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Optimisation of Process Parameters Friction Stir Welding

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ABSTRACT

Friction stir welding (FSW) is a relatively new solid-state joining process. This joining technique is energy efficient, environment friendly, and versatile. In particular, it can be used to join high-strength aerospace aluminum alloys and other metallic alloys that are hard to weld by conventional fusion welding. The FSW parameters such as tool rotational speed, welding speed, welding tool shoulder diameter, and welded plate thickness play a major role in determining the strength of the joints. Aluminium alloys have gathered wide acceptance in the fabrication of light weight structures requiring a high strength and good corrosion resistance.

Keywords: *Aluminium Alloy; Friction Stir Welding; Hardness; Taguchi Technique; Analysis of Variance.*

1.0 Introduction

1.1 History of friction stir welding

Friction Stir Welding (FSW) was invented by Wayne Thomas at The Welding Institute (TWI) Ltd in 1991 and overcomes many of the problems associated with traditional fusion welding techniques such as shrinkage, solidification cracking and porosity. FSW is a solid state process which produces welds of high quality in difficult to weld materials such as aluminium and is fast becoming the process of choice for manufacturing light weight transport structures such as boats, trains and aero planes. Since its invention, the process has received world-wide attention, and today FSW is used in research and production in many sectors, including aerospace, automotive, railway, shipbuilding, electronic housings, coolers, heat exchangers, and nuclear waste containers.FSW has been proven to be an effective process for welding aluminium, brass, copper, and other low melting temperature materials. The latest phase in FSW research has been aimed at expanding the usefulness of this procedure in high melting temperature materials, such as carbon and stainless steels and nickel- based alloys, by developing tools that can withstand the high temperatures and pressures needed to effectively join these materials. Fabricators are under increasing pressure to produce stronger and lighter products whilst using less energy, less environmentally harmful materials, at lower cost and more quickly than ever before.

FSW, being a solid state, low energy input, repeatable mechanical process capable of producing very high strength welds in a wide range of materials, offers a potentially lower cost.

2.0 Introduction of Friction Stir Welding

Friction Stir Welding (FSW) is a solid state joining process that uses friction generated by a rotating cylindrical tool and applied pressure to heat and plasticize metal on either side of a joint creating a solid functional weld.

Friction generated heat is more effective at recognizing the microstructure of metals and metal alloys than other forms of Fusion Welding, but FSW can be a much slower process. Friction Stir Welding is used to weld soft metal like Aluminium

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which cannot be welded by traditional/conventional processes.
The welding of aluminium and its alloys has always represented a great challenge for researchers and technologists. FSW is a new welding process that has produced low cost and high quality joints of aluminium alloys. For carrying out research work in any area, the first and an important phase is to review the available literature for the selected topic and the research problem can be formulated with clear objectives.

Friction stir welding (FSW) is a relatively new joining process produces no fumes; uses no filler material; environmentally friendly and can join several metal alloys such as aluminium, copper, magnesium, zinc, steels, and titanium. FSW sometimes produces a weld that is stronger than the base material.

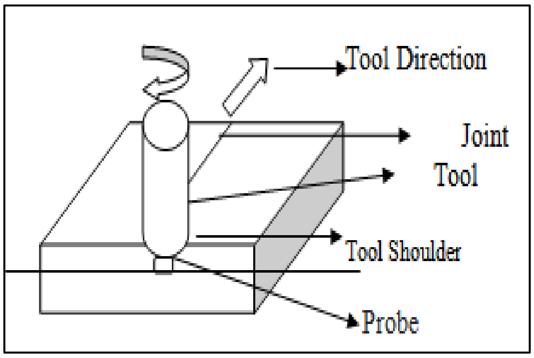
In FSW process heat generated by friction between the surface of the plates and the contact surface of a special tool, composed of two main parts: shoulder and pin. Shoulder is responsible for the generation of heat and for containing the plasticized material in the weld zone, while pin mixes the material of the components to be welded, thus creating a joint. This allows for producing defect-free welds characterized by good mechanical and corrosion properties.

The advantages of FSW are due to the fact that the process is carried out with the material to be welded in the solid state. Avoiding melting prevents the production of defects, due, for instance, to the presence of oxygen in the melting bath, and limits the negative effects of material metallurgical transformations and changes strictly connected with changes of phase. Finally, the reduced thermal flux, with respect to traditional fusion welding operations, results in a reduction in residual stress state in the joints and, consequently, in distortions in the final products.

As compared to the conventional welding methods, FSW consumes considerably less energy. No cover gas or flux is used, thereby making the process environmentally friendly. The joining does not involve any use of filler metal and therefore any aluminum alloy can be joined without concern for the compatibility of composition, which is an issue in fusion welding. When desirable, dissimilar aluminum alloys and composites can be joined with equal ease. The materials used in airframe structures and in jet engine components are critical to the successful design, construction, certification, operation and maintenance of aircraft . Materials have an impact through the entire life cycle of aircraft, from the initial design phase through manufacture and certification of the aircraft, to flight operations and maintenance and, finally, to disposal at the end-of-life. Aluminum alloys are very promising for structural applications in aerospace, military, and transportation industries due to their low density, high specific strength and resistance to corrosion, and especially regarding high energy cost. AA 6063 is an aluminium alloy, with copper as the primary alloying element. It is used in applications requiring high strength to weight ratio, as well as good fatigue resistance. It is weldable only through friction welding, and has average machinability.

1.3 Principle of operation

Fig 1: Friction Stir Welding Process



A constantly rotated non consumable cylindrical tool with a profiled probe is transversely fed at a constant rate into a butt joint between two clamped pieces of butted material. The probe is slightly shorter than the weld depth required, with the tool shoulder riding atop the work surface. Frictional heat is generated between the wear resistant welding components and the work pieces. This heat, along with that generated by the mechanical mixing process and the adiabatic heat within the material, cause the stirred materials to soften without melting.

As the pin is moved forward, a special profile on its leading face forces plasticized material to the rear where clamping force assists in a forged consolidation of the weld.

2.0 Objectives

Therefore keeping in view the background, literature review and gaps thereon, this research work aims at:-

- Multi factors at a time have to be taken into account.
- Various CTP parameters should be taken into account.
- Parameters should be well optimised by using Taguchi method.
- Different tool pin should be used for better joint.

3.0 Methodology

3.1 Selection of work piece and tool

In the present investigation Aluminum 6063 plates were used to prepare the welded joint. The work piece was sliced to the dimension of 100 mm (L) X 100 mm (W) X 6.8 mm (T) using power hacksaw.

The Chemical properties of the base material are given in the table 1.The tool used in this investigation was made of HSS. The tool was designed with straight cylindrical pin and it has the following dimensions, tool shoulder diameter 18mm, pin diameter 6mm, and pin length 6.5 mm.

3.2. Selection of process parameters:

In the present study four process parameters such as Tool Rotation Speed, Thickness of Sheet, Diameter of Tool, Tilt Angle, which are mostly contribute to heat input and subsequently influence the mechanical properties of the welded joints were selected in two different levels. The table 2 shows the process parameters and their levels.

3.3. Experimental planning

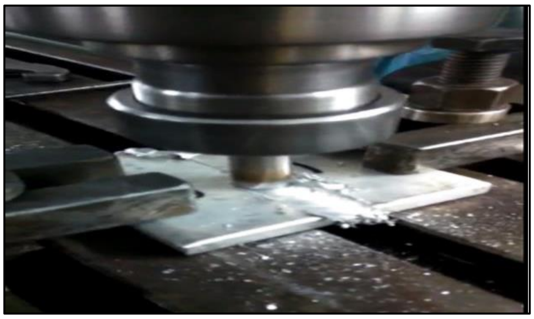
The friction stir welding process is performed on vertical milling machine. Friction stir welds is to be made on the plates of aluminum alloy 6063.The plates are to be cut from the sheet of aluminum alloy material.

Single- pass friction stir butt joint is to be made using a friction stir welding tool which was fabricated from a material HSS.The total length of the tool should be 125mm.The shoulder diameter should be 18mm and pin diameter should be within(0.85-5.0) mm. The welded plate is in rectangular shape with a size of (150mm×100mm×6mm). The used welding parameters are tool rotational speed, thickness and tool tilt angle. The weld plates is to be suitably clamped in the suitable fixture for hold the plates in such a manner that both the plates cannot move from its position during the welding process. The fixture provides a base to place the plates for ensuring the proper flat position.

Table 2: Process Parameters and their Levels

Level	1	2	3
Rotation Speed (rpm)	1410	2120	2830
Tilt Angle (degree)	0	1	2
Tool Type (geometry)	Tapered	Threaded	Cylindrical

Fig 2: FSW Set up



3.4. Taguchi method:

The main objective in the Taguchi method is to design robust systems that are reliable under uncontrollable conditions the method aims to adjust the design parameters (known as the control factors) to their optimal levels, such that the system response is robust – that is, insensitive to noise factors, which are hard or impossible to control. The method presented in this study is an experimental design process called the Taguchi design method.

Taguchi proposed that engineering optimization of a process or product should be carried out in a three-step approach:

- System design,
- Parameter design,
- Tolerance design.

We are considering mainly parameter design of Taguchi method in our experiment. Parameter designis related to finding the appropriate design factor levels to make the system less sensitive to variations in uncontrollable noise factors, i.e., to make the system robust.The steps included in the

Taguchi parameter design are: selecting the proper orthogonal array (OA) according to the numbers of controllable factors or parameters; running experiments based on the Orthogonal array ; analyzing data; identifying the optimum condition; and conducting confirmation runs with the optimal levels of all the parameters. The main effects indicate the general trend of each parameter. Analysis of variance (ANOVA) is the statistical treatment most commonly applied to the results of the experiments to determine the percentage contribution of each parameter against a stated level of confidence of Taguchi suggests two different routes for carrying out the complete analysis. In the standard approach the results of a single run or the average of repetitive runs are processed through the main effect and ANOVA (raw data analysis). The second approach, which Taguchi strongly recommends for multiple runs, is to use the signal-to-noise (S/N) ratio for the same steps in the analysis.

In order to examine process parameters effects on hardness of the joints, the statisticaltechniques of Taguchi method and analysis of variance (ANOVA) were selected. Taguchi method utilizesOAs from experimental design theory to study a large number of variables with a small number ofexperiments. OAs are subsets of the full factorial experiment which are balanced, i.e., each variable settingoccurs the same number of times and none of two experiments are the same (or even mirror images). UsingOAs significantly reduces the number of experimental configurations to be studied. Taguchi has simplifiedtheir use by providing tabulated sets of standard OAs and corresponding linear graphs to fit specific projects [16].

Three stages of Taguchi approach to design the experiments are as follows:[16]

1. Planning a matrix experiment to determine the effect of the control factors,
2. Conducting the matrix experiment,
3. Analyzing and verifying the results.

In this work, four factors at four levels were selected based on the literature and qualitative experiments.The matrix experiment was designed according to the Taguchi parameter design methodology, L9 OAto investigate the effect of four controllable factors (tool rotational speed, thickness of specimen, tiltangle and tool pin geometry) on the tensile shear strength.

Fig 3: Workpiece after FSW

Table 1: Chemical Composition of Base Material [6] :

Material	Si	Fe	Cu	Mn	Mg	Cr	Zn
Al 6063	0.2 – 0.6	0.35	0.1	0.1	0.45 – 0.9	0.1	0.1

4.0 Observation

Level	1	2	3
Rotational Speed (rpm)	1410	2120	2830
Tilt Angle (degree)	0	1	2
Tool Type (geometry)	Taper	Threaded	Cylinder

The parameters we have considered for investigation are tool rotation speed, tool type and tool tilt angle. The selected process parameters and the levels are shown in the table 3.

4.1. Hardness test result

The Rockwell Hardness test makes use of indentation to measure the hardness of the different specimens. The machine generally has different types of scales to get the readings but here B scale was used to check readings.The specimen is first loaded with the help of minor load then after that major load is applied with the minorload still applied. The indentation on the specimen is done by the indenter then reading is noted on the B scale and a dimensionless number of hardness is got in the form of HRC number. If the penetration of indenter ismore the hardness will be less and vice-versa. Reading of the test is given below in the table no.4.

Fig 4: Rockwell Hardness Machine

Selection of Orthogonal Array

Based on the number of factors and levels a suitable Taguchi orthogonal array for the experiment is selected by using MINITAB 17 statistical software. Since there are three factors having three levels each, L9 OA is chosen as shown in table 4 .

Table 4: Orthogonal Array for L9 with Hardness:

Experiment no.	Input parameters			Hardness
	Rotational Speed	Tilt Angle	Tool Types	
1	1			76
2	1			73
3	1			75
4	2			75
5	2			76
6	2			75
7	3			77
8	3			76
9	3			74

From the Rockwell Hardness Test Parent material hardness is found to be 70.

4.2. Optimization by taguchi method

In order to optimize FSW process parameters, hardness was analyzed. To assess the influence of factors on the response, the means for each control factor can be calculated. The steps included in the Taguchi parameter design are: selecting the proper orthogonal array (OA) according to the numbers of controllable factors or parameters; running experiments based on the Orthogonal array ; analyzing data; identifying the optimum condition; and conducting confirmation runs with theoptimal levels of all the parametersoptimal levels of all the parameters.. The main effects indicate the general trend of each parameter. Analysis of variance (ANOVA) is the statistical treatment most commonly applied to the results of the experiments to determine the percentage contribution of each parameter against a stated level of confidence of Taguchi suggests two different routes for carrying out the completeanalysis. In the standard approach the results of a single run or the average of repetitive runs are processed through the main effect and ANOVA (raw data analysis).

Table 5: L9 Table Used for Taguchi Analysis :

Rotation Speed	Tilt Angel	Tool Type	Hardness
1410	0	Tapered	76
1410	1	Threaded	73
1410	2	Cylindrical	75
2120	0	Threaded	75
2120	1	Cylindrical	76
2120	2	Tapered	75
2830	0	Cylindrical	77
2830	1	Tapered	76
2830	2	Threaded	74

5.0Result & Discussion

5.1. General linear model

Hardness Vs Tool Type, Tilt Angle, Rotation Speed

Factor Coading (-1, 0, +1)

The factors we have considered for investigation are tool rotation speed, tool type and tool tilt angle. The selected process parameters and the levels are shown in the **Table 6**.

5.2. Anova analysis

The main purpose of the ANOVA is the application of a statistical method to identify the effect of individual factors on the process response. Results from ANOVA can determine very clearly the impact of each factor on hardness. The ANOVA table is calculated and listed in Table 7.The Taguchi experimental method could not judge the effect of individual parameters on the entire process, thus the percentage of contribution using ANOVA is used to compensate for this effect.

The confidence intervals of the differences between means, which is a range of values that is likely to include the population differences.

T-value: The T-value in one-way ANOVA is a test statistic that measures the ratio between the difference in means and the standard error of the difference. We can use the T-value to determine whether to reject the null hypothesis, which states that the difference in means is 0. However, the P-value is used more often because it is easier to interpret. Minitab uses the T-value to calculate the P-value. Number of observation in your sample. The DF for a term show how much information that term uses. Increasing our sample size provides more information about the population, which increases the total DF. Increasing the number of terms in our model uses more information, which decreases the DF available to estimate the variability of the parameter estimates.

Degree of Freedom: The total degrees of freedom (DF) are the amount of information in your data. The analysis uses that information to estimate the values of unknown population parameters. The total DF is determined by the AdjSS :Adjusted sums of squares does not depend on the order. The factors are entered larger predicted R values have better predictive ability.

SE of Difference: The standard error of the difference between means (SE of Difference) estimates the variability of the difference between sample means that you would obtain if you took repeated samples from the same populations. Use the standard error of the difference between means to determine how precisely the differences between the sample means estimate the differences between the population means. A lower standard error value indicates a more precise estimate. Minitab uses the standard error of the difference to calculate

Table 6: Factor Information

Factor	**Type**	**Levels**	**Values**
Tool Type	Fixed	3	Taper, Threaded, Cylindrical
Tilt Angle	Fixed	3	0, 1, 2
Rotation Speed	Fixed	3	1410, 2120, 2830

Table 7: Analysis of Variance:

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Tool Type	2	6.0000	3.0000	9.00	0.010
Tilt Angle	2	2.6667	1.3333	4.00	0.020
Rotation Speed	2	2.6667	1.3333	4.00	0.050

Table 8: Model Summary:

S	**R-sq**	**R-sq (adj)**	**R-sq (pred)**
0.577350	94.44%	77.78%	89.38%

Table 9: Coefficients

Term	Coef	SE Coef	T- Value	P- Value	VIF
Constant	75.000	0.192	389.71	0.000	
Rotation Speed					
1410	-0.667	0.272	-2.45	0.134	1.33
2120	-0.000	0.272	-0.00	1.000	1.33
Tilt Angle					
0	0.667	0.272	2.45	0.134	1.33
1	0.000	0.272	0.00	1.000	1.33
Tool Type					
Taper	0.000	0.272	0.00	1.000	1.33
Threaded	-1.000	0.272	-3.67	0.067	1.33

Regression Equation: In order to correlate process parameters and Hardness of welded joints, a nonlinear regression model was developed to predict Hardness of FSW Al 6063 alloy based on experimentally measured Hardness. Regression coefficients were calculated using statistical software, MINITAB 17. After determining significant coefficients, final model developed using only these coefficients to estimate Hardness as

Hardness= 75.000 - 0.667 Rotation Speed_1410 - 0.000 Rotation Speed_2120 + 0.667 Rotation Speed_2830 + 0.667 Tilt Angle_0 + 0.000 Tilt Angle_1 - 0.667 Tilt Angle_2 + 0.0 Tool Type_ taper -1.000 Tool Type_threaded + 1.000 Tool Type_cylidrical.

5.3. Discussion

It can be observed from the Table 5 that the hardness have been considerably improved by friction stir welding. Hardness is found to be lower at lower rotational speed (1410rpm). This is due to the insufficient heat generation resulting in poor plasticization zone and insufficient deformation by poor stirring action and insufficient deformationby the tool pin that may be reasons to decrease in properties . The resulting properties of material can be improved by providing sufficient heat to plasticise the material in order to ensure complete deformation with proper material flow and grain refinement through dynamic recrystallisation using higher rotational speeds.

5.4 Estimation of optimum performance characteristics

For calculating the maximum value of Hardness, firstly select the maximum value of tool rotational speed. Secondly select the tool type and then select the maximum value of tilt angle.The process parameters of Friction Stir Welding has been optimised as shown.

Hardness = A3 + B1 + C3 − 2T

Where,

T = Overall mean of hardness = 72.3 (table 4)

A3 = Average hardness at the third level= 76 (table 4)

B3 = Average hardness at the first level= 73 (table 4)

C3 = Average hardness at the third level= 74 (table 4)

Substituting the values of various terms in above Equation

Hardness =76+73+74-2x72.3

= 78.4

The 95% confidence interval of confirmation experiments (CIce) and of population (CIpop) calculated. Which is CIce = ±0.0321 and CIpop = ±0.0213.

The predicted optimal range (for a confirmation runs of nine experiments) is 70.4 < hardness < 78.9

5.5 Confirmation test

Three confirmation experiments were conducted at the optimum setting of the process parameters. The hardness was set at the third level (A3), second at the first level (B1), and hardness at the third level (C3). The average hardness of material in the process was found to be 75.7, which was within the confidence interval of the predicated optimal of hardness.

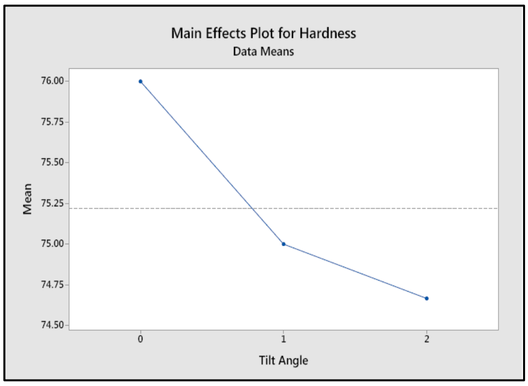
Graph represent Hardness on Y-axis and Tilt angle on X-axis.

The Graph shows that hardness decreases with increase in Tilt angle. The reason behind this, is change in the properties of material. Initially, when tilt angle is zero the hardness is maximum. And as tilt angle goes on increasing, hardness started to decrease.

When the tilt angle is more than zero, insufficient heat is generated which results in poor plasticisation zone.

Along with this, insufficient deformation also takes place with poor stirring action and tool pin

Fig 5. Main Effect Plot for Hardness Vs Tilt Angle

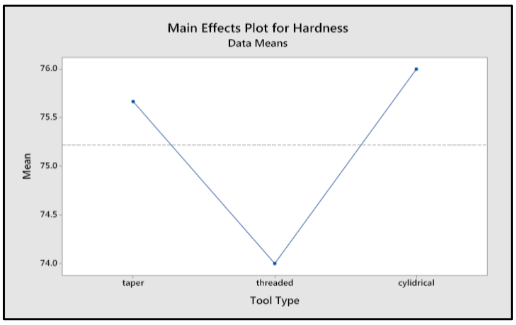


Graph represent Hardness on Y-axis and Tool Type on X-axis.

The Graph shows that-

Hardness is maximum when tool type is tapered

Fig 6: Main Effects Plot for Hardness Vs Tool Type



Hardness is minimum when tool type is threaded.

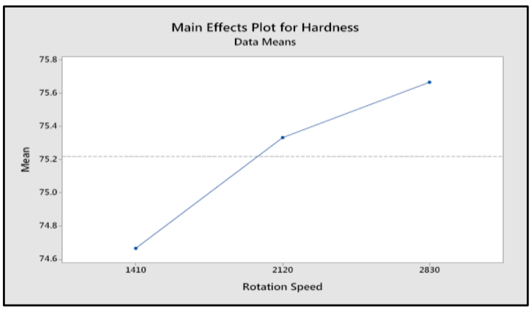
Hardness is again maximum when tool type is Cylindrical.

When tool type is Threaded, poor plasticize zone is created by insufficient heat generation, and poor stirring action produce less deformation, therefore hardness is minimum. When tool type is tapered and cylindrical, sufficient amount of heat is provided to plasticise the material and complete deformation take place with proper material flow, therefore hardness is maximum. In case of cylindrical tool, all factor are better. Therefore hardness is more.

Graph represents Hardness on on Y-axis and Rotational Speed on X-axis.

The Graph shows that the Hardness increases as the rotational speed increases.

Fig 7: Main Effects Plot for Hardness Vs Rotation Speed



The reason is-at low speed, insufficient heat is generated due to this poor plasticize material is produced, and insufficient deformation took place by poor stirring. Therefore Hardness is low.

At high speed, sufficient amount of heat is provided to plasticize the material, so that complete deformation takes place with proper material flow and grain refinement through dynamic re crystallization. Therefore Hardness is high.

Graph shows cumulative representation of hardness :

This graph represents change in hardness with all three factors namely:

Rotational Speed, Tilt Angle, and Tool Type

Graph shows cumulative representation of hardness :

This graph represents change in hardness with all three factors namely: Rotational Speed, Tilt Angle, and Tool Type.

Fig 8: Main Effects Plot for Hardness

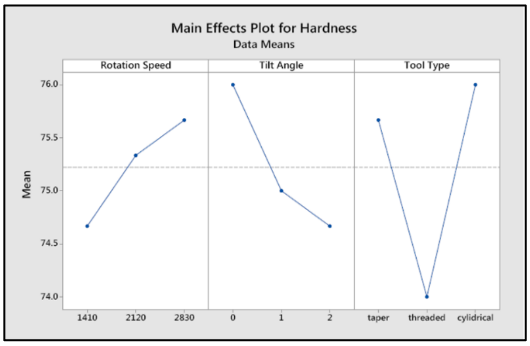
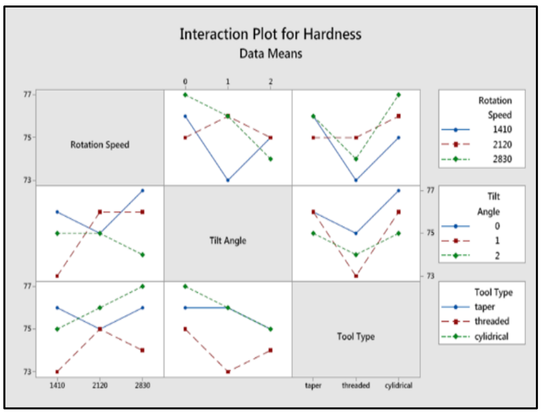


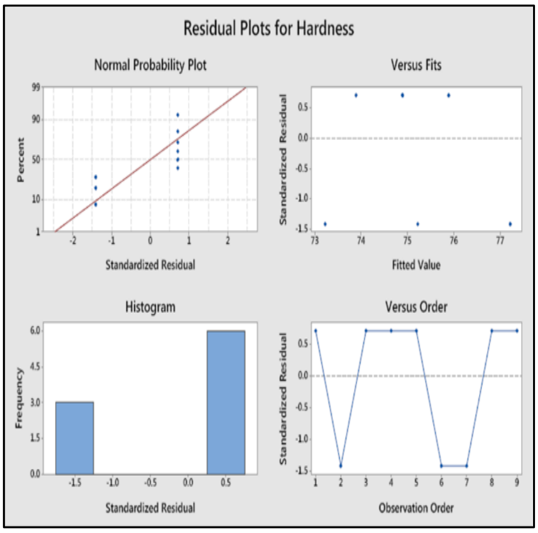
Fig 9: Interaction Plot for Hardness



Graph represents Interaction between all three factors including two at time:

Rotational Speed with Tilt Angle and Tool Type.Similarly Tilt Angle with Rotational speed and Tool Type.

Fig 10: Residual Plot for Hardness



Residual is the fitting error i.e. it is the difference between the actual sample value and the observable estimate. Standardized Residual is defined as the residual divided by the standard deviation of residuals.

Normal Probability Plot of The Residuals :The normal plot of the residuals displays the residuals versus their expected values when the distribution is normal. Use the normal probability plot of residuals to verify the assumption that the residuals are normally distributed. The normal probability plot of the residuals should approximately follow a straight line.

Residuals Versus Fits :The residuals versus fits graph plots the residuals on the y-axis and the fitted values on the x-axis. Use the residuals versus fits plot to verify the assumption that the residuals are randomly distributed and have constant variance. Ideally, the points should fall randomly on both sides of 0, with no recognizable patterns in the points.

Residuals versus order: The residual versus order plot displays the residuals in the order that the data were collected. Use the residuals versus order plot to verify the assumption that the residuals are independent from other.

6.0 Conclusions

The butt joining of Aluminum alloy was successfully carried out using FSW technique. The samples were characterized by hardness. The following conclusions were made from the present investigation.

- We observed that the Tilt angle having more influence on the mean of Hardness.
- Observed that the 2830 rpm, 0 degree tilt angle and cylindrical tool was best to maximize the hardness.
- The tool tilt angle of 0° is favorable to weld low alloy steels with good mechanical and metallurgical properties.

Regression models were developed to predict the mechanical properties for various tool rotational speeds, tool type and tool angles without requiring experimental tests. The validity of the model developed was proved with an experimental test.

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