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# Optimization of FSW process parameters for maximum UTS of AA6061/rutile composites using Taguchi technique

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**Abstract.** In the friction stir welding process, preferred joint property is vastly reliant on the selection of optimal welding conditions. The present study aims to use the Taguchi technique to find the optimal process conditions for achieving superior Ultimate Tensile Strength (UTS) in friction stir welded Aluminum Matrix Composite (AMC) joints. AMCs reinforced with rutile particles which have a potential application in the aerospace, automotive, and marine industries are used in the present work. Taguchi parametric design technique was used to identify the effect of rotational speed, tool traverse speed, and tool geometry on joint strength. Taguchi approach confined the optimum level of process variables and these variables were optimized. The investigation showed that the parameters within the selected value range will seriously affect the output. The predicted value of the output response was 155.48 MPa, which was validated by further experiments using the optimum process variables. Analysis Of Variance (ANOVA) results indicated that the UTS of the composite joint is mainly affected by the tool traverse speed followed by rotational speed, and tool geometry. The microstructural study unveiled that grain size is dependent on process variables and finer grains offer better joint properties.



## 1. Introduction

Friction Stir Welding (FSW) is gaining massive popularity among researchers due to its numerous advantages, most significant of which is its capability to join otherwise hard to weld composites [1,2]. FSW is a solid-state welding technique that achieves a temperature significantly lower than the melting point of the pieces to be joined, as opposed to conventional fusion welding techniques that are typically employed for welding metals [3,4]. Defect-less joints with better mechanical properties can be obtained in the composite materials which are previously labeled as hard-to-weld materials [5]. Porosity, cracks, and non-uniform dispersion/agglomeration of reinforcement, which are typical in conventional welding processes, are absent in Friction Stir (FS) welds, which have a better surface quality and do not require post-weld cleaning [6–8]. The impact of machine variables on the nature of the material flow, the formation of microstructure, and hence on the joint strength of FS welds has been investigated [9].

Recently several investigations were carried out

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to understand the effect of parameters like rotational speed, tool traverse speed, and tool geometry on the joint properties [10–13]. Most studies use traditional experimental methods, changing one variable at a time and keeping the remaining variables unchanged to assess the impact of each variable. This traditional approach of conducting experiments is time-consuming and expensive [14]. To identify important factors from many factors, by reasonably reducing the number of trials, Taguchi statistical design method can be used. But this method does not consider the interaction between parameters. These interactions can be occasionally neglected to save time, cost, and resources. By performing further experiments, neglected interactions can be evaluated if required [15].

Nevertheless, the application of the Taguchi method in FSW of aluminum alloys, dissimilar alloys, and composites has been presented in various reports [16–19]. However, it is observed that only a limited amount of research has been done on rutile reinforced aluminum composites, and no work has yet been published on the 'FSW process variable optimization' of rutile reinforced aluminum composites using the Taguchi technique. Hence in the present work, the Taguchi technique is employed to evaluate the effect of major process variables on Ultimate Tensile Strength (UTS) of FS welded joints of AA6061/Rutile composite.

## 2. Taguchi technique

Taguchi technique is a powerful tool used to enhance the performance of the design, process, product, and entire system with a substantial reduction in experimental cost, time, and resources [20]. By combining the experimental design model and the principle of the quality loss function, the Taguchi technique has achieved robust process and product design and solved many complex industrial tasks. Moreover, this method evaluates the most prominent variables in the entire process. The ideal process variables attained by the Taguchi technique are unaffected by the change in environmental factors and other noise conditions [21]. The trial number increases as the number of process variables and their levels increases. To eliminate this intricacy, the Taguchi method employs a distinct design of Orthogonal Array (OA) to evaluate the full range of variables with a limited number of trials. In the study of the S/N (Signal-to-Noise) ratio, Taguchi divides quality behaviors into three categories: "larger-the-better", "lower-the-better", and "nominal-the-better". In this study, UTS is considered the output response, and the combination of process variables that gives a higher UTS is considered the ideal process variable value. Hence in this work "Larger-the-better" category is selected and the trial which gives the best S/N ratio is considered as the ideal process variable [16]. Furthermore, Analysis of Variance (ANOVA) is used to determine the significance of each process variable to improve the output response.

## 3. Experimental procedure and setup

### 3.1. Material

Rutile-reinforced AA6061 matrix composite was used as the workpiece material in this study. Rutile is a low-cost, amply available mineral with superior mechanical properties, very good corrosion resistance and wears resistance, and higher thermomechanical properties [22]. Rutile reinforced AA6061 composites were proposed for the automobile and aerospace industries. Table 1 lists out the chemical composition and UTS of composites.

### 3.2. Process variables

According to numerous researchers, the quality of the FS welded joint is determined by several factors, including rotational speed, tool traverse speed, axial force, tool geometry, tool material, tool tilt angle, backplate material, and workpiece material. In this work, process variables (rotational speed, tool traverse speed, and tool geometry) with three levels were identified. Trails were performed on 5 mm thick AA6061/rutile plates to determine the range of variables that can result in defect-free joints.

When the rotational speed was less than 600 rpm, pinholes and wormholes were observed in the weld area due to insufficient heat development and improper material flow. And when the speed was higher than 1300 rpm, the tunnel hole was observed, because a lot of heat was developed in the welding area, which led to the turbulence of the material flow [23]. Similarly, when the tool traverse speed was lower than 60 mm/min, pinholes appeared, which were caused by the high heat input per unit length and the lack of vertical transfer of the material. However, tool traverse speeds greater than 100 mm/min limit heat exposure time, degrade material plasticization and flow, and result in a tunnel hole. In this investigation, three types of tool geometries were chosen namely, the tool with Threaded Cylindrical (TC), triangle (Tr), and square

**Table 1.** Composition (in wt%) and UTS of AA6061/rutile composite.

| Al | Cr | Cu | Fe | Mg | Mn | Rutile ($TiO_2$) | Si | UTS (MPa) |
|---|---|---|---|---|---|---|---|---|
| Remaining | 0.05–0.35 | 0.15–0.4 | 0.7 | 0.8–1.2 | 0.15 | 3 | 0.4–0.8 | 160 |

**Table 2.** Process variables, their range, and values.

| | RS[a] (rpm) | TS[b] (mm/min) | TG[c] |
|---|---|---|---|
| Range | 600–1300 | 60–100 | |
| Level-1 | 600 | 60 | Threaded Cylindrical (TC) |
| Level-2 | 950 | 80 | Triangle (Tr) |
| Level-3 | 1300 | 100 | Square (Sq) |

[a]RS: Rotational Speed; [b]TS: Traverse Speed; [c]TG: Tool Geometry.

(Sq) pins. Table 2 shows the process variable and their feasible range and levels used in the study.

### *3.3. Experimental design*

Experiments were designed based on Taguchi's OA considering the following points:

1. Number of variables and their interactions;
2. Levels of process variables.

In the present study three variables, each with three levels were considered. It was decided to ignore the 2nd order interaction between the variables to save time and resources. Each three-level variable has two Degrees Of Freedom (DOF), and the entire process has six DOF. According to Taguchi's technique, the DOF of the experiment should be less than or equal to chosen OA. Hence in this analysis, L9 OA with 8 DOF was chosen.

The composite plates of 5 mm thickness were machined from stir cast composite billet by Computer Numerical Control (CNC) milling. Composite plates were held rigidly in a custom-made fixture using clamps. Joints were prepared using the single-pass welding technique where the rotating tool was moved once through the weld line. Three different types of tool pin profiles were used namely TC, Tr, and Sq. The tool is made of tool steel that has been hardened to 64 HRC. Pin dimensions were chosen in such a way that, all three profiles possess the same dynamic volume so that they displace the same amount of material during their operation. A pin with sharp edges has a higher dynamic to static volume ratio than a straight cylindrical pin, which has a significant impact on material flow. Among the three-pin profiles, Sq has a ratio of 1.57, Tr has 1.2, and TC has 1.02. Because of the tool pulsating effect, the tool with an Sq pin produces more frictional heat than other pin profiles [11], whereas the tool with a TC pin exhibits a uniform material flow around the pin and from top to bottom of the pin.

FSW joint was prepared in butt joint configuration on CNC vertical center as shown in Figure 1. To obtain tensile strength specimens as per ASTM E8, welded composites were cut normal to the welding direction using wire Electrical Discharge Machining (EDM). In each trial, three specimens were made and tested to limit the noise levels. The test was performed on the universal testing machine.

**Figure 1.** Experimental setup.

## 4. Experimental results and discussion

### *4.1. S/N ratio*

In this investigation, UTS is considered as the important characteristic to define the quality of the FS welded joint. The mean and S/N ratio for each trial were computed to assess the effect of variables on the output response. Signals represent the effects on the average output response, whereas noise represents the effects on the deviances from the sensitivity of the trial responses in the S/N ratio. A suitable S/N ratio must be selected based on expertise, prior knowledge, and the process setup. When the objective is fixed and there is no signal factor (static design), it is possible to choose the S/N ratio based on the trial outcome. The S/N ratio was selected in this investigation based on the chosen criteria (the larger the better) and after maximizing the output. In the Taguchi technique, the deviation of the output from the ideal value is calculated by the S/N ratio ($\delta_n$) [24]. The $\delta_n$ (larger the better) of an 1st trial is computed as:

$$\delta_n = -10 \log \left( \frac{1}{n} \sum Y_{klm}^2 \right), \tag{1}$$

where $n$ represents the number of tests done with the same process variable combinations (in this study three tests T1, T2, and T3) and $Y_{klm}$ is the output response of $k$th quality behavior in the 1th trial, at the $m$th test.

**Table 3.** L9 OA experimental design, responses, and S/N ratio.

| Serial no. | Process variable | | | UTS (MPa) | | | Means | S/N ratio |
|---|---|---|---|---|---|---|---|---|
| | RS[a](rpm) | TS[b] (mm/min) | TG[c] | T1 | T2 | T3 | | |
| 1 | 600 | 60 | TC | 127 | 126 | 129 | 127.333 | 42.099 |
| 2 | 600 | 80 | Tr | 137 | 139 | 139 | 138.333 | 42.819 |
| 3 | 600 | 100 | Sq | 146 | 146 | 149 | 147.000 | 43.347 |
| 4 | 950 | 60 | Tr | 143 | 142 | 141 | 142.000 | 43.046 |
| 5 | 950 | 80 | Sq | 151 | 151 | 149 | 150.333 | 43.541 |
| 6 | 950 | 100 | TC | 148 | 148 | 150 | 148.667 | 43.444 |
| 7 | 1300 | 60 | Sq | 143 | 141 | 142 | 142.000 | 43.046 |
| 8 | 1300 | 80 | TC | 143 | 142 | 145 | 143.333 | 43.127 |
| 9 | 1300 | 100 | Tr | 151 | 149 | 148 | 149.333 | 43.483 |

[a]: RS-Rotational Speed; [b]: TS-Traverse Speed; [c]: TG- Tool Geometry.

**Table 4.** Means and S/N ratio of UTS.

| Levels | Means | | | S/N ratio | | |
|---|---|---|---|---|---|---|
| | RS[a] | TS[b] | TG[c] | RS | TS | TG |
| L1 | 137.56 | 137.11 | 139.78 | 42.75 | 42.73 | 42.89 |
| L2 | 147.00 | 144.00 | 143.22 | 43.34 | 43.16 | 43.12 |
| L3 | 144.89 | 148.33 | 146.44 | 43.22 | 43.42 | 43.31 |

[a]: RS-Rotational Speed; [b]: TS-Traverse Speed; [c]: TG- Tool Geometry.

**Table 5.** ANOVA for UTS (S/N ratio).

| Source | DF | Adj SS | Adj MS | *F*-value | *P*-value | PoC |
|---|---|---|---|---|---|---|
| RS | 2 | 147.43 | 73.72 | 30.46 | 0.03 | 35.86 |
| TS | 2 | 192.17 | 96.09 | 39.71 | 0.03 | 46.74 |
| TG | 2 | 66.69 | 33.35 | 13.78 | 0.07 | 16.22 |
| Error | 2 | 4.84 | 2.42 | – | – | 1.18 |
| Total | 8 | 411.14 | – | – | – | 100 |

The FSW of composites was performed according to the design criteria, and the quality behavior of the joint (UTS) was measured to observe the effect of process variables. The results of the trials were then transmuted into S/N ratios and means. Output responses (UTS) were measured using the L9 OA experimental design, and nine S/N ratios and nine means were computed and reported in Table 3. The analysis of the mean for each trial yields the optimal combination of variable levels, confirming the best UTS value for the given set of data. The response means indicates the average value of output response for each process variable at distinct levels. The average of all responses at a particular level is expressed as the mean of that level. The response means of a given set of data and the S/N ratio of UTS for the variable at three distinct levels were computed and shown in Table 4. A higher S/N ratio refers to superior joint properties. Hence the ideal level of process variables is the level with maximum S/N ratio [25]. The S/N ratio and mean effect for UTS were computed using Minitab software which revealed that higher UTS was obtained in a trial with the rotational speed of 950 rpm, tool traverse speed of 100 mm/min, and tool with Sq pin profile.

### *4.2. Analysis of Variance (ANOVA)*

To recognize the parameters which statistically have a major impact, an ANOVA test was performed. ANOVA test helps in identifying the importance of each process variable that affects the UTS of the FS welded joint [26]. Table 5 gives the ANOVA results for UTS of the S/N ratio. Further, the F test was also used to find out the process variable which has a major effect on UTS. When F is large, the change of the variable has a major impact on the output response. ANOVA results revealed that the chosen process variables are critical factors, affecting the UTS of composite joints in the order of tool traverse speed, rotational speed, and tool geometry.

### *4.3. Contribution of process variables*

Each process variable has an effect on the response of the output. The Percentage of Contribution (PoC) is the fraction of total deviation seen in trials that is attributable to each relevant variable and their interactions. The sum of squares of each significant item is used to calculate the PoC of the responses. Also, it reveals the relative power of a variable to limit the deviation. The deviation can be limited to the quantity stated by the PoC by precisely controlling the variable levels. The PoC of the rotational speed, tool traverse speed, and tool geometry are shown in Table 5.

### 4.4. Assessment of ideal performance characteristics

The technique explained in this study for UTS optimization and prediction can replace the traditional experimental method, which is costly and time-consuming and is based on trial and error. The focus of this research was to find the critical variables and their PoC on the UTS of FS welded AA6061/rutile composites using Taguchi L9 OA with the least number of trials possible. Considering the higher S/N ratio, analysis of the results leads to the conclusion that variables at level A2, B3, and C3 gives maximum UTS, as shown in Figure 2.

Following the completion of the trials based on L9 OA and the identification of an ideal process variable combination, one of the two options was developed:

1. The reported combination of variables is similar to those in the trial list;
2. The reported variable combination is absent in the trial list.

It can be inferred that the above set of variable levels was not present in the chosen experiment design. This is obvious as the multi-factor nature of the experimental design was adopted to reduce the number of trials. The ideal value of the UTS is predicted at the optimum levels of critical variables. The calculated mean of the output response is given as:

$$UTS = RS_2 + TS_3 + TG_3 - 2M, \tag{2}$$

where $M$ represents the global mean of UTS, $RS_2$ is the average UTS at the 2nd level of tool rotational speed, $TS_3$ is the average UTS at the 3rd level of tool traverse speed and $TG_3$ represents average UTS for the tool with Sq pin profile. Substituting these values in the equation we get:

$$UTS = 147 + 148.33 + 146.44 - 2 * 143.15$$
$$= 155.48 \text{ MPa}. \tag{3}$$

### 4.5. Confirmation test

To verify the enhancement in the UTS of the FS welded joint, a confirmation trial was conducted using ideal process variable combinations. Three joints were made at the optimum level of process variables, i.e., the tool traverse speed at Level 3, rotational speed at Level 2, and tool with square pin geometry. The average UTS of the FS welded joint was found to be 154 MPa. UTS of joint produces using optimum process variable, was within the confidence level of the calculated UTS.

## 5. Microstructure analyses

As illustrated in Figure 3, the thermo-mechanical effect divides the weld region into three distinct zones. The mid-region which was previously occupied by the FSW tool pin is known as the Nugget Zone (NZ). Very fine and equiaxed grains were observed in this zone caused by the stern stirring of the tool. Huge frictional heat developed at this zone, which caused the material to recrystallize.

Adjacent to NZ, the inclined and elongated grain region was observed. This region is known as the Thermo-Mechanically Affected Zone (TMAZ). The plasticized material was dragged by the rotating tool, causing grains to elongate and tilt into the material flow direction as the tool rotated. Next to TMAZ was the Heat Affected Zone (HAZ), which was only affected by the thermal action and not by mechanical force. Softening of the grains was observed due to the

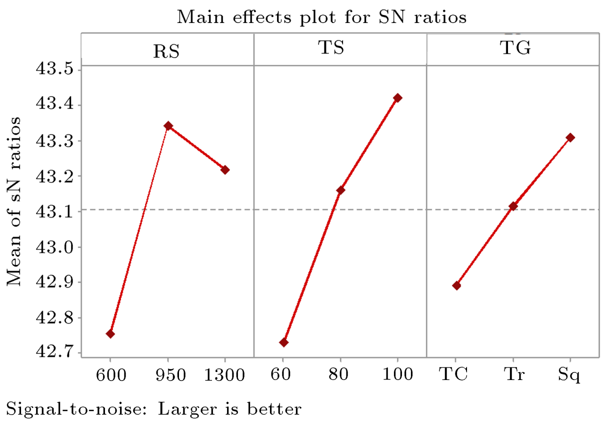



**Figure 2.** Main effect plots for S/N ratio of UTS.

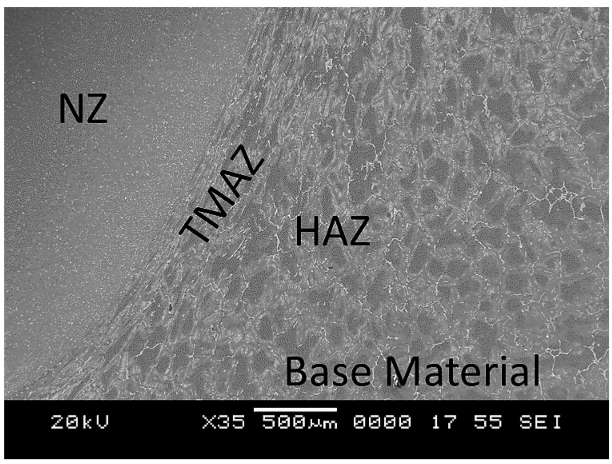
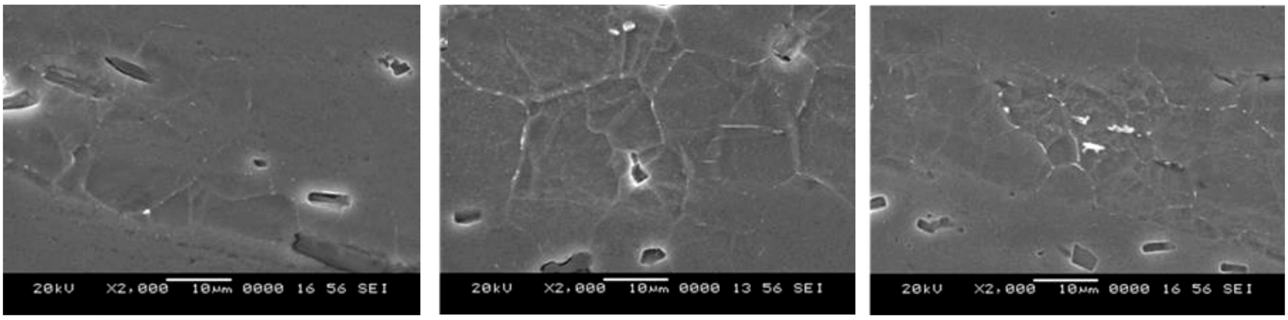



**Figure 3.** Microstructure at the weld region.




(a) (b) (c)

**Figure 4.** Microstructure at the NZ of the weld obtained by (a) TC, (b) Tr, and (c) Sq tool.

variation in a thermal cycle, making it the weakest region in the weld zone. It has been observed that all the tensile test samples were broken in this region during the tensile test.

### *5.1. Effect of process parameters on grain structure*

Grain refinement and grain size are dependent on the amount of heat supply and the rate of cooling [22,23]. Optimum heat supply and slower cooling of the material, assist in grain growth, whereas faster cooling of the weld zone, suppresses the grain growth. The development of numerous nucleation sites for grain growth is dependent on the amount of heat supply and stirring effect of the tool. In FSW, tool traverse speed controls the duration of heat transfer to the weld zone, which controls the cooling rate, whereas rotational speed controls the quantity of heat generation in the weld zone. As the rotational speed increases, the amount of frictional heat developed at the weld area also increases. On the other hand as the tool traverse speed increases, the duration of heat supply decreases which in term increases the cooling rate. At lower tool traverse speeds, grain growth is detected, whereas finer grains are observed at higher tool traverse speeds, since the material cools faster at higher tool traverse speeds, inhibiting grain growth.

The size of the grain at the top region of the weld zone is higher than the bottom of the weld zone. At the top surface, both the shoulder and pin of the tool plastically deform the material by producing a large amount of heat caused by the frictional interaction between the rotating tool and stationary workpiece. However, the frictional heat generated at the bottom surface of the weld zone is lower because the length of the tool pin is slightly shorter than the thickness of the workpiece. Also, the bottom plate acts as the heat sink, through which the generated heat is dissipated to the surroundings. Hence the heat available at the top region is higher than the bottom surface. Grain growth is caused by higher heat input and slower heat dissipation, therefore the top surface of the weld zone had larger grains than the bottom surface.

Weld prepared using the Sq tool produces finer grains compared to the other tools due to the pulsating effect caused by the sharp edges of the Sq pin. Pulsating effect of the Tr pin is 25% lesser than the Sq tool, whereas the cylindrical tool doesn't produce any pulsating effect. The Sq tool generates more frictional heat, allowing for finer grain than the other two tools. According to the Hall-Petch mechanism, mechanical properties such as UTS improve as grains become finer and finer [14]. As the grains became finer, the resistance to dislocation movement increased, improving the plastic flow resistance. Figure 4 depicts the microstructure of the NZ for joints prepared with the Sq, Tr, and TC tools. Finer grain leads to improved joint characteristics, which was confirmed by the UTS test.

During the FSW process, the material in the stir region undergoes severe plastic deformation. Besides, the interaction between the FSW tool pin and the reinforcement particles results in the fragmentation and redistribution of the particles [27]. It is obvious that due to the abrasion during the FSW process, the sharp edges and corners of the reinforcement particles become blunt in the NZ. Compared to the parent materials, the NZ possesses uniformly distributed smaller-sized particles with an ow-aspect-ratio [23]. Homogenously distributed fine reinforcement particles help in enhancing the UTS of the welded sample.

### *5.2. Effect of process parameters on UTS*

The effect of each of the independent process parameters on the UTS was depicted in Figure 5, which confirms the interdependencies of the process parameters and the output response.

#### *5.2.1. Effect of tool traverse/welding speed*

From Figure 5, it has been learned that increase in the tool traverse speed within the chosen range results in an increase in UTS. As observed in the trial runs, weld formed by selecting tool traverse speed beyond

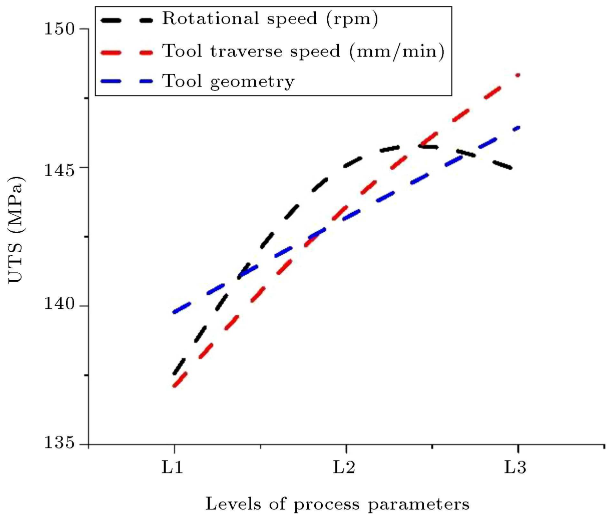



**Figure 5.** Effect of process parameters on UTS.

the chosen range leads to the welding defects such as voids, pinholes, and tunnel holes. Tool traverse speed affects the duration of heat transfer in the weld region and thereby controls the rate of cooling. The joint shows lesser UTS at the lower welding speed due to the higher heat supply caused by the slow movement of the tool. Higher heat input and reduced cooling rate result in improper plasticization and turbulent material flow causing poor consolidation of the material in the weld region [13,28]. Hence, the UTS of the joint shows a lesser value at a lower welding speed. The joint strength gradually increases as the welding speed increases due to the proper plasticization and smooth material flow resulting from the optimum heat input. Welding speed beyond the chosen range results in defects due to the poor plasticization and consolidation of the material.

*5.2.2. Effect of tool rotational speed*

It has been found from Figure 5 that, initially UTS increases as the rotational speed increases, and a further increase in the speed reduces these values. These patterns are consistent with the literature, which shows that higher speeds result in an excessive supply of heat at the weld zone [5,29]. Whereas increased rotational speed causes more heat to be produced, as well as turbulent material flow, which causes poor material consolidation and hence lowers the UTS [30].

*5.2.3. Effect of tool pin geometry*

A tool with a TC pin enables the smooth flow of material from top to bottom as well as from the front to the rear side of the pin [23]. TC tool offers clean, smooth joints with better surface finish, whereas surface finish of the joint prepared with Tr and Sq pin was less compared to that obtained using TC tool. Mechanical properties of the joint prepared with the Sq tool show a better result followed by Tr and TC tool respectively [17]. A tool with sharp edges provides a pulsating effect during the welding process, which assists in proper stirring and better consolidation of the plasticized material. For the same speed, the Sq tool provides a 33% more pulsating effect than the Tr tool and hence, produces joints with better mechanical properties. According to the results of the experiments, joints created with the Sq tool had better joint properties than joints produced with the other two tool geometries for the same process parameter values.

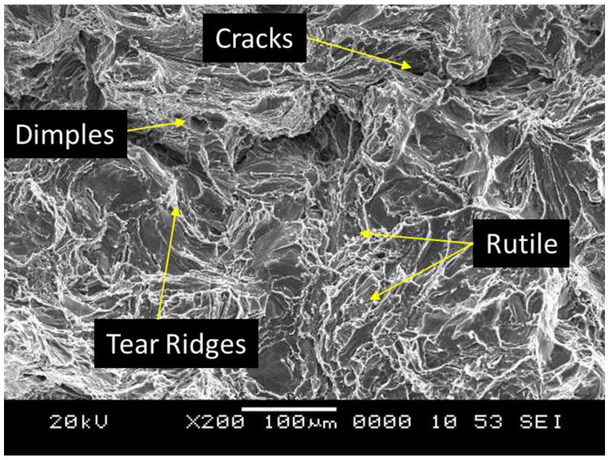



**Figure 6.** Fractured surface of the tensile test specimen.

Figure 6 depicts the fracture surface of the tensile specimen indicating that the fracture was ductile. Variations in the grain size and presence of hard particles exhibit uneven resistance to deform during the tensile test. The HAZ has the lowest strength in the weld zone because it goes through a heat cycle that softens the grains and causes grain growth. As a result, during the tensile test, strain occurs mostly in the HAZ, which is stretched at high strain rates, resulting in neck formation and fracture [31,32]. Due to recrystallization of grains lesser strain was acting on NZ. Hence, cracking and fracture always occurred in the HAZ, resulting in low strength and ductility along with the transverse orientation of the weld.

## 6. Conclusions

Rutile reinforced composites were joined through the Friction Stir Welding (FSW) technique. Taguchi's L9 OA design is adopted to get optimum process variables for the maximization of Ultimate Tensile Strength (UTS). The following are some of the study key findings:

1. The percentage contribution of process variables was investigated, and it was found that rotational speed contributed 35.86%, tool traverse speed contributed 46.74%, and tool geometry contributed 16.22%;
2. The rotational speed of 950 rpm, tool with square

pin geometry, and tool traverse speed of 100 mm/min were the ideal values of process variables that yielded superior UTS;

3. A microstructure analysis revealed that a specimen with a finer grain structure had a higher UTS. Furthermore, all of the specimens were fractured at Heat Affected Zone (HAZ), which had softened, coarse grains;
4. Because of the variation in heat distribution between the top and bottom surfaces, the top surface of the weld zone had coarser grains than the bottom surface.

## Nomenclature

| | |
|---|---|
| FSW | Friction Stir Welding |
| AMC | Aluminium Matrix Composite |
| UTS | Ultimate Tensile Strength |
| RS | Rotational Speed |
| TS | Tool Traverse Speed |
| TG | Tool Geometry |
| TC | Threaded Cylindrical |
| Tr | Triangle |
| Sq | Square |
| OA | Orthogonal Array |
| PoC | Percentage of Contribution |
| NZ | Nugget Zone |
| TMAZ | Thermo Mechanically Affected Zone |
| HAZ | Heat Affected Zone |

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