Influence of Flat Friction Stir Spot Welding Process Parameters on Quality Characteristics of AA6082 Weld

Bhoopendra Singh[1], A. K. Gautam[2]

[1]M.Tech Scholar, [2]Assistant Professor
Maharishi University of Information Technology,
Lucknow, U. P.

***Abstract*: Friction stir spot welding (FSSW) has been proposed as an effective technology to spot weld the so-called "difficult to be welded" metal alloys. In the paper, a variation of the FSSW process has been considered. The method of flat friction stir spot welding (FFSSW) was used to investigate the tensile behaviour of three thin dissimilar aluminium alloys (Two sheets of AA6082-T6 and one sheet of AA6061-T6). Tool with probe and a probe less tool is used in this two-step process of joining. Experiments were conducted at various tool tilt angles (TTA), tool rotational speeds (TRS), dwell time (DT) and Tool plunge depths (TPD). The quality welds were produced at optimized process parameters (TTA 20, TRS 2125 rpm, DT 15 s and TPD 0.1 mm). Elimination of protuberance and reduction of keyhole in the joint is achieved for improving bonding length.**

Taguchi analysis was used to optimize the parameters of this investigation for obtaining high tensile strength. Micrographs of joints were examined using optical microscopy and scanning electron microscopy (SEM). The complete bonding with finer grains at stir zone (SZ) improved the strength of FFSSW joint. Energy-dispersive X-ray (EDX) and X-ray diffraction (XRD) analysis of specimen indicates the presence of Mg2Si precipitates in SZ. The fracture behaviour of upper and lower interfaces was examined. X-ray diffraction results in compressed residual stress are also obtained as it helps in obtaining the weld free from cracks. The mechanical properties of three-sheet FFSSW joints were compared with other similar techniques of joining. Better understanding of mechanical properties and weld behaviour of three sheets FFSSW is done with the help of fractography and SEM.

***Keywords*: Friction stir welding, Stif zone, Al-Cu metal, resistance spot welding, Heat affected zone (HAZ). Thermo-mechanically affected zone (TMAZ).**

INTRODUCTION

Industries demand materials that deliver significant mass reduction while ensuring user safety and durability, fuel economy gains and enhanced performance. Weight of product can be reduced by replacing traditional materials like steel with lightweight materials like aluminium, magnesium, etc. Various evolving applications of these emerging lightweight materials in automotive, aerospace, shipbuilding and industries led to research in developing alternative joining technologies for similar and dissimilar materials. Conventional spot welding is the primary method of joining automotive sheet materials due to its ease of implementation, productivity and lower cost. However, the process has disadvantages such as incompatibility, electrode wear and poor joint strength. Various solid state friction based welding methods are developed as they are energy efficient and considered as green technologies. Above problems are overcome by friction stir welding (FSW) technique. FSW technology has been widely recognized for its ability to provide joints with improved welding properties and low distortion in a wide variety of aluminium alloys. Improper process parameters setting in FSW may lead to the formation of defects like voids, flash, etc. Self-piercing riveting (SPR) is another method for joining, which is broadly used in automotive industry. But due to cost of rivets, Friction stir spot welding (FSSW) can be alternative process to reduce the cost. FSSW provides several technical advantages including shorter welding time, lower energy requirements, ease of automation and easy welding of dissimilar metal alloys with uneven thickness. Problem associated with keyhole formed inevitably during retraction of tool in FSSW. These problems are avoided by various researchers in recent years by incorporating evolutionary enhancements to FSSW. Various refilling approaches for reducing the keyhole have been developed such as refill FSSW (RFSSW), double-sided FSSW, modified friction stir clinching (MFSC), protrusion FSSW (PFSSW), etc.

Three-sheet welded configuration introduced by the automotive industries has been facing new challenges as compared to two-sheet lap joints. Flat friction stir spot welding (FFSSW) of three sheets is complicated compared to two sheets as extra interface is introduced with different combination of materials. The technique of FFSSW is introduced in this work to study the influence of parameters on the joint strength and weld microstructures. FSSW method has been applied for joining metallic and polymeric materials. Various researchers have investigated the significant effects of different process parameters for FSSW process on microstructure, mechanical properties, failure modes, fatigue behavior, mechanical properties of different zones. Ojo et al. investigated the effect of TRS, TPD and DT on failure load (FL), expelled flash volume (EFV) and effective bonded size (EBS) of conical pin FSSW of AA2219-O alloy. The percentage contribution of TRS and PD on multi responses are 48.42% and 39.54% respectively. Chu et al. applied Box-Behnken DOE approach in response surface methodology to investigate the effects of TRS, DT and plunge rate on TSS of AA2198 sheets using probe less friction stir spot welding (P-FSSW). The optimized value for failure load of 7.83 KN was achieved at DT of 7.2 s, TRS of 950 rpm and plunge rate of 30 mm/min. Paidar et al. investigated the influence of TRS on microstructural, mechanical properties and fracture behavior of dissimilar aluminium alloys (AA2024-T3 & AA7075-T6) joined using modified friction stir clinching (MFSC) process. TSS and cross tensile load is increased from 6.7 KN to 9.4 KN and 4.3 KN to 6.8 KN respectively as the TRS is increased. With this novel joining process, quality joints are produced eliminating hook defect. Sun et al. investigated the effect of applied load, TRS and welding speed on microstructural and the mechanical properties of FFSSW welded AA6061-T6 alloys with configuration of three sheets. Three different test modes (Type I, Type II and Type III) showed a fracture load of 6.4, 6.3 and 4.4 KN respectively. Kluz et al. studied the effect of tool plunge depth, tool rotational speed and duration of welding on joint load capacity and failure mode of AA7075-T6 sheets using refill friction stir spot welding (RFSSW). Joint strength was increased 8.3%, 11.5% and 17.9% for 3.5 s, 2.5 s and 1.5 s respectively. Ravi et al. compared FSSW joints prepared with sandwich and tri-metallic sheets (Al6082-T6/HDPE/Al6082-T6/HDPE/ Al6082-T6). The fracture load was found to be 1.4 KN and 2.8 KN for sandwich sheets and tri-metallic sheets respectively. Around 60% reduction in load bearing capacity was observed in sandwich sheets for all the tool configurations. Shahrabadi et al. investigated the effect of TRS and PD on metallurgical and mechanical properties of a drawing quality special killed low carbon steel (DQSK) using novel method of PFSSW. The TRS of 2500 rpm and PD of 0.3 mm have provided the maximum load, elongation and fracture energy. Enami et al. investigated the effect of TRS, DT and PD on strength of Al 2024 joint prepared using FFSSW. 23% increase in strength of joint was found after addition of alumina Nano powder in keyhole.The main objective of the work is to investigate the fracture points on the weld zone as well as to analyse the mechanical strength of the weld. An attempt has been made to optimise the parameters to maximise the tensile strength of the FSW joint.

MATERIALS AND METHODS

Materials

The material used in the present research work are:-

- **AA6082 Alloy: -** AA6082 is selected for FSSW. It has the highest strength among 6xxx series alloy. It is mostly used in automotive parts and aircraft applications. The chemical and mechanical properties of the used material are as follows

Parameter	**Values**
Ultimate Tensile Strength (MPa)	140-330
Yield Strength (MPa)	280
Elongation	10%

Element	**Content**
Si	0.7-1.3
Fe	0.0-0.5
Cu	0.0-0.1
Mn	0.4-1.0
Mg	0.6-1.2
Zn	0.0-0.2
Ti	0.0-0.1
Cr	0.0-0.25

- **H13 Steel:-** H13, hot die steel is used as a tool with probe and without probe. It has good hardness characteristics such as red hardness, wear hardness and it also have high toughness that are the most requisite Flat FSSW. The chemical composition of H13 die steel is shown in Table below.

Element	**Content**
C	0.40
Mn	0.40
Si	1.00
Cr	5.25
Mo	1.35
V	1.00

Methodology

Experimental Setup

The Flat FSSW process is done with vertical milling machine. This machine welds the plates of AA6082 with the help of drilling process and the weld is created by frictional heat generated by the rotation of the tool on the workpiece.

For measuring the mechanical strength of the welded joint nine samples of three layers are prepared with the help of flat FSSW process. The nine samples are prepared and Pre-drilled cavity Base Plate and Fixture with Three AA 6082 plates are empanelled for this research work.

Experimental Procedure

In the present research work three sheets of AA6082of area 100x30x1mm are subjected to Flat FSSW. Firstly, the surface of aluminium sheets is cleaned with the help of acetone to remove dirt and organic impurities attached to its surface. Two plates of same dimension i.e. 100x30x1 mm and third plate of dimension 50x30x1 mm is used for the experiment. Plate having dimension (50x30x1) mm is placed below the two plates.

The total procedure is divided into two step

- Step 1:- The arrangement of three sheets are placed on pre-dent plate having diameter 6 mm and depth of the dent 3 mm. Now another fixture called cover plate having diameter of 20 mm is placed on this arrangement having hole in it for entry of the tool. Now, the rotating tool with probe having shoulder diameter 20 mm, probe of 2.9x6 mm is used for joining three aluminium plates with the help of frictional force produced in the set up. During this process a keyhole is formed on the upper side of the plates and protrusion on the lower side of the plates due to flow of the work piece material in the pre drilled cavity of the base plate. The base plate have pre drilled cavity on one surface and the another surface of the same plate is without cavity. Now the position of the base plate is changed, having flat surface on upward side is used.
- Step 2:- Now the weld having protrusion is placed above it and probe less rotating tool having flutes on its surface is used for removing the keyhole and the protrusion of the weld under the application of certain load. In this process tool rotation speed having range 400 rpm, 975 rpm and 1550 rpm is used at the dwell time 4 s, 6s and 8s.

Analysis

Taguchi Based Experiment

Taguchi Method

Taguchi method is also known as robust design method was invented by Genichi Taguchi. This method helps in improving the quality of the manufactured goods. It uses two or three parameters to evaluate the effect of variability of particular process characteristics. The three categories of process parameter characteristics areas follow:

i) Lower the Better
ii) Nominal the Better
iii) Higher the Better.

The quality of the characteristics was calculated on the basis of signal to noise (S/N) ratio. The desirable value of the output is represented by Signal and the undesirable value of the output characteristics is represented by Noise. The main goal of S/N ratio is to expand the process that is not sensitive to noise and increases the tensile strength. The S/N ratio can be calculated as:

$$S/N \text{ ratio } (\eta) = -\ 10 \log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_i^n\right]$$

Selection of orthogonal array (OA)

The orthogonal array selection depends on the following items on the basis of their order of priority:

- The number of factors and interactions of interest.
- The number of levels for the factors of interest.
- The desired experimental resolution or cost limitations.

In this, three levels and three factors are taken into reflection. L9 OA is used in this investigation. 2 is the degrees of freedom (DOF) for each factor, where number of level is -1 i.e. 3-1=2) and 3×2=6 is the total degrees of freedom. The DOF of the OA should be greater than the total DOF of the factors. As the DOF of L9 is 8.

Analysis of Variance

ANOVA method was proposed by Sir Ronald Fisher to compare the outcome of the actual experiment. It is a numerical method which splits the total variation into liable sources. The main objective of ANOVA is to find out how the process parameters affect the response and the factors reviewed in the experiment. In this investigation rotational speed of tool, dwell time (DT) and plunge depth (PD) are considered as a significant factors affecting the hardness and tensile strength of the welded joint. Rotational speed of tool and plunge depth is considered as highly significant factors because ‘p’ value is less than 0.05.The dwell time (DT) plays a minor role in affecting the tensile strength.

RESULT

Result for Analysis of Tensile Strength

L9 Designed Experimental Layout (Tensile Strength)

Sr.No	Input Parameter Coded values			Input Parameter Un-coded Values			
	A	B	C	RPM	DT	PD	TSS
1	1	1	1	400	4	2.6	48.1
2	1	2	2	400	6	2.8	20.5
3	1	3	3	400	8	3.0	46.6
4	2	1	2	975	4	2.8	19.1
5	2	2	3	975	6	3.0	13.7
6	2	3	1	975	8	2.6	35.0
7	3	1	3	1550	4	3.0	42.1
8	3	2	1	1550	6	2.6	19.4
9	3	3	2	1550	8	2.8	11.7

Experimental values of Tensile strength on the basis of L9 OA

S.No	Input Parameter Coded Values			Tensile Strength (TSS)	SN Ratio (S/N)	Mean Value
	A	B	C			
1	1	1	1	20	26.0206	20
2	1	2	2	14	22.9225	14
3	1	3	3	17	24.6089	17
4	2	1	2	16	24.0824	16
5	2	2	3	19	25.5750	19
6	2	3	1	42	32.4649	42
7	3	1	3	33	30.3702	33
8	3	2	1	48	33.6248	48
9	3	3	2	49	33.8039	49
Average					28.1636	28.6666

Response table for S/N Ratios

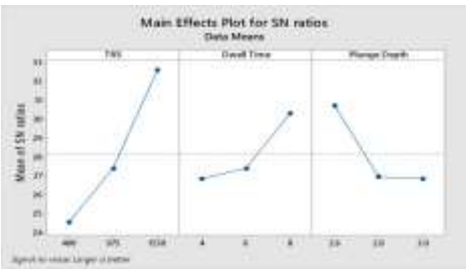
Level	RPM	DT	PD
1	24.52	26.82	30.70
2	27.37	27.37	26.94
3	32.60	30.29	26.85
Delta	8.08	3.47	3.85
Rank	1	3	2

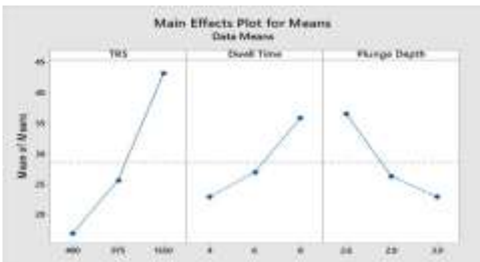
Response table for Means

Level	RPM	DT	PD
1	17.00	23.00	36.67
2	25.67	27.00	26.33
3	43.33	36.00	23.00
Delta	26.33	13.00	13.67
Rank	1	3	2

The value obtained on the basis of mean values are A3B3C1

Result for Parameter Effect





Main effects of process parameters

Process Parameter	Level	S/N Ratio			Mean		
		RPM	DT	PD	RPM	DT	PD
Average Value	L1	24.52	26.82	30.70	17.00	23.00	36.67
	L2	27.37	27.37	26.94	25.67	27.00	26.33
	L3	32.60	30.29	26.85	43.33	36.00	23.00
Main Effects Difference	L2-L1	2.85	0.55	-3.76	8.67	4.00	-10.34
	L3-L2	5.23	2.92	-0.09	17.66	9.00	-3.33
	(L3-L2)-(L2-L1)	2.38	2.37	-3.85	8.99	5.00	-13.67

Result for Hardness Analysis

S.No	Input Parameter Coded Values			Hardness (MHV)	SN Ratio (S/N)	Mean Value
	A	B	C			
1	1	1	1	60.75	35.6709	60.75
2	1	2	2	62.25	35.8827	62.25
3	1	3	3	65.25	36.2916	65.25
4	2	1	2	63.25	36.0212	63.25
5	2	2	3	64.75	36.2247	64.75
6	2	3	1	64.75	36.2247	64.75
7	3	1	3	65.25	36.2916	65.25
8	3	2	1	63.75	36.0896	63.75
9	3	3	2	66.25	36.4237	66.25
Average					**36.1245**	**64.02**

Result for Variation analysis for S: N analysis

Source	Degree of Freedom	Adjusted sum of square	Adjusted mean square	F-Value	Percent Value (p-value)	Percentage contribution (%PC)
RPM	2	8.3889	4.1944	151.00	0.007	35.61%
DT	2	9.0556	4.5277	163.00	0.006	38.44%
PD	2	6.0556	3.0277	109.00	0.009	25.71%
Error	2	0.0556	0.02778			0.24%
Total	8	23.5556				100%
S = 0.166667 R-Sq = 99.76% R-Sq(adj) = 96.06%						
*Significance at 95% level						

Conclusions

In this work, AA6082 alloy was welded by the use of flat FSSW (F-FSSW). To analyse the process parameter's effect on tensile strength and hardness, various experimental analyses are carried out such as micro structural analysis, SEM analysis, X-ray Diffraction, Residual stress analysis. The various points can be concluded from this experimental work is as follows:

- Rotational speed of tool, Dwell time, and plunge depth are the significant parameters for tensile strength.
- The percentage contribution of rotational speed is 64.94%, Dwell time is 15.98%, and plunge depthis18.31% in case of tensile strength.
- The optimum values of tensile strength is 57.88 < TS <59.45.
- The percentage contribution of rotational speed, shoulder rotational speed is and welding speed for hardness are 35.61%, 38.44%, and 25.71% respectively.
- The optimum values of hardness is 36.26< MH <36.95.
- The defect-free joints were welded by F-FSW means keyhole and cracks are eliminated.
- The result of the residual stress is compressive residual stress with negative values which helps in eliminating the cracks.
- Protrusion formed in this welding process was removed to achieve the good strength of weld.

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