Mechanical and Metallurgical Characterization of Friction Stir Lap Welding Process for Aluminium and Titanium Alloy

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Abstract - *The butt joint with the help of the friction stir welding process is common and easy but when the think about the lap joint then the joining of two overlapping surfaces becomes difficult. Further FSW process traditionally used for joining of similar material, light metals, and alloy. To overcome the above problems this research work is carried out. In this research paper, the lap weld joint of dissimilar materials i.e. Aluminium 6061 and Titanium grade-2 are studied which is joined with help of the FSW process and the joint between them is a lap joint. The rotational tool speed, tool feed, and tool offset are used as process parameters while ultimate tensile strength as a response. The orthogonal array is used to design the experiments that give various combinations of process parameters and according to this workpieces are manufactured. Then Taguchi's analysis and ANOVA are used to optimization of process parameters for the responses. In the end, the metallurgical study of the joint is also conducted to investigate the joint at the microscopic level*

Keywords: Friction Stir Welding, Aluminium, Titanium, Tensile Test, Design of Experiment, ANOVA, Metallurgical Analysis

1.INTRODUCTION

Friction Stir Welding (FSW) very advanced joining process and it overcomes most of the disadvantages of the conventional welding process. In this process, the rotating tool having a designed pin profile is moved between the interface of overlapping workpieces. Thus, friction and heat are generated between them and plastic deformation takes place which leads to the joining of both workpieces.

2. EXPERIMENTAL SET-UP

The vertical milling machine is used for this process with a combination of the FSW tool and a rigid fixture. Both aluminium and titanium plates having the dimension are 115×30×3 mm. The tungsten carbide tool is used for this process as tungsten is harder than given workpieces while Mild Steel is used as fixture material which has sufficient strength to withstand the force and torque offered by the tool while welding operation.

2.1 Workpieces

The titanium and aluminium workpieces are shown in the following figure.

Fig-1: Aluminium And Titanium Workpiece

2.2 Tool

The tungsten carbide tool is shown in the following figure. It consists of three parts body shoulder and tapered cylindrical pin profile. The pin profile having 10^0 taper angle, 5 mm length, and 5 mm base angle.

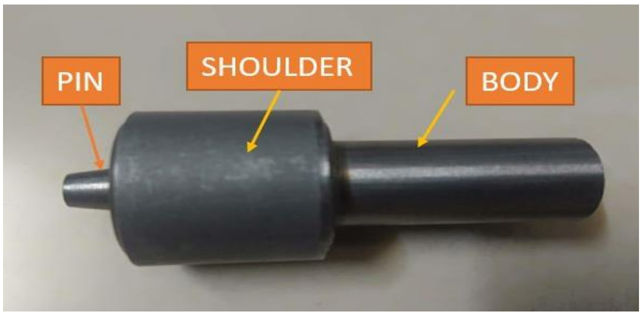


Fig-2: Tungsten Carbide Tool

2.3 Fixture

The fixture is shown in the following fig-3. Almost all parts of the fixture are made up of Mild steel.

Fig-3: Fixture

2.4 Process Parameter Selection

The tool rotational speed, tool feed (welding speed or transverse speed), and tool offset is used as process parameters**.** They are shown in the following table-1

Table-1: Process Parameters and Their Levels

Sr no.	Levels of parameter		
	Rotational tool speed (rpm)	Tool feed (mm/min)	Tool offset (mm)
1	600	10	-2
2	800	15	0
3	1000	20	2

3. EXPERIMENTATION

The following steps are used in this experimentation

1) Selection of input parameter
2) Clamping of fixture table
3) Clamping of workpiece on the fixture
4) Clamping the tool in the collet
5) Checking of the given arrangement
6) Starting of machine
7) Welding action takes place
8) Stops the machine
9) Remove the workpiece from the fixture
10) Put the workpiece on the table for air cooling
11) Repeating the above process for new workpieces

Fig-4: Vertical Milling Machine **Fig-5**: Tool Position

Fig-6: FSW on Al-Ti

4. TENSILE TEST

The tensile test is performing for evaluating the ultimate maximum load-carrying capacity of the joint. The digital varier scale is used to measure the cross-sectional area of the weld joint.

Table-2: Cross-Sectional Area of Welding Joints

Weld joint	Cross-section (b × t)	Area (mm^2)
1	35.85 × 6.23	223.34
2	32.70 × 6.74	220.42
3	33.27 × 6.61	219.92
4	33.08 × 6.80	224.95
5	32.76 × 6.93	227.03
6	30.04 × 6.90	207.27
7	34.32 × 6.72	230.60
8	33.54 × 6.74	226.08
9	36.72 × 6.23	228.81

Fig-7: Tensile Test of Workpiece On UTM

4.1 CALCULATION

The ultimate tensile strength of the joint is calculated from the following equation. The load is taken in newton (N) and the area in mm^2. The UTS is calculated for experiment 1.

$$\sigma = P / A$$
$$= 7400 / 223.34$$
$$= 33.13 \text{ MPa}$$

The welding joint strength is calculated as 33.13 MPa for the FSW experiment 1 and similarly, UTS for all workpieces are calculated by using the corresponding value of load and cross-section area.

Table-3: Tensile Test Result

Sr. No.	Rotational tool speed (rpm)	Tool feed (mm/ min)	Tool offset (mm)	Ultimate load (kN)	Ultimate tensile strength (MPa)
1	600	10	-2	7.4	33.13
2	600	15	0	6.4	29.04
3	600	20	2	6.0	27.28
4	800	10	0	13.2	58.68
5	800	15	2	9.2	40.52
6	800	20	-2	8.4	40.52
7	1000	10	2	20.4	88.46
8	1000	15	-2	16.4	72.54
9	1000	20	0	16.0	69.92

4.2 Effect of Tool Feed

The tool feed used in this process is 10,15,15 mm/min. The effect of tool feed on the tensile strength of the joints is shown in chart-1 and it is concluded the relationship between the tool feed and UTS is inversely proportional to each other. As the tool feed increases, the tool suddenly impacted the workpiece and deformed the workpiece position by creating tremendous vibrations. Thus joints become weak and UTS of the joint is reduced.

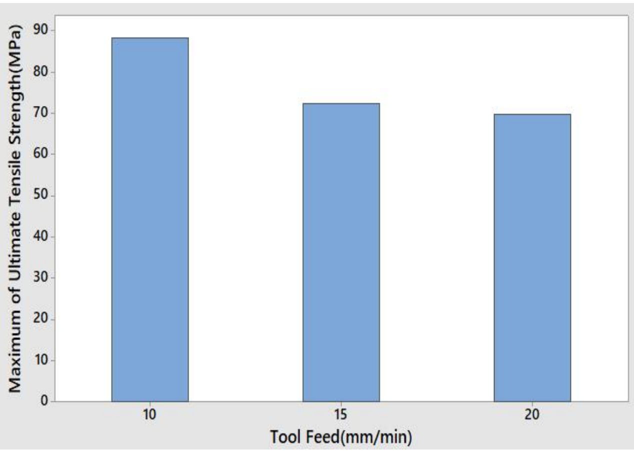


Chart-1: Effects of Tool Feed

4.3 Effect of Tool Offset

In this project work, zero, negative and positive tool offsets are used. When the tool axis is at the exact center of the joint then there is zero tool offset. There are 0 mm, -2 mm, and 2 mm tool offsets used in welding. When the tool offset is zero or negative then the tool pin is just touching the titanium surface and most of the tool pin portion is moved in the aluminium side. In this case, the tensile strength obtained is minimum because not enough tool pin stirring has occurred between both plates due to the lap joint. When the pin offset was positive i.e. 2 mm, the tensile strength of the joints was increased.

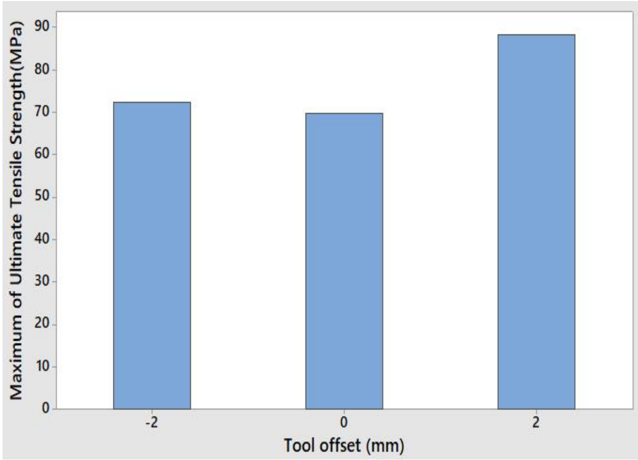


Chart-2: Effect of Pin Offset

4.4 Effect of Tool Rotational Speed

Three tool rotational speeds were used in this process i.e. 600 rpm, 800 rpm, and 1000 rpm. It is observed that the relationship between rotational speed and ultimate tensile strength is directly proportional. Maximum rotational speed gives the maximum tensile strength of the joint. From chart-3, it is shown that minimum tensile strength is obtained at 600 rpm and maximum tensile strength is obtained at 1000 pm. The maximum friction is also generated due to high rotational speed, thus the weld joint has high heat input, and the strength of the joint increases.

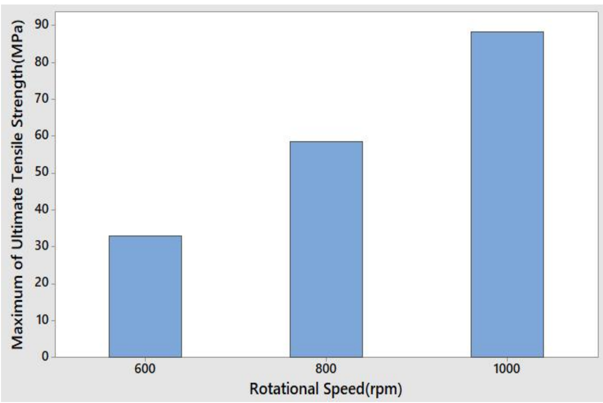


Chart-3: Effect of Tool Rotational Speed

5. OPTIMIZATION OF PROCESS PARAMETER

Taguchi's analysis is one of the tool or method used to minimize the number of experiments that are to be performed by particular process parameters with one or more levels. Taguchi's analysis is used for the design of the experiment i.e. formation of the orthogonal array. The L9 array is used for this project work. "Larger is better" is need for optimization as the strength requirement of the joint should be maximum.

5.1 SN Ratios

The SN ratio is used to find out a set of input process parameters at the various level that reduced variability present in the process. The following table-4 shows the SN ratios of a given process. The maximum SN ratios show the significance of the process parameters and the corresponding value of the parameter is set that can reduced variability. From the table-4, the maximum SN ratios are indicated 27.65 at level 3, 24.79 at level 1, and 23.67 at level 2 for the rotational tool speed, tool feed, and tool offset respectively. Thus corresponding process parameter with its level is the optimum set that gives optimum output response.

Table-4: Response Table for Signal to Noise Ratios

Level	Rotational Speed (rpm)	Tool Feed (mm/min)	Tool Offset (mm)
1	19.16	**24.79**	22.86
2	22.86	22.70	**23.67**
3	**27.65**	22.18	23.14
Delta	8.49	2.61	0.81
Rank	1	2	3

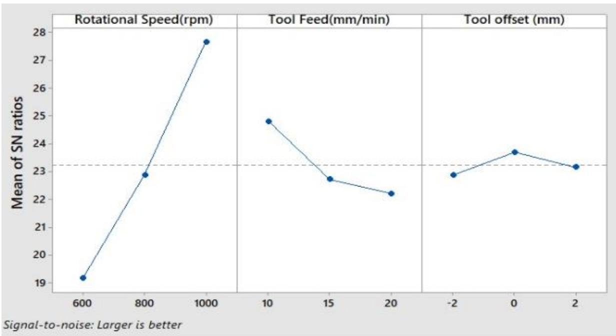


Chart-4: Mean Effect Plot for SN Ratios

The mean effect plot for SN ratios is shown in the above chart-4. This chart gives the same result as the response table, but here certain relationships between process parameters and response parameters easily understand. The rotational speed is directly proportional to the response whereas the tool feed is inversely proportional. And tool offset just near to 0 or the center of joint gives an optimum response.

5.2 Mean

The main effect plot for means is shown in the following table-5. It examines the difference between the mean of process parameters levels and creates the effect when process parameters differently affect the responses.

Table-5: Response Table for Signal to Noise Ratios

Level	Rotational Speed (rpm)	Tool Feed (mm/min)	Tool Offset (mm)
1	18.21	36.88	29.73
2	28.42	29.02	32.21
3	47.29	28.02	31.98
Delta	29.08	8.86	2.48
Rank	1	2	3

Table-5 shown that the maximum difference between the levels of the parameter is 29.08 for rotational speed and a minimum difference of 2.48 for tool offset. Thus slope or inclination of line of rotational tool speed is more as compare to tool offset which is seen in chart-5. Thus it is concluded that there is more magnitude of the main effect for rotational speed. Each level of rotational speed affects responses differently.

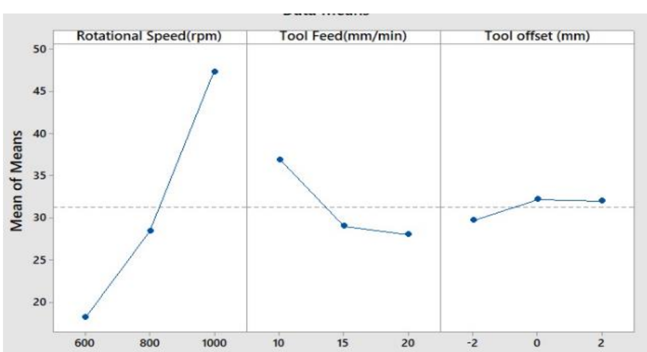


Chart-5: Main Effect Plot for Means

According to the graph, it is seen that the line for rotation speed is steeper as compare to tool feed. Also after the 0 mm offset, the line becomes a little bit horizontal, and the magnitude of the main effect is minimum.

5.4 ANOVA

Analysis of Variance (ANOVA) was used to find out the importance of input factors and gives information about the quantitative contribution of process parameters with the comparison of the output response means at the different levels. ANOVA is carried out to evaluate the effects of process parameters on joint strength and load by using the responses. In this test, it is considered that the mean of the two or more input process parameters is similar. It uses the information of the mean of the response parameter then finds the importance of one or more process parameters.
In this test basically, two hypotheses are made for the analysis i.e. Null hypothesis and Alternative hypothesis.

Null hypothesis (H_0) – It states that all means of process parameters are the same.

Alternative hypothesis(H_1) – It states that one mean of process parameter is different.

To perform an ANOVA, ultimate tensile strength is used as the continuous response variable and rotational tool speed, tool feed, and tool offset are used as the categorical factor with three levels.

Table-6: ANOVA for Ultimate Tensile Strength

Source	DF	Seq SS	Contri-bution	Adj SS	Adj MS	F-Value	P-Value
Rotati-onal Speed (rpm)	2	0.000642	90.72%	0.000642	0.000321	443.82	0.002
Tool Feed (mm/min)	2	0.000056	7.96%	0.000056	0.000028	38.94	0.025
Tool offset (mm)	2	0.000008	1.12%	0.000008	0.000004	5.48	0.154
Error	2	0.000001	0.20%	0.000001	0.000001		
Total	8	0.000707	100.00 %				

The result of is ANOVA is shown in the above table and If the p-value is less than 0.05, then it is concluded that at least one durability mean is different and the null hypothesis becomes wrong thus it is rejected so accept the alternative hypothesis.

a) The *p*-value of the rotational speed and tool feed is 0.002 and 0.025 respectively which is less than 0.05 thus they are statistically significant process parameters. This indicates that the probability of the null hypothesis being correct is less than 5%. That's why the null hypothesis is rejected while the alternative hypothesis is accepted.

b) It shows that there is a relationship between the means of process parameters.

c) The *p*-value of tool offset is 0.154 which is higher than 0.05. thus tool offset is not a statistically significant process parameter and indicates strong evidence for the null hypothesis. Thus, the null hypothesis retains and rejects the alternative hypothesis.

d) The contribution of rotational speed, tool feed, and tool offset is 90.72%,7.76%, and 1.12% respectively. Thus, tool rotation speed contributes more as compare to tool feed and tool offset.

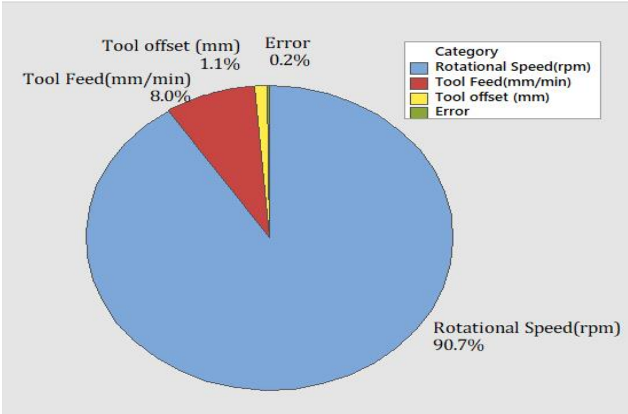


Chart-7: Contribution of Process Parameter to UTS

Table-7: Analysis of Variance for Ultimate Load

Source	DF	Seq SS	Contri-butin	Adj SS	Adj MS	F-Value	P-Value
Rota-tional Speed (rpm)	2	1.44456	89.3%	1.44456	0.722280	217.98	0.005
Tool Feed (mm/min)	2	0.15285	9.45%	0.15285	0.076427	23.07	0.042
Tool offset (mm)	2	0.01365	0.84%	0.01365	0.006824	2.06	0.327
Error	2	0.00663	0.41%	0.00663	0.003314		
Total	8	1.61769	100.00 %				

From the above table-7, it is concluded as,

a) The *p*-value of the rotational speed and tool feed is 0.005 and 0.042 respectively which is less than 0.05 thus they are statistically significant process parameters. This indicates that the probability of the null hypothesis being correct is less than 5%. That's why the null hypothesis is rejected while the alternative hypothesis is accepted.

b) It shows that there is a relationship between the means of process parameters.

c) The *p*-value of tool offset is 0.325 which is higher than 0.05. thus tool offset is not a statistically significant process parameter and indicates strong evidence for the null hypothesis. Thus, the null hypothesis retains and rejects the alternative hypothesis.

d) The contribution of rotational speed, tool feed, and tool offset is 89.30%,9.45%, and 0.84% respectively. Thus, tool rotation speed contributes more as compare to tool feed and tool offset.

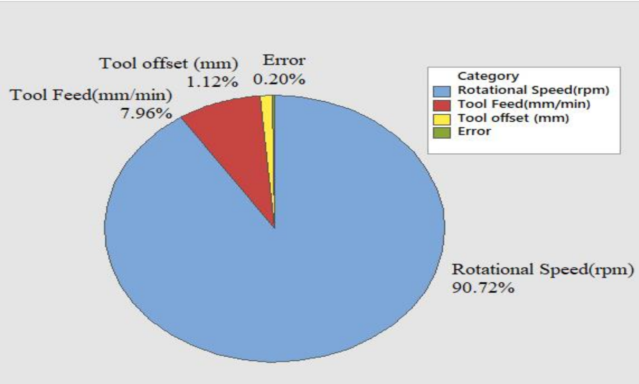


Chart-7: Contribution of Process Parameter To UTS

6. METALLURGICAL ANALYSIS.

Fig-8 a gives the macroscopic view of the alumium and titanium alloy surface. As the tungsten carbide material used for a tool that has a very high hardness, thus it is to forms a vortex and turbulent flow of aluminium and titanium material during the stirring action of the tool at the interface. The aluminium is weak as compared to titanium and it is placed above titanium so that more deformation and diffusion of material occurs in the case of aluminium. The aluiminium particles are diffused to the dispersed Titanium. The regular and straight ring-like texture was formed on aluminium due to the rotation and transverse action of the tool. This ring-like texture is known as crown and it is one of the topological characteristics of the FSW joints. There was no evidence of wear developed on the tool surface. Fig-8 shows that the metallurgical bonding between the alumiun and titanium. It was observed that the aluminum particles mixed with titanium at the stir zone of the lap joint.

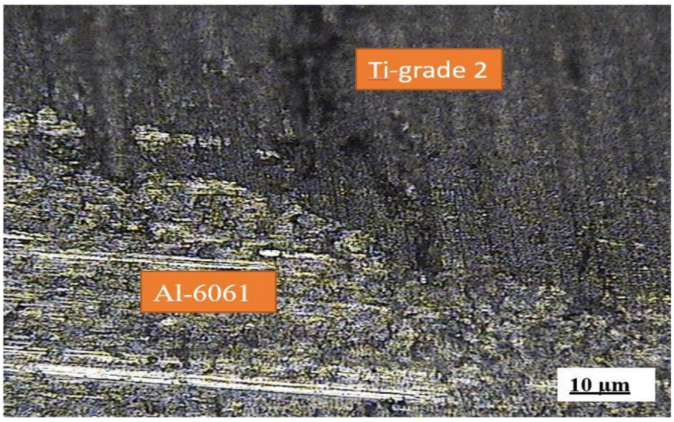
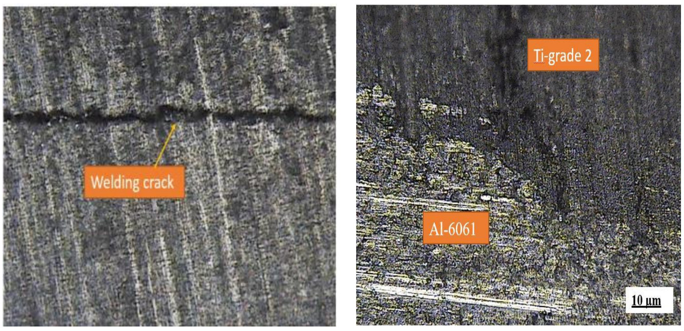


Fig-8: Metallurgical Bonding of Al-Ti

Sometimes, due to the machine vibration, a high amount of tool transverse speed, short cooling time, and various undefined reasons, the welding defects formed in the welding joint interface. This defect may be produced at the macroscopic or microscopic level. This welding defect creates a weak welding joint and so that the tensile strength of the joint is reduced.



a) Welding crack b) Voids

Fig-9: Welding Defect

- As indicated in Figure, when the pin offset is maximum, then the tool pin is moved between the interface of Al -Ti and the large-sized titanium particle embedded in the stir zone.
- The welding defect such as welding cracks and voids have appeared at the interface of aluminium and titanium abutting edges. Due to the machine vibrations and high tool feed the welding cracks are formed at some section welding joint.
- The vortex and turbulent flow pattern or texture are developed at the stir zone on aluminium.
- High tool speed is responsible for welding crack and thus welding joint strength is reduced.

6.1 Temperature Zone Weld Join

The base metal of aluminium is shown original equiaxed grain microstructure as an initial state. Also, the titanium particles are dispersed in the aluminum matrix which is seen in the stir zone. Thus, most of the titanium particles are pulled away from the titanium surface into the aluminum due to the forge effect of the tool pin. The fine and equiaxed grain is formed in the aluminium at the stir zone because of dynamic recrystallization.

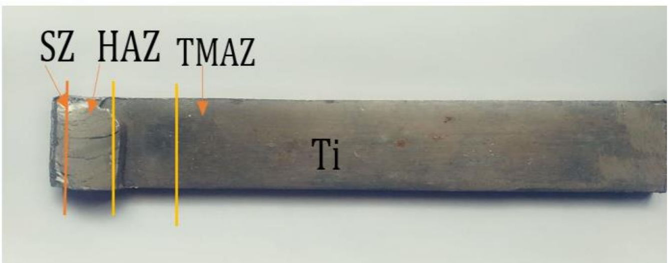


Fig-10: Temperature Zone in Joint

The heat generation and plastic deformation are not sufficient in the TMAZ of aluminum for the development of dynamic recrystallization. That's why the elongated and deformed grains are observed in the TMAZ of aluminium. The HAZ of aluminium is observed between BM and TMAZ which shows the coarse grain as compared to the base metal of aluminium. For the titanium, the base metal shows a coarse grain. In the case of titanium, the BM includes to some extent coarse grains. The HAZ of titanium is similar to the base metal and generally, it is very difficult to find TMAZ in case titanium

6.2 Effect of Fsw Parameters on Macrostructure

As the high tool feed result in a sudden impact of the tool at the interface of Al-Ti. Thus small cracks are produced at the interface during the welding operation and they increased when the tensile test is to be performed on the sample. Thus this crack becomes large which develops the fracture of workpieces. When high tool rotation is used in this process, high friction and high heat generation are developed at the stir zone and fine grain is formed at the interface. as the tool offset is toward aluminium (-2 mm) which is softer thus heat and friction development are reduced here and simultaneously elongated grain are formed at the interface and if tool offset is toward titanium (2mm) which is harder thus heat and friction development is maximum here and so that fine grain is formed at the interface.

7. CONCLUSION OF RESEARCH WORK

The closure of this research work is studied to understand the overall output of the research work. The aluminium and titanium welding joint have been successfully implemented. All joints were in good condition. The maximum and minimum values of responses are shown in the following table-8. These results are obtained by the tensile test.

Table-8: Tensile Test Result

Experiment No.	Rotational tool speed	Tool feed (mm/min)	Tool offset (mm)	Ultimate load (kN)	Ultimate tensile load (MPa)
7	1000	10	2	P_{max} =20.4	σ_{max} =88.46
2	600	20	0	P_{min} = 6.4	σ_{min}= 29.04

The Taguchi analysis and ANOVA were used as tools or methods for the optimization process. The SN ratios give the optimum set of process parameters which obtained at various level. If the FSW process is performed with the help of this optimum parameter then the optimum output of responses is obtained.

Table-9: Optimum Set of Process Parameters

Level	Rotational Speed (rpm)	Tool Feed (mm/min)	Tool Offset (mm)
1	-	10	-
2	-	-	0
3	1000	-	-
SN_{max}	27.65	24.79	23.67

The ANOVA test for considering both responses, the rotational speed and tool feed is the statically significant process parameter as their p-values which obtained are less than the 0.05 while tool offset is statically insignificant as it has p-value more than 0.05.

Table-10: ANOVA test result

Responses	Process Parameter	P-value	Remark
Ultimate Tensile Strength	Rotational Speed	0.002	Significant
	Tool Feed	0.025	Significant
	Tool Offset	0.154	Insignificant
Ultimate Load	Rotational Speed	0.005	Significant
	Tool Feed	0.042	Significant
	Tool Offset	0.327	Insignificant

The metallurgical bonding between the aluminium and titanium is obtained during welding operations and this result is shown by the metallurgical analysis. The voids and welding cracks such defects are observed in welding joints at the macroscopic and microscopic levels. The higher the tool speed there is higher the possibility of welding cracks. The heat input to the stir zone is minimum for zero or negative tool offset as tool contact to both workpieces was not achieved here. Thus, resulting in lowering the strength of the joint. The higher the rotational speed always gave the higher strength of joints, as more friction developed as stir zone.

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