Optimizing weld quality of a friction stir welded AA6061/Rutile composite

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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 at the application of the Taguchi approach to finding out the optimal process conditions to get superior ultimate tensile strength in the friction stir welded aluminium 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 influence of rotational speed, tool traverse speed, and tool geometry on joint strength. Taguchi approach confines the optimum level of process variables and optimization of these variables was performed based on this study. Investigation reveals that the parameters within the chosen range of values, critically affect the output. The predicted value of the output response is 155.48 MPa which was validated by conducting further trials with optimum process variables. 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.

KEYWORDS: Taguchi technique, friction stir welding, aluminium matrix composite, analysis of variance, UTS.

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]. In comparison with the conventional fusion welding techniques which are commonly used for welding metals, FSW is one of the solid-state welding techniques in which temperature attains during the process is much lower than the melting temperature of the parts to be joined [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]. Defects such as porosity, cracks, non-uniform dispersion/agglomeration of reinforcement, which are commonly observed in conventional welding process are missing in friction stir (FS) welds and exhibits better surface finish and eliminates the need of post-weld cleaning [6-8]. A great deal of effort had been put to understand the impact of machine variables on the nature of the material flow, formation of microstructure and thereby on joint strength of FS welds [9].

Recently several investigations were carried out to understand the effect of parameters like rotational speed, tool traverse speed, and tool geometry on the joint properties [10-13]. Most of the studies adopted the traditional experimental method by varying one variable at a time and maintaining the remaining variables constant, to evaluate the impact of each variable. This traditional approach of conducting experiments is time-consuming and expensive [14]. To identify significant factors from many, by conducting a reasonably reduced number of trials, Taguchi statistical design approach can be adopted. But this method does not consider the interaction between parameters. These interactions can be occasionally neglected to save time, cost and resources. By performing the further experiment, neglected interactions can be evaluated if required [15].

Nevertheless, the application of the Taguchi method in FSW of aluminium alloys, dissimilar alloys, and composites has been presented in various reports [16-19]. However, it is observed that limited study has been done on rutile reinforced aluminium composite and no work has been reported yet on the ‘FSW process variable optimization’ of rutile reinforced aluminium composite through Taguchi. 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 quality loss function principles, the Taguchi technique enables robust process and product design and solves numerous 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. Taguchi outlines three distinct classes of quality behaviors (“Larger-the-better”, “lower-the-better” and “nominal-the-better”) in the study of S/N (Signal-to-Noise) ratio. In the present study, UTS is considered as output response and a process variable combination which gives higher UTS is considered as 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]. Moreover, Analysis of Variance (ANOVA) is done to find out the importance of each process variables to get a better 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 one of the low cost, amply available mineral, possesses superior mechanical properties, very good corrosion and wear resistance and higher thermo-mechanical 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

The quality of the FS welded joint depends on several factors as indicated by several researchers such as rotational speed, tool traverse speed, axial force, tool geometry, tool material, tool tilt angle, back-plate material and the workpiece material. In this work, process variables (rotational speed, tool traverse speed and tool geometry) with three levels were identified. Trails were done using 5mm thick AA6061/rutile plates to establish the feasible range of variables that yield defect-free joints.

When the rotational speed was less than 600 rpm, pinholes, wormholes were observed at the weld region resulting from inadequate heat development and improper material flow. Whereas at a rotational speed higher than 1300 rpm, tunnel holes were seen, as enormous heat is developed at weld region, resulting in turbulent material flow [23]. Likewise, pinholes were seen when the tool traverse speed was less than 60 mm/min, resulting from higher heat input per unit length and lack of vertical transfer of material. Whereas, tool traverse speed greater than 100 mm/min, reduces the duration of heat exposure, disrupts the plasticization and flow of the material, resulting 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 (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. To restrict the time and resource consumption, it was finalized to ignore the 2nd order interaction between the variables. Each variable with three levels has 2 DOF (degrees of freedom) and altogether process has 6 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 5mm thickness were machined from stir cast composite billet by 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 prepared with tool steel, 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. Compared to the straight cylindrical pin, a pin with sharp edges have a higher dynamic to static volume ratio, which has a significant influence on material flow. Among the three pin profiles, SQ has a ratio of 1.57, TR has 1.2 and TC has 1.02. The tool with an SQ pin develops more frictional heat than other pin profiles resulting from pulsating effect of the tool [11]. Whereas the tool with 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. Welded composites were cut normally to the weld direction using wire EDM to get tensile strength specimen according to ASTM E8 standard. In each trial, three specimens were made and tested to limit the noise levels. The test was performed on the universal testing machine.

4 EXPERIMENTAL RESULTS AND DISCUSSION

4.1 S/N ratio

In this investigation, Ultimate tensile strength (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. In the S/N ratio, signals indicate the effect on average output response and noise represents the effects on the deviances from the sensitiveness of the trial responses. A suitable S/N ratio must be selected based on expertise, prior knowledge, and the process setup. Depending on the outcome of the trial, it is possible to select the S/N ratio, when the objective is fixed and in the absence of a signal factor (Static design). In this study, the S/N ratio was selected as per the chosen criteria ("Larger the better"), following maximizing the output. In the Taguchi technique, deviation of the output from the ideal value is calculated by the S/N ratio (δ_n) [24]. The δ_n ("larger the better") of an lth 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 kth quality behavior in the lth trial, at the mth test.

As per the design criteria, the FSW of composites was performed 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. Based on L9 OA experimental design, output responses (UTS) were measured, nine S/N ratios and nine means were computed and shown in Table 3. The study of the mean for each trial will provide the best combination of variable levels that confirms the best value of UTS as per the given set of values. 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 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 the 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 reveals 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 Analysis of Variance (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 S/N ratio. Further, the F test was also used to find out the process variable which has a major influence 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 variables possess its impact on the output response. The percentage of contribution (PoC) is the fraction of the total deviation seen in the trials related to every important variable and the interaction among them. The PoC on the response is mathematically represented as the sum of squares of every major item. 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 based on trial and error which is expensive and time-consuming. Present work focused on identifying the critical variables and PoC of each variable on UTS of FS welded AA6061/rutile composite by performing the least number of trials through Taguchi’s L9 OA. Considering higher S/N ratio, levels for the key variables were concluded as A2, B3, and C3, as shown in Figure 2.

Once the trials were conducted based on L9 OA and an ideal process variable combination is established, either of the following two possibilities was evolved.

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 were 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 2^{nd} level of tool rotational speed, TS_3 is the average UTS at the 3^{rd} level of tool traverse speed and TG_3 represents average UTS for the tool with square pin profile. Substituting these values in the equation we get

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

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 FS welded joint was found to be 154 Mpa. UTS of joint formed using optimum process variable was inside the confidence level of the calculated, predicted UTS.

5 MICROSTRUCTURE ANALYSIS

The disparity in the thermo-mechanical effect divides the weld region into three distinct zones as shown in Figure 3. 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 resulting in recrystallization of the material.

Adjacent to NZ, the inclined and elongated grain region was observed known as the thermo-mechanically affected zone (TMAZ). As the tool rotates, the plasticized material was dragged by the rotating tool, causing grains to elongate and inclined into the material flow direction. Next to TMAZ was Heat affected zone (HAZ), affected only by the thermal effect and there is no mechanical force involved. Softening of the grains was observed due to the 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 in terms controls the cooling rate whereas, the quantity of heat generation in the weld zone dependent on rotational speed. 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. Grain growth is observed at lower tool traverse speed whereas, finer grains were observed at higher tool traverse speed, as the material cools faster during higher tool traverse speed thereby suppressing the 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. Whereas at the bottom surface of the weld zone, as the length of the tool pin is slightly lesser than the workpiece thickness, the frictional heat generated in this area lesser. 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. Higher heat input and slower heat dissipation cause grain growth, hence bigger grains were observed at the top surface of the weld region than at 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. Higher frictional heat is developed by the SQ tool, which enables the finer grain than the other two tools. As per the Hall-Petch mechanism, as the grains become finer and finer, the mechanical properties such as UTS will improve [14]. The resistance to dislocation movement is increased as the grains become finer thereby improves the plastic flow resistance. The microstructure at the NZ is shown in Figure 4 for the joints prepared by using 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 a low 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 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 trends are in line with the reported literature, in which higher speed results in excessive heat supply at the weld zone [5,29]. Whereas increased rotational speed results in higher heat input, as well as turbulent material flow resulting in improper consolidation of the material and thereby, reduce 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 triangle and square pin was less compared to that obtained using TC tool. Mechanical properties of the joint prepared with SQ tool shows 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 joint with better mechanical properties. From the performed experiments, it has been observed that joints produced with the SQ tool show improved joint properties compared to those obtained using the other two tool geometries for the same process parameter values.

Figure 6 depicts the fracture surface of the tensile specimen indicating the fracture was ductile. Variations in the grain size and presence of hard particles exhibit uneven resistance to deform during the tensile test. In the weld zone, the HAZ shows the lowest strength as it experiences a thermal cycle that softens the grains and also resulting in grain growth. Thus, during the tensile test, strain occurs principally in the HAZ, stretched to great levels of strain rate, ultimately causing neck formation and fracture [31,32]. Due to recrystallization of grains lesser strain is 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 FSW technique. Taguchi's L9 OA design is adopted to get optimum process variables for maximization of UTS. The following points were drawn from the study

1. Percentage of Contribution of process variables were investigated and it is observed the contribution of rotational speed was 35.86%, tool traverse speed was 46.74% and tool geometry was 16.22%.
2. The ideal value of process variables that yields superior UTS is the rotational speed of 950 rpm, tool with square pin geometry, and tool traverse speed of 100 mm/min.
3. Microstructure study reveals that higher UTS was observed in a specimen which is having a finer grain structure. And all the specimens were fractured at HAZ which possesses softened, coarse grains.
4. The top surface of the weld zone consists of coarser grains than at the bottom surface due to the variation in the heat distribution between the top and bottom surface.

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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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Figure 5 Effect of process parameters on UTS

Figure 6 Fractured surface of the tensile test specimen

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 (rpm)	TS (mm/min)	TG
Range	600 - 1300	60 - 100	
Level-1	600	60	Threaded Cylindrical (TC)
Level-2	950	80	Triangle (TR)
Level-3	1300	100	Square (SQ)

*RS-Rotational Speed, TS-Traverse Speed, TG- Tool Geometry

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

Sl	Process Variable			UTS (MPa)			Means	S/N ratio
No	RS(rpm)	TS(mm/min)	TG	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

*RS-Rotational Speed, TS-Traverse Speed, TG- Tool Geometry

Table 4. Means and S/N ratio of UTS

Levels	Means			S/N ratio		
	RS	TS	TG	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

*RS-Rotational Speed, TS-Traverse Speed, 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

Figure 1. Experimental Setup

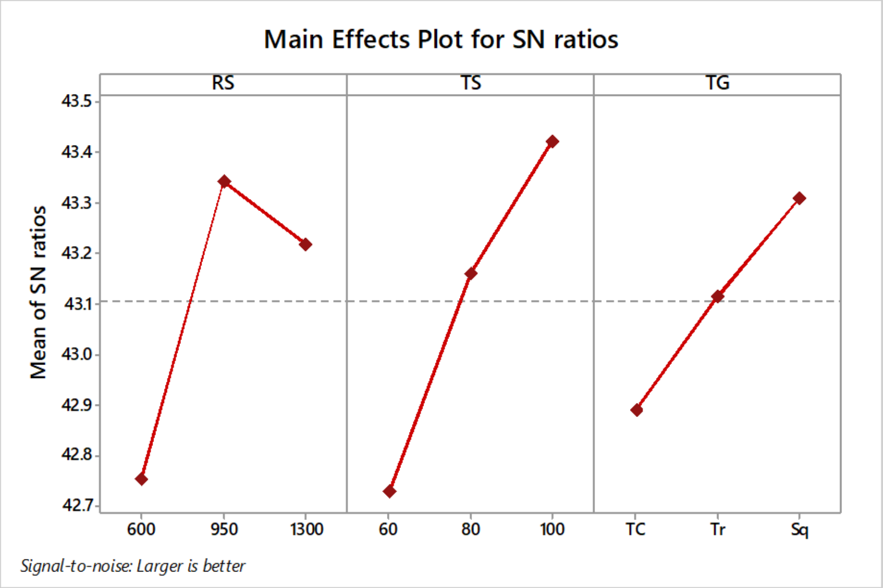

Figure 2. Main effect plots for S/N ratio of UTS

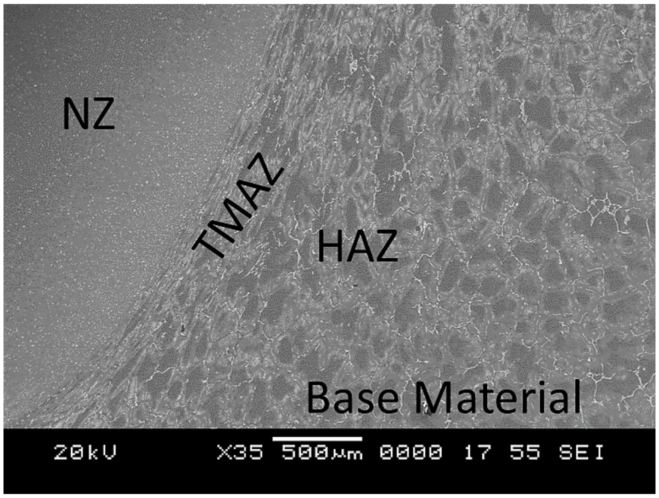

Figure 3. Microstructure at the weld region

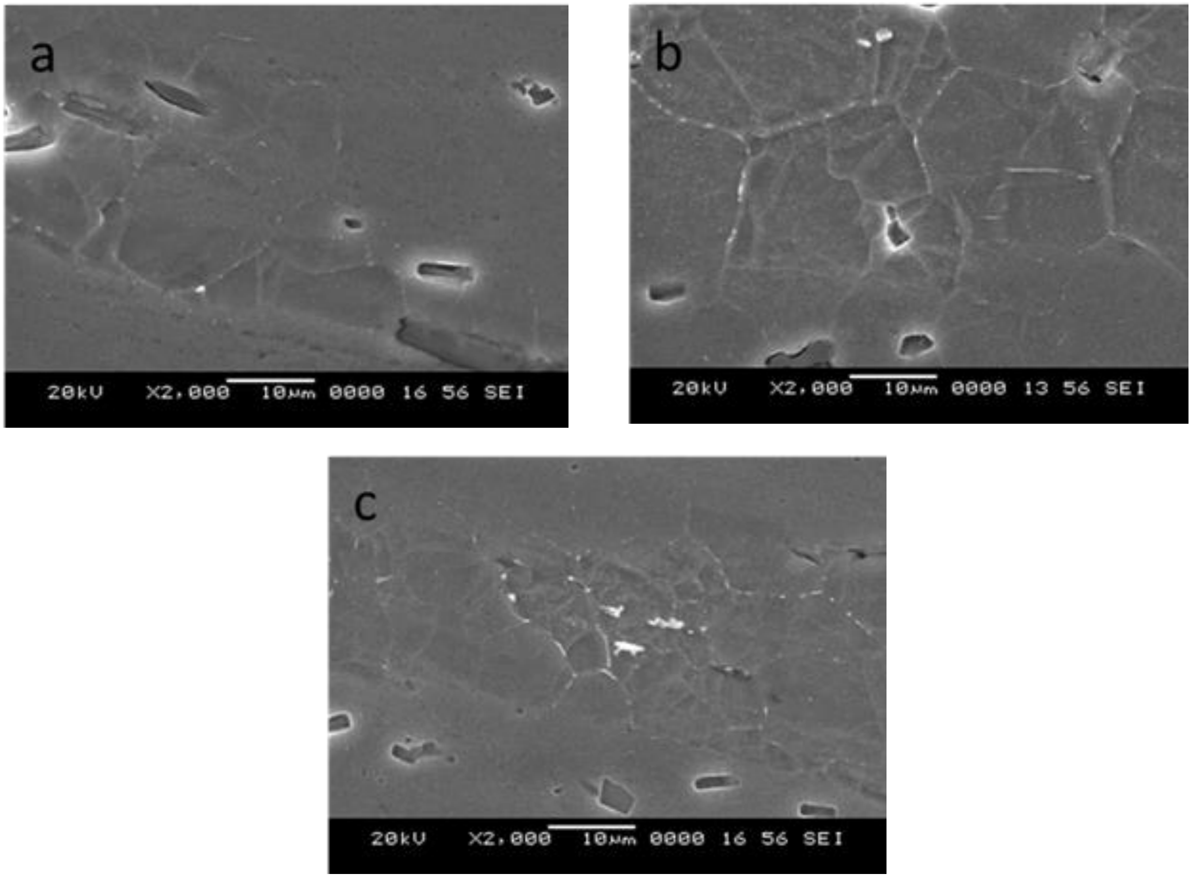

Figure 4. Microstructure at SZ of the weld obtained by a) TC, b) TR and c) SQ tool

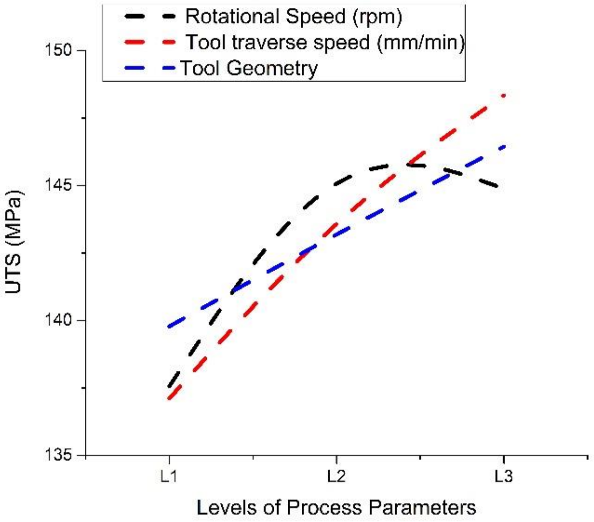

Figure 5. Effect of process parameters on UTS

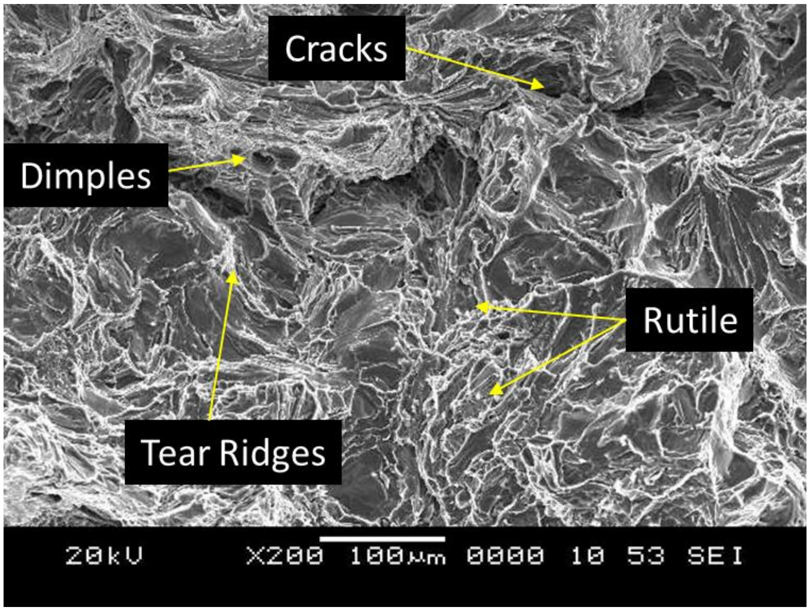

Figure 6. Fractured surface of the tensile test specimen

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