Research Article

The Effect of Stir-Squeeze Casting Process Parameters on Mechanical Property and Density of Aluminum Matrix Composite

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This present investigation focusing on preparation of Al-based hybrid composites in which Al6082 is engaged as the main alloy reinforced with two reinforcements of $ZrSiO_4$/TiC. The combination of the stir-squeeze process helps to make different specimen by change of four parameters such as stir speed, stir time, reinforcements, and squeeze pressure. In this process, two reinforcements are reserved as constant about 7.5 wt%. The four levels of each parameter are stir speed (300, 400, 500, and 600 rpm), stir time (10, 15, 20, and 25 min), reinforcement (2.5, 5, 7.5, and 10 wt%), and squeeze pressure (50, 60,70, and 80 MPa). According to the *L*16 orthogonal array Taguchi design, the specimens are created to analyze the mechanical properties of tensile strength and hardness along with porosity. In addition, the optimization technique is used to determine the optimal parameter on improving tensile strength. The optimization process can be assisted by the software namely Minitab-17 which helps to study analysis of variance, regression model, and contour plots. The observed result of ANOVA showed that stir speed (41.8%) is the maximum influenced parameter that increases TS, followed by squeeze pressure (25.7%), stir time (12.7%), and reinforcement (1.96%), and optimum tensile strength is found at the parameters of stir speed 600 rpm, stir time 10 min, reinforcement 2.5 wt%, and squeeze pressure 80 MPa. The fractured surface of tensile strength also examined by the SEM test. The combined parameters of S4-T1-R1-P4 achieve the highest TS, and it is observed that there are nearly no pore defects and good diffusion as a result of the reinforcements to be properly mixed. It is noticeable that the TiC and Al 6082 matrix, as well as the various $ZrSiO_4$ exhibit stronger bonds.

1. Introduction

AMCs which strengthened with ceramic elements like TiC, SiC, and Al_2O_3 reveal more benefits such as good tensile and impact strength, abrasion resistance, hardness, impact strength, as well as excellent physical features [1]. 6082 aluminum alloy is one of the important alloys in 6XXX series that is mainly applied in several fields of aviation, navigation, automobiles, and construction business [2]. Sekar et al. [3]

analyzed mechanical properties of Sic/Z ZrO2 reinforced AA6082 composites prepared via combined stir and squeeze casting and the outcome of UTS and hardness value are more when compared to base metal due to addition of silicon carbide and zirconium dioxide. Stir casting mainly produce effective parts through molten metal transfer into standard molds. Mechanical properties of the developed composites varied due to some criteria such as the size and shape of reinforcements, weight ratio, and bonding between

base metal and additives [4]. However, particulate reinforcing MMC which widely spread over all industries have been hindered because of more cost in producing components in complex shapes [5]. Umanath et al. studied the enhancement of Al6063/with $SiC-MoS_2$-reinforced alloys which is mostly based on particle sizes of additives and corrosion resistance reduced while rising of the temperature [6]. Among the several available processes for producing AMMCs, STC is the least costly method to make composite materials amongst remaining approaches like powder metallurgy and plasma sintering (PS), and it suggests a widespread option for materials gathering and process conditions [7]. Casting faults such shrinkage cavity, porosity, and misrun defects are frequently introduced by the conventional process. The SC process is a technique for pressurised extrusion moulding of materials. This technique has a great degree of manufacturing flexibility and can successfully reduce or even eliminate casting flaws [8]. Ravikumar et al. studied the performance of AA 6082/Tic by conducting inspections like SEM, XRD, and destructive experiments [9]. The addition of Tic/WC (4–10% wt) in 6082 Al enriched wear resistance [10]. $ZrSiO_4$ is the ultimate oxidization resistance mostly involved in several productions [11]. Adediran et al. fabricated $Al7075-TiO_2$ composites via STC, the ultimate tensile strength was exhibited better while considering the STC parameters of temperature about 750°C and stirrer speed of 500 rpm [12]. Zhu et al. studied the fabrication of Al6082 with nano SiC composites done by squeeze casting, and TS and YS were improved in T6-treatment process than base alloy [13]. However, stir casting creates high porosity of composites which leads to defects and reduce material and mechanical strengths. To minimize deficiencies and acquire better features, stir casting was improved with the squeezing process [14]. Input parameters in stir and squeeze casting significantly disturb the quality of composites and help to decide the mechanical characteristics [15]. Vijian et al. utilised the Taguchi technique to enhance the material property by influencing process variables of squeeze pressure, die preheating temperature, and duration of pressure, and squeeze pressure is the best involvement factor for enlightening TS and BHN of matrix composites [16]. TiC and SiC are in the form powder frequently applied in enhancing of composites of Al alloy [17]. However, there are few studies on the impact of reinforced particles on AA 6082 obtained by the squeeze-stir casting. S. Dadbakhsh et al. studied the equal channel angular pressing method (ECAP) for ageing treatments in order to strengthen a common 6082 Al alloy. It was discovered that the alloy can be strengthened by ageing it both before and after ECAP processing. Through the application of the proper postaging treatment, the ECAPed specimen's strength and ductility were increased [18]. According to Kumar et al. work [19] aluminum's tensile surface is marked by an uneven distribution of dimples that causes ductile failure, while aluminum fly ash composites made using the stir cast method are known for brittle failure because of the matrix's plastic flow. The hardness and strength of the composites increased with the inclusion of boron carbide, according to Ghasali et al. [20] who created Al/boron carbide

composites utilising a microwave furnace for sintering. Aluminum alloy, alumina (Al2O3), and boron carbide metal matrix composites produced by stir casting are the focus of research by Vijaya Ramnath et al. This work involves the creation of these composites and a mechanical analysis of their mechanical properties [21]. $Al6082/Al_2O_3/Al_2SiO_5$ composites are created by utilising the stir casting method for the study of fracture toughness. The Taguchi technique is used to study the effects of input parameters such as the weight percentage of Al_2O_3, the stirring speed, and the stirring time on the hardness, tensile strength, impact strength, and fracture toughness of cast $Al6082/Al_2O_3/Al_2SiO_5$ composites. The weight percentage of Al_2O_3 is a larger influencing component for the experimental design, according to Taguchi's L9 orthogonal array. To create samples of MMCs with each factor having three levels, three process parameters—wt.% of Al_2O_3 (3, 6, 9), stirring speed (150, 200, 250 rpm), and stirring duration (5, 10, 15 min.) are used. To visually observe the dispersion of Al_2O_3 particles in the matrix of Al 6082, microstructural characterisation using a scanning electron microscope (SEM) is performed [22]. The emergence of hybrid reinforced composite with inexpensive Al6082 has been influenced by the demand of lightweight and robust materials. To meet the demands of the automotive sector, a substitute material with high product quality and accurate casting is needed. The manufacture of composites by squeeze casting has been undertaken by a number of researchers, but only a small number of research works have been conducted on the optimization parameters in the combined stir-squeeze casting. The significance of this research is to fabricate the $Al6082/ZrSiO_4/TiC$ hybrid composites and identify the optimum parameters for enhancing the mechanical properties to promote the use of Al6082 in various applications. The four-leveled parameters were evaluated using the Taguchi technique to identify a special set of input parameters that would improve the specified output and hardness (HN), tensile strength (TS), and porosity (PO) for prepared composites and are investigated.

2. Materials and Methods

2.1. Stir Casting. The basic alloy, designated as AA 6082 was melted in a resistive heating furnace with a stirrer. Tables 1 and 2 indicate the chemical composition of AA 6082 and the properties of Tic/ZrSiO4, respectively. Mechanical properties of the Al 6082 alloy such as tensile strength, yield strength, elongation, and hardness are 280 MPa, 210 MPa, 14%, and 80 respectively. At various weight percentages, melted AA 6082 mixed with $ZrSiO_4$ and TiC. $ZrSiO_4$/TiC were used in the casting of 6082 to produce a hybrid composite. Na_3AlF_6 (10 grams) were added to the base material throughout the melting process in order to reduce the production of slag and increase casting effectiveness and stir casting complete setup seen in Figure 1. A secure lifting mechanism helped to move stirrer into contact with the compound's constituent elements. Al alloy was kept inside crucible and melt it around 800°C in an electric furnace. After weighing with a digital weigh scale, zirconium silicate/

TABLE 1: AA 6082 chemical elements.

Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr	Al
0.8	0.5	0.1	0.6	1.2	0.2	0.1	0.25	Bal

TABLE 2: Reinforcement properties.

Properties	TiC	ZrSiO$_4$
Molar mass (g/mol)	59.8	183
Colour	Black	Colourless
Density (g/cm^3)	4.91	4.55
Melting point (°C)	3150	1550

FIGURE 1: Stir casting setup.

titanium carbide (5 w.t%) powder was burned at 325°C in another furnace. Then, Al alloy metals and reinforcements were blended and heated to a temperature of around 820°C. To create Al-based composites, the prepared melted particles were placed into the required mould after being continuously stirred by a stirrer connected to the motor for 5–7 minutes. Continue the process to create several samples by adjusting the stirrer speeds, mixing duration, and weightiness percentage of reinforcement ingredients. The parameters with levels are shown in Table 3. After reviewing the previous published articles, it is noticed that many researchers have selected mostly three parameters in the casting process. In this work, to get excellent result, four parameters are taken to analyze the mechanical properties. Based on the $L16$ array, the combinations of parameter levels are changed and conduct the different test of porosity, tensile test, and hardness test. The overall experimental results are displayed in Table 4. The setup of the squeeze casting is shown in Figure 2. The molten metal was poured into the desired die and its dimensions are $35 * 30 * 75$ mm^3. In the squeeze process, a plunger is used to apply the pressure (60 MPa) from top of the die and holding that plunger for 1–2 minutes and then remove the solidified part from the preferred die. The stir casting parameters are used typically by stirrer size, speed, time, blade angle, stirrer position, temperature, and reinforcement's percentage. Mostly, due to not taking the pressure into the account as a parameter, the stir casting procedure results in increased porosity of specimens. Stir casting is supplemented with squeeze

casting, a mixture of stir casting and high pressure, in order to reduce casting flaws such as porosity and to produce superior characteristics. Using a manufacturing method called stir-squeeze casting, solid metal may be turned into liquid and back into the solid form. Many industries that require complex shapes with excellent structural integrity find it to be quite helpful. The developed composites are used in different applications such as Cranes, Beer barrels, Ore skips, and Milk churns.

2.2. Taguchi Design Experiments. Among the various optimization techniques (CCD and BBD of RSM), Taguchi techniques are the best approaches for examining the effects of numerous factors through the design of experiments (DOE) and the application of numerical tools. Along with a robust design, this method is used to decrease the number of parameters that do not vary DOE. The Taguchi technique is a method for choosing the best process parameters and variables for a certain process response (output). The technique's goal is to provide quality product at a lower cost [23].

2.3. Analysis of Variance. To determine the involvement of each stir-squeeze casting parameters significantly influencing the response of tensile strength, the ANOVA is utilised. The purpose of this analysis of variance is to identify the most important parameter that affects tensile strength as well as the importance of other parameters. In order to investigate the relationships between variables and their effects on the dependent variables, the grey relational analysis is employed in addition to the ANOVA table [24].

3. Result and Discussion

3.1. Porosity. Porosity was calculated for all prepared Al samples by differentiating the theoretical and experimental density [25] and the percentage of porosity (PO) was measured using formula (1). The density values of Tic and ZrSiO$_4$ reinforcements are 4.91 g/cm^3 and 4.55 g/cm^3, respectively.

$$\% \text{ porosity} = \frac{\left(\rho_{\text{theory}} - \rho_{\text{experiment}}\right)}{100}. \tag{1}$$

Theoretical density is measured by the following formula:

$$\rho_{\text{theory}} = (\rho * \text{wt. fraction})_{\text{Al6082}} + (\rho * \text{wt.fraction})_{(\text{Tic/Zrsio4})}. \tag{2}$$

The percentage of porosity of AMCs varied based on density in SSC specimens because of the inappropriate interfacial bondage between Al alloy and TiC/ZrSiO$_4$ particles. The bondage depends on the selected parameters. Figure 3 showed the porosity result of all specimens. It was observed that the highest (4.58%) and lowest porosity (2.91%) were

TABLE 3: Casting parameters with different levels.

Parameters	Levels			
	1	2	3	4
Stir speed (S)	300	400	500	600
Stir time (T)	10	15	20	25
Reinforceme®(R)	2.5	5	7.5	10
Squeeze pressure (P)	50	60	70	80

TABLE 4: Experimental results for the SSC process.

| Exp. no.	Process parameters				Experimental results		
	Stir speed (S), (rpm)	Stir time (T), (min)	Reinforcement (R), w.t%	Squeeze pressure (P), (MPa)	Tensile strength (TS), (MPa)	Hardness (HN)	Porosity (PT), (%)
L1	300	10	2.5	50	189.83	82	3.25
L2	300	15	5.0	60	197.52	73	3.75
L3	300	20	7.5	70	202.58	76	3.89
L4	300	25	10.0	80	200.80	69	3.78
L5	400	10	5.0	70	215.57	80	4.15
L6	400	15	2.5	80	257.52	76.2	4.28
L7	400	20	10.0	50	198.79	71.5	4.58
L8	400	25	7.5	60	252.74	75.5	3.93
L9	500	10	7.5	80	275.71	82.3	4.32
L10	500	15	10.0	70	204.91	82.4	2.92
L11	500	20	2.5	60	205.72	75.2	3.88
L12	500	25	5.0	50	225.26	79.2	3.15
L13	600	10	10.0	60	286.89	88.7	3.26
L14	600	15	7.5	50	200.56	85.2	2.78
L15	600	20	5.0	80	266.75	83.8	3.42
L16	600	25	2.5	70	282.32	82.6	2.91
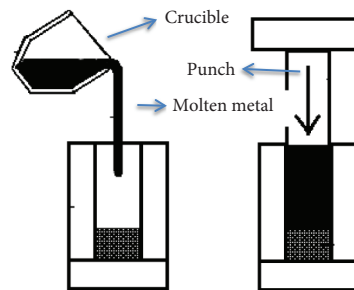
FIGURE 2: Squeeze casting process.

recognized at L7 (S2-T3-R4-P1) and L16 (S4-T4-R1-P3) specimens which possessed 400 rpm, 20 mins, 10 wt%, and 50 MPa and 600 rpm, 25 mins, 2.5 wt%, and 70 MPa, respectively. This could have been related to the problems like poor wettability properties, particle accumulation, clustering, and pore nucleation in the interface with insufficient mechanical stirring and uneven dispersion of reinforcements [26, 27], and the ratio of agglomeration is increased by the increased weight % of reinforced particles and can be decreased through the SSC process, which may have contributed to the substantial increase in porosity. The overall observational outcomes are exposed in Table 4.

3.2. Tensile Strength. According to the ASTM B557M standard, tensile tests were performed on the fabricated specimens in Figure 4. Before applying load (5 KN), the entire specimens were cleaned and polished with help of the abrasive paper in order to eliminate slag from the surface. Some of the tensile test specimens as per standard dimension are displayed in Figure 5. The tensile strength (TS) is calculated based on elongation, stress, and strain and the results are shown in Figure 6. It is found that the maximum TS (286.89 MPa) was attained at L13 while minimum TS (189.83 MPa) was attained at L1 experiment. This is due to the load applied; reinforcement strengthens and the grain
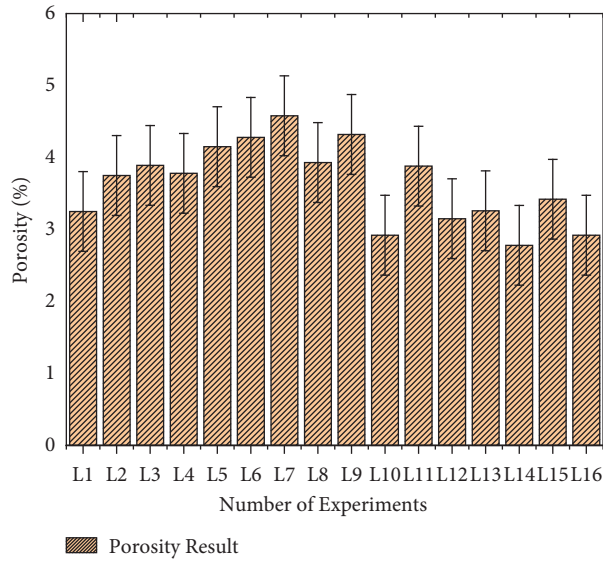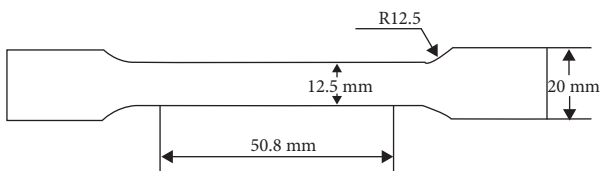
FIGURE 3: The porosity result.

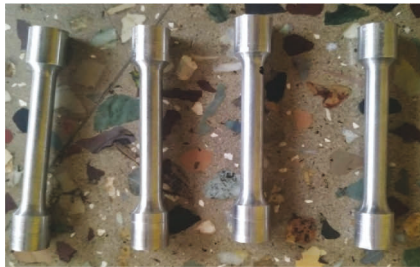FIGURE 4: The ASTM B557M standard-tensile test.

FIGURE 5: Some of the tensile test specimens.

size of TiC porosity gap is reduced because of grain refinement and squeeze pressure and also developed composites which possess brittleness and low ductility. According to the Orowan mechanism, tiny particles prevent dislocations from moving freely within the matrix [28]. The difference in Al matrix and nanoparticles at room temperature and the fact that the hard reinforcements [29] ($ZrSiO_4$/TiC) in the matrix decreased the ductility of the produced composites might both be considered contributing factors to the increased strength of nanocomposites. But among all the kinds of composites under the study, the ductility of the squeeze cast nanocomposite was the best.

3.3. Hardness. The hardness test is performed as per the ASTM E10-18 standard at room temperature by the Brinell hardness machine with a 1/16-inch ball indenter and 350 kg load are used. The hardness machine front view is displayed in Figure 7. Three trails are taken at various locations of each specimen and finally make it the average value. The BHN value varied due to different weight % of reinforcement mixed with Al6082. The highest (88.7 Hv) and the lowest (66 Hv) values of hardness are obtained at samples $L13$ (S4-T4-R1-P3) and $L4$ (S1-T4-R4-P4) and possess 600 rpm, 10 mins, 10 wt%, and 60 MPa and 300 rpm, 25 mins, 10 wt%, and 80 MPa, respectively. From the observational results, it is exposed due to increasing of reinforcement and squeeze pressure which increase the hardness value. The overall HN reading all experiments are displayed in Figure 8.

3.4. Microstructure Analysis of the Prepared Samples. Figures 9 and 10 display microstructures of optical images of the two fractured surface of insignificant and significant parameters on Al6082/$ZrSiO_4$/TiC composites. The optical microstructure images comprise three different phases: pore, matrix, and reinforcement particles [30]. Figure 9 shows that the lowest tensile strength is obtained by the combine parameter of S1-T2,-R4-P1. From the observation of the image, it is noticed that the reinforcement particles are not fully uniformed and also there are many pore faults in the microstructures. It proposes that $ZrSiO_4$/TiC and the 6082 matrices are not well united under the experimental condition. Figure 10 displays that the maximum TS is attained by the combine parameter of S4-T1-R1-P4 and noticed that almost no pore defect, good diffusion due effect of the reinforcements mixed properly. It is evident that there is a tighter bonding amongst the different $ZrSiO_4$ as well as the TiC and Al 6082 matrix.

Figure 11 shows the main plot (smaller is the best) on signal to noise ratio for TS. The stir speed of 600 rpm, stir time of 10 min, reinforcement of 2.5 wt%, and squeeze pressure of 80 MPa are optimum for tensile strength. The highest TS is perceived from the smaller the better S/N response. The influence of the control parameters on TS
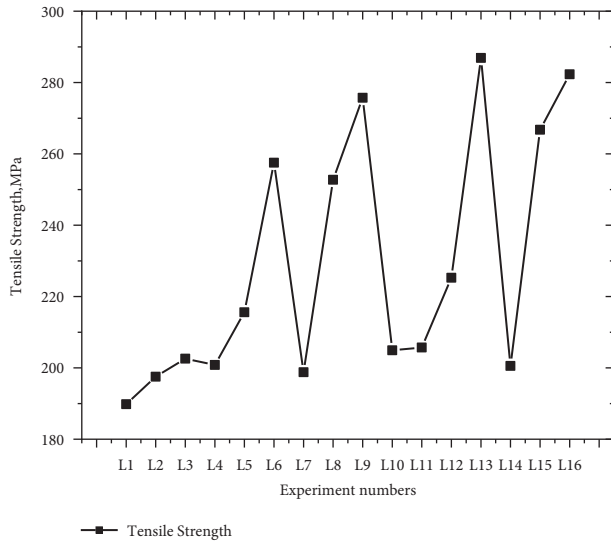
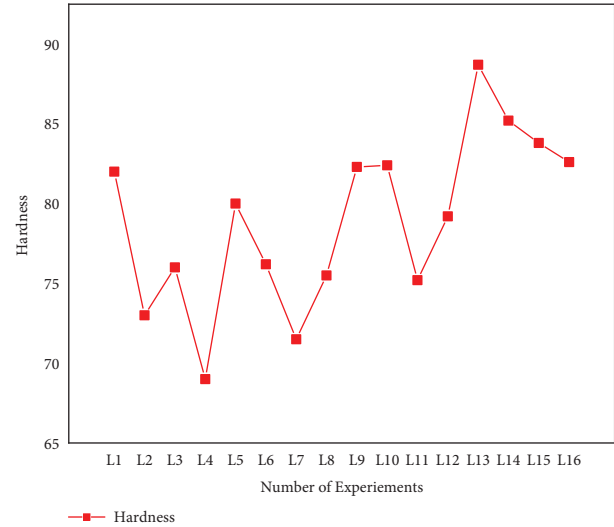FIGURE 6: Tensile test result.

FIGURE 8: Hardness observation results.
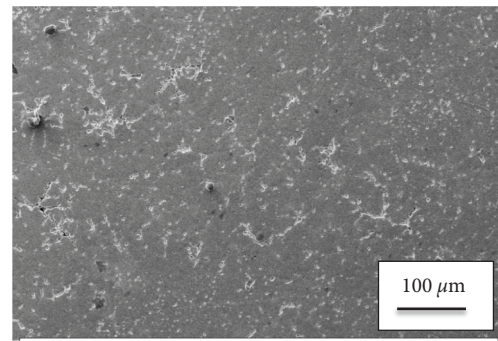

FIGURE 7: Hardness machine.

FIGURE 9: Microstructure image of the tensile fractured surface for an insignificant parameter (S1-T2,-R4-P1).

acknowledged with the S/N ratio response is shown in Table 5. The optimal process condition attained S4-T1-R1-P4 for the specified parameter levels, whereas the lowest tensile strength is obtained at the combinational parameters of S1-T2, -R4-P1.

3.5. ANOVA. The ANOVA approach is useful for examining the variability of an output in relation to a number of inputs. An analysis of variance is designed for the investigation of variables that significantly affect the achievement characteristic. The study was conducted at a level of 5% correlation, or the confidence level of 95%. Table 6 displays ANOVA outcomes as the response characteristic of Al6082/ZrSiO$_4$/

TiC composites. The table exposes the stir speed (41.8%) as the significant parameter, followed by squeeze pressure (25.7%), stir time (12.7%), and reinforcement (1.96%) that have an influence on tensile strength behavior for Al6082/ZrSiO$_4$/TiC hybrid composites. The residual error is 17.84% due to less involvement of two process parameters (T&R) to improve the mechanical properties, but the overall contribution percentage of all parameters is around 83% for increasing tensile strength. So, this ANOVA model is significant and acceptable.

3.6. Linear Regression Model Analysis. In order to demonstrate the relationship between predictor variables and response variables, a multiple linear regression analysis examination model was utilised to fit a linear equation to the experimentally perceived data. The software MINITAB 17 was used to create a linear regression model display in view of the experimental results. In this method, a regression equation is created that increases the connection between significant terms from an ANOVA. The regression equation (1) helped for TS is
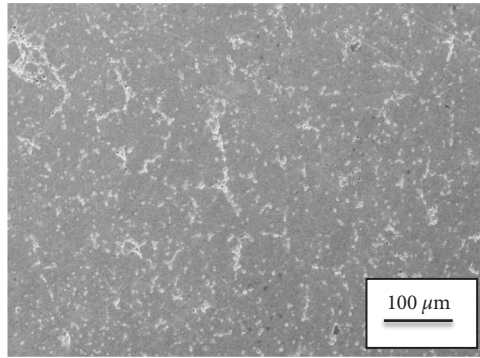
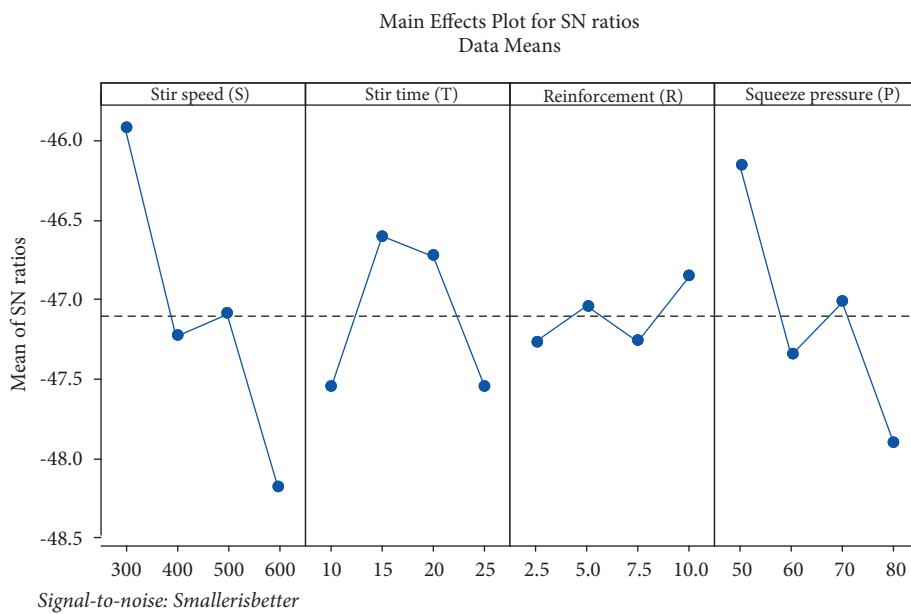FIGURE 10: Microstructure image of the tensile fractured surface for a significant parameter (S4-T1-R1-P4).

FIGURE 11: Mean of SN ratio graph.

Tensile Strength (TS) = 70.0 + +0.1811 Stir speed

$$- 0.04 \, \text{Stir time} - 1.06 \, \text{Reinforcement} \quad (3)$$

$$+ 1.304 \, \text{Squeeze pressure}.$$

3.7. Interaction Graph for TS.
The effect of parameters in various combinations on the produced composites' tensile strength is shown in Figure 12. It has been discovered that for certain phenomenon, the TS will change when a parameter is changed in either term of their levels or interactions. The interaction $S * R$, $T * R$, $R * P$ changing with closely constant values while the level of these parameters will increase. The rise in these interactions is very small and it can be deliberated as constant variation. Nevertheless, for the case of other parameter interactions such as $S * T$, $S * P$, $T * P$ when the level of these parameters increases. In these combinations, stir speed and squeeze pressure play a dominant role in tensile strength. Moreover, only minor variations in the numeric value of each case due to a change in parameter levels were seen, which is essentially identical to the phenomenon of these results. Some of the data indicate that some parameter combinations or interactions have very little effect on the TS of hybrid composites.

3.8. SEM for Fractured Surfaces.
It is possible to learn crucial information regarding the influence of a sample's innate microstructural properties on its strength by analyzing the fracture surfaces of tensile samples. In Figures 13 and 14, the fractured surfaces of the tensile samples ($L1$ and $L13$) are exhibited. On the fracture surface of $L1$ sample in Figure 13, large voids of various sizes, shapes, and shallow dimples are distributed. Overload is the main factor that causes fracture, and the coalescence of further voids determines failure. The areas around second phase particle inclusions, grain structure, and displacement pileups are where the voids may develop. As a result, the microgaps become larger, merge, and eventually form a continuous fracture surface, decreasing the tensile strength as the strain increases throughout the tensile test. Figure 14 shows that the less

TABLE 5: Response table for SN ratios (smaller is better).

Levels	Stir speed (S)	Stir time (T)	Reinforcement ®	Squeeze pressure (P)
1	−45.92	−47.55	−47.27	−46.16
2	−47.23	−46.60	−47.04	−47.35
3	−47.09	−46.72	−47.26	−47.01
4	−48.18	−47.54	−46.85	−47.90
Delta	2.27	0.95	0.41	1.74
Rank	1	3	4	2

TABLE 6: Analysis of variance for tensile strength.

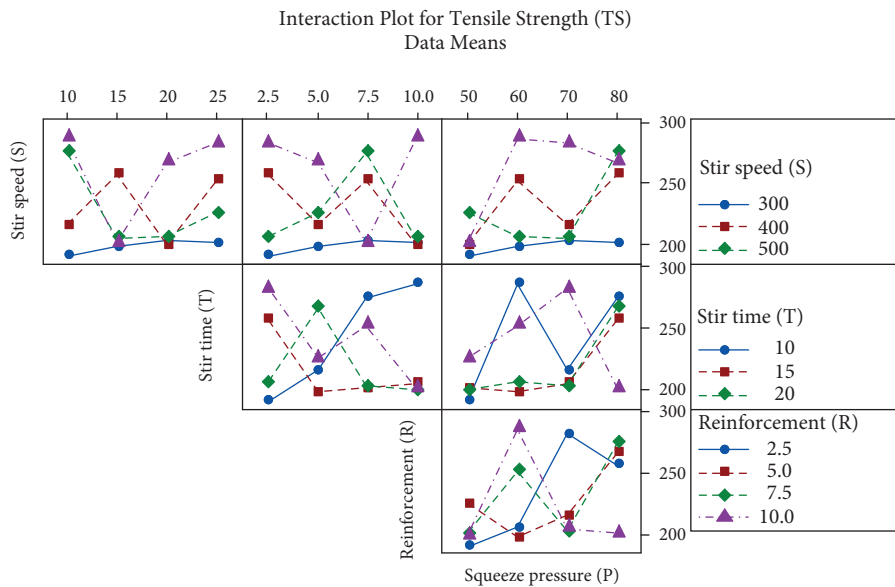| Sources	DF	Seq SS	Adj SS	Adj MS	F	P	% Contributions
Stir speed (S)	3	10.3664	10.3664	3.4555	2.35	0.0251	41.8
Stir time (T)	3	3.1689	3.1689	1.0563	0.72	0.0604	12.7
Reinforcement (R)	3	0.4721	0.4721	0.1574	0.11	0.0951	1.96
Squeeze pressure (P)	3	6.3835	6.3835	2.1278	1.45	0.0385	25.7
Residual error	3	4.4139	4.4139	1.4713	—	—	17.84
Total	15	24.8048	—	—	—	—	100

FIGURE 12: Interaction plot for tensile strength between the input parameters.
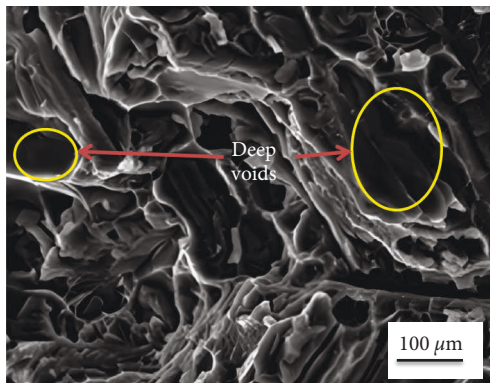

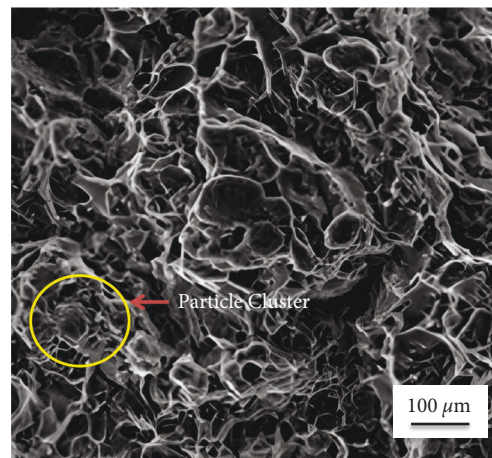FIGURE 13: SEM fracture image of sample-L1 (S1-T2, -R4-P1).

FIGURE 14: SEM fracture image of sample-L13 (S4-T1-R1-P4).

quantity of cracks, dimples, and voids are found at sample *L*13 due to reinforcement particles are almost uniformly distributed with Al 6082.

4. Conclusion

This research work addressed that the porosity, tensile strength, and hardness on AA6082/TiC/ZrSiO$_4$ hybrid composites prepared through stir-squeeze cast method. Four input parameters with four different levels have been nominated to produce Al composites which are stirrer speed, stir time, weight % of reinforcement, and squeeze pressure. The Taguchi approach (*L*16) helped to decrease the number of experiments and make the parameters combination to conduct experiments. The important results of this research are followed below.

(i) The highest (4.58%) and lowest porosity (2.91%) were recognized at L7 (S2-T3-R4-P1) and L16 (S4-T4-R1-P3) specimens which possessed 400 rpm, 20 mins, 10 wt%, and 50 MPa and 600 rpm, 25 mins, 2.5 wt%, and 70 MPa, respectively.

(ii) Optimum process parameters for stir-squeeze casting method is stirrer speed of 600 rpm, stir time of 10 min, reinforcement of 2.5 wt%, and squeeze pressure of 80 MPa, and the lowest tensile strength is obtained at the combinational parameters of S1-T2,-R4-P1.

(iii) It is exposed that due to increasing of reinforcement and squeeze pressure which increase the hardness 88.7 Hv.

(iv) The ANOVA table reveals the stir speed of 41.8% as the important stir-squeeze parameter, followed by squeeze pressure of 25.7%, stir time of 12.7%, and reinforcement of 1.96% that have an influence on tensile strength behavior for Al6082/ZrSiO$_4$/TiC hybrid composites.

Data Availability

The data used to support the findings of this study are included within the article. The data are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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