,S2,F1 (1600,62,1.5)	N2,S2,F1 (1600,62,1.5)
Impact Strength(Mpa)	379.67	694.32

STATISTICAL ANALYSIS

Table-5: Process parameters and their level

Process parameters	range	Level 1	Level 2	Level 3
Tool rotational speed (N), rpm	1200 - 2000	1200	1600	2000
Welding speed(S), mm/min	48 -72	48	60	72
Axial force (F), kN	1.5 – 2.5	1.5	2	2.5

Table-6: S/n response table for tensile strength (ts):

Levels	N	S	F
1	41.9563	42.0792	42.5114
2	42.5883	42.3945	42.6073
3	42.8830	40.9540	42.3089

Table-7: S/n response table for impact strength (is):

LEVELS	N	S	F
1	54.8534	55.6749	56.0914
2	55.4208	56.9960	55.8431
3	54.3551	51.9583	52.6947

ANNOVA RESULTS:

Table-8: Tensile Strength versus Tool rotation speed (N), Welding speed(S), Axial force (F)

Factor	Dof	Sum of squares (ss)	Mean squares (mss)	F-test	% of contribution (cr)
N	2	943.4836	471.7418	3.41	20.07250632
S	2	869.4720	434.7360	3.14	18.49791797
F	2	2341.4752	1170.7376	0.43	49.81461832
RES	20	545.9468	27.2973	1	11.61495739
TOTAL	26	4700.3777			100

Table-9: Impact Strength versus Tool rotation speed (N), Welding speed(S), Axial force (F)

Factor	Dof	Sum of squares (ss)	Mean squares (mss)	F-test	% of contribution (cr)
N	2	259692.6444	129846.322	1.48	8.97702904
S	2	589427.7497	294713.8749	3.37	20.37527878
F	2	296196.4475	148098.2238	1.69	10.23888881
RES	20	1747540.508	87377.0254		60.40880337
TOTAL	26	2892857.35			100

Table-10: Confirmation Experiment for Impact strength

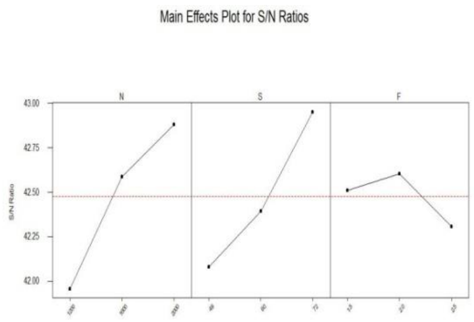
	Optimal impact parameters	
	Predicted	Experimental
Setting level	N2,S2,F1 (1600,62,1.5)	N2,S2,F1 (1600,62,1.5)
Impact Strength (kn/mm²)	979.67	694.32

Table-11: Confirmation Experiment for Tensile strength:

	Optimal tensile parameters	
	Predicted	Experimental
Setting level	N3,S3,F2 (2000,72,2)	N3,S3,F2 (2000,72,2)
Tensile Strength (Mpa)	149.33	152.81

GRAPHS

Tensile test for s/n



Impact test for s/n

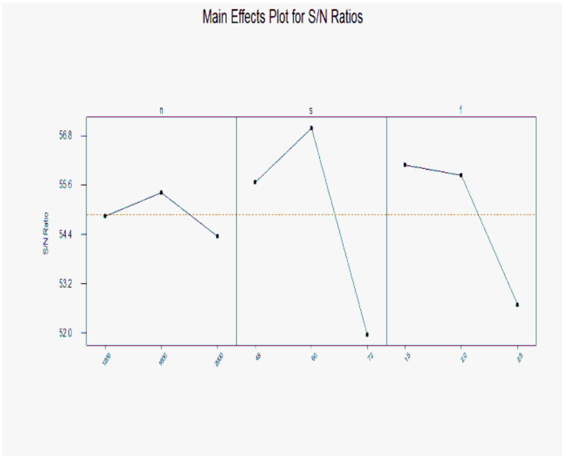


Table – 12: Design matrix and experimental results of 6061 Al Alloy

Original Value			Tensile Strength Mpa	Impact Strength Kn/mm²	Tensile SN	Impact SN
Tool rotational speed(r.p.m)	Welding speed(mm/min)	Axial force(kn)				
1200	48	1.5	109.13	702.14	40.7588	41.0915
1200	48	2	125.32	728.25	41.9604	44.73427
1200	48	2.5	133.05	1973.89	42.4802	44.66551
1200	60	1.5	112.24	714.16	41.0029	45.45354
1200	60	2	122.16	730.04	41.7385	40.11047

1200	60	2.5	131.48	1260.43	42.3771	44.51032
1200	72	1.5	121.68	224.14	41.7043	42.26349
1200	72	2	137.42	248.42	42.7609	32.98864
1200	72	2.5	145.61	261.60	43.2638	43.70461
1600	48	1.5	124.61	552.13	41.9110	43.06105
1600	48	2	136.24	572.43	42.6860	45.30296
1600	48	2.5	145.48	594.54	43.2560	43.88807
1600	60	1.5	122.68	694.32	41.7754	45.19761
1600	60	2	132.61	709.24	42.4515	43.90526
1600	60	2.5	143.47	737.23	43.1291	41.61469
1600	72	1.5	124.89	484.12	41.9305	44.88505
1600	72	2	139.61	507.16	42.8983	42.65927
1600	72	2.5	152.00	523.20	43.6368	38.97999
2000	48	1.5	115.52	441.25	41.2531	42.08359
2000	48	2	127.89	462.42	42.1367	39.25875
2000	48	2.5	136.13	487.52	42.6790	42.22995
2000	60	1.5	131.48	595.45	42.3771	42.78877
2000	60	2	144.32	606.16	43.1865	41.54372
2000	60	2.5	155.81	618.32	43.8519	40.73896
2000	72	1.5	139.32	491.24	42.8802	40.76843
2000	72	2	152.81	509.13	43.6830	41.92151
2000	72	2.5	163.23	523.20	44.2559	39.05779

CONCLUSIONS

- A suitable material was selected and suitable tool profile is fabricated for FSW process
- Weld joints of 6061 AL alloy obtained at tool rotation speed 2000 rpm, welding speed 72mm/sec, and axial force 2kn
- exhibits maximum ensile strength than the joints at other process parameters.
- Weld joints of 6061 AL alloy obtained at tool rotation speed 1600 rpm, welding speed 60mm/min, and axial force 1.5KN exhibits maximum Impact strength than the joints at other process parameters.
- The best input parameter combination for getting high impact strength is identified by taguchi's S/N ratio analysis. For high impact strength, the optimum parameters are tool rotation speed 1500 rpm, welding speed 60mm/min, and axial force 2.5KN.
- The best input parameter combination for getting high tensile strength is identified by taguchi's S/N ratio analysis. For high tensile strength, the optimum parameters are tool

rotation speed 2000 rpm, welding speed 72mm/sec, and axial force 2kn.

- The mathematical model developed in this study, will be useful in determining the change in tensile strength, if there is change in any one of the parameters of FSW.

- Grain size obtained at the welded geometry is nearly equal to the grain size obtained on the surface of the work piece.

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