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Research Article

Optimization of stir casting parameters for the tensile behavior of nano Al_2O_3 and ZrO_2 reinforced Al-Mg-Si alloy metal composites

Annapoorna K[1,2,a], Shobha R[2,b], Bharath V[1,*,c], Rajanna S[3,d], Manjunath Vatnalmath[4,e] Madeva Nagaral[5,f], V Auradi[4,e], C G Shivaprasad[6,g]

[1]*Dept. of Mechanical Eng., RNS Institute of Technology, Visvesvaraya Technological University, India*
[2]*Dept. of Industrial Eng. and Management, Ramaiah Institute of Technology, Bengaluru, Karnataka, India*
[3]*Dept. of Mechanical Eng., Government Engineering College, Mosale Hosahalli, India*
[4]*Dept. of Mechanical Eng., Siddaganga Institute of Tech., Visvesvaraya Technological University, India*
[5]*Aircraft Research and Design Centre, Hindustan Aeronautics Limited, Bangalore 560037, Karnataka, India*
[6]*Hindustan Management Academy, Hindustan Aeronautics Limited, Bangalore 560037, Karnataka, India*

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Abstract

Stir casting is a frequently used method in the metallurgical process of casting aluminium composites. The microstructure and performance of the composites are influenced by the stirring casting parameters. The majority of research conducted in this area focused on producing composites using stir casting parameters that were predetermined, without utilizing an optimization method. This work aims to optimize the stir casting parameters for the manufacturing of Al-Mg-Si (Al6061) alloy reinforced with hybrid nano Al_2O_3 and nano ZrO_2 in order to enhance its performance. The Taguchi optimization technique was employed to analyze the important effects of stir casting parameters on the ultimate tensile strength of a hybrid metal matrix composite. The composites were produced by the ultrasonic aided stir casting method, employing a set of process parameters determined by the Taguchi L16 orthogonal array. The S/N (Signal to Noise ratio) and Regression model were utilized to determine the optimal values and assess the influence of process parameters on the tensile qualities. The Minitab 21 software was utilized to perform simultaneous optimization of the attributes. The findings indicated that the composition of the nano reinforcement, stirring temperature, stirring speed, and stirring time all had a substantial impact on improving the UTS (Ultimate Tensile Strength) of the material.

1. Introduction

In recent years, the modern in service performance demands the materials with a bundle of properties, which are difficult to achieve using monolithic materials [1, 2]. New generation hybrid nano metal matrix composites have been satisfying the recent demand of advance engineering. For several years, researchers have been investigating the mechanical properties of light metal matrix composite materials that incorporate ceramic particles as reinforcements due to their exceptional performance. Aluminium matrix composites, which are strengthened by ceramic particles, have become increasingly popular in the military, aerospace, and electrical industries because of their improved mechanical properties [3, 4]. Ongoing research is being conducted to enhance the characteristics of metal matrix composites in the domains of automotive, aerospace, electrical, and marine sectors. Aluminium 6061 is a metal alloy that possesses a low

*Corresponding author: bharathv88@gmail.com
[a]orcid.org/0000-0003-2543-4801; [b]orcid.org/0000-0003-0210-3540; [c]orcid.org/0000-0001-6765-4728; [d]orcid.org/0000-0001-9209-5104; [e]orcid.org/0000-0003-3138-9453; [f]orcid.org/0000-0002-8248-7603; [g]orcid.org/0000-0001-6549-6340
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density, high ductility, good corrosion resistance, and is relatively inexpensive [5]. It finds uses in engineering fields such as automotive and aerospace, where mechanical features like high tensile strength and high wear resistance are crucial. Aluminium alloys possess low hardness and exhibit less wear resistance, hence restricting their use. The incorporation of rigid ceramic reinforcing particles into aluminium and its alloys results in the formation of a composite material with a discontinuous metal matrix. This composite exhibits almost isotropic properties [6, 7]. There is a lack of study on Aluminium metal matrix composites that are strengthened by hybrid nano particles. Alumina is a highly utilized engineering ceramic material because of its exceptional elastic modulus, wear resistance, and resistance to chemical corrosion [8, 9]. Zirconia possesses several distinctive characteristics, including high toughness that contributes to its strong mechanical strength, exceptional resistance to crack propagation, outstanding thermal resistance, and low thermal conductivity at elevated temperatures. These features have been demonstrated to surpass those of other ceramics [10, 11]. There is an increasing global interest in the production of HMMC's (Hybrid Metal Matrix Composites). HMMC materials comprise a combination of the qualities of their reinforcements and have enhanced mechanical and tribological capabilities. Hence, the incorporation of a hard nanostructure material such as Al_2O_3 into a ZrO_2 matrix with high toughness appears to be a very promising approach for creating a superior composite reinforcement and enhancing the overall mechanical properties of the composite [12, 13]. The literature review reveals that numerous research studies have been published on the use of nano particles as reinforcement in aluminium metal matrix composites. However, there is a limitation of works specifically focused on the use of hybrid nano particle reinforcement and also there is a limited research on the impact of weight fraction, stirring speed, stirring time, and temperature when using Alumina and Zirconia as reinforcement. In addition, there is a scarcity of research that investigate the combined impact of various process factors, such as percent weight fraction, stirring speed, and stirring duration [14]. Stir casting is a widely acknowledged and commercially utilized manufacturing process for Metal Matrix Composites (MMCs). It is considered a potential route for mass production [15, 16]. The process of combining reinforcement and matrix is a crucial step to achieve a uniform dispersion of reinforcing particles within the matrix. Stir casting provides enhanced bonding between the matrix and particles by incorporating the stirring movement of particles into the molten material. In order to thoroughly investigate the impact of different process parameters, the Taguchi design is utilized [17]. This design methodology provides an effective and methodical approach by reducing the number of tests while encompassing a broad variety of parameter combinations [18, 19]. It allows for the investigation of factors like stirring speed, stirring time, temperature, and nano particle composition simultaneously [20]. This study aims to create a new material by incorporating nano alumina and zirconia as reinforcements into an aluminium metal matrix composite. The goal is to enhance the mechanical properties of the material and improve the distribution and wettability of the reinforcing particles. To achieve this, a two-stage mixing process combined with preheating of the reinforcing particles is being utilized. The study will also examine how different stir casting parameters, including as stirring speed, time, temperature, and weight percentage of reinforcement, affect the final tensile strength of the Al/Alumina/Zirconia HMMC's. This will be done using Taguchi DOE [21]. The ANOVA, or Analysis of Variance, is employed to examine the collective impact of the aforementioned parameters, including their interactions.

2. Experimental Details

2.1 Reinforcement Materials and Matrix

Al6061 aluminium metal was used as the base for this study, and nano Al_2O_3 and nano ZrO2 were used to make it stronger. An Energy Dispersive X-ray Analysis (EDAX) machine was used to check the chemical compositions make-up of the raw material. The chemical make-up of the Al6061 metal is shown in Table 1.

Table 1. displays the precise chemical composition of the Al6061 alloy.

Constituent	Mg	Si	Ti	Cr	Mn	Fe	Cu	Zn	Al
Wt. %	0.81	0.62	0.1	0.13	0.11	0.35	0.2	0.12	Balance

Table 2. displays the characteristics of the matrix and reinforcing material.

Material	Density (gm/cc)	Melting point(deg C)	Modulus of Elasticity (GPa)	Brinell Hardness	Poisons Ratio	Tensile Strength (MPa)
Al6061	2.7	585	68.9	30-33	0.33	110-182
Al_2O_3	3.98	2072	370	450-500	0.21	650-660
ZrO2	5.68	2715	94.5	130-145	0.34	300-330

2.2 Composite Fabrication

The stir casting process is a vital technique used to manufacture metal matrix composites (MMCs) that have improved characteristics. This experiment focuses on investigating the effects of varying parameters (stirring speed, stirring time, temperature), Composition (nano Zirconia and nano Alumina) on the properties of Al6061-based composites. The Taguchi L16 orthogonal array design was employed for an efficient experimental setup. This method allows for studying multiple factors with minimal experimentation. The array consists of 16 distinct combinations of components being studied, as displayed in Table 4, in order to optimize the variables of stirring time, speed, and temperature and wt. % of reinforcement. The hybrid metal matrix composite is fabricated using Al6061 Alloy with a chemical composition outlined in Table 1. The reinforcement materials employed were nano alumina (n-Al_2O_3) and nano zirconia (n-ZrO_2), with an average particle size ranging from 50 to 90 nanometres. Figure 1 and 2 depict the stir casting experimental setup (Manufacturer: Swamequip) that was utilized for producing Metal Matrix Composites (MMCs). The setup comprises an electrical induction furnace, a crucible, a stirring apparatus, thermocouples, a weighing scale, a digital timer, and an ultrasonic vibrator.

Al6061 ingots were placed inside the induction furnace and melted until it reaches the desired molten state at the temperature (700, 725, 750, 775°C) a degassing agent was added into molten Al6061 to remove the slag. Preheat the nano ZrO2 (0.50, 0.75, 1.00 and 1.25 wt %) and nano Al_2O_3 (0.50, 0.75, 1.00 & 1.25 wt.%) particles at 250 deg C to eliminate any moisture and ensure uniform dispersion during stirring. At 1.25 wt. %, the particle-matrix interface is optimized, allowing for effective load transfer between the reinforcements and the matrix, leading to improved mechanical properties. A stainless-steel stirrer coupled with electric motor was immersed into the molten aluminum alloy.

Fig. 1. Stir casting machine

Fig. 2. Stirring of molten metal

A fixed amount of preheated n-Al_2O_3 powder and n-ZrO_2 powder was introduced into the mixture while stirring at varying speeds (400, 450, 500, 550 RPM) for different durations (6, 8, 10, and 12 minutes) to create a swirling motion. An ultrasonic vibrator was then applied for 5 minutes, followed by an additional 5 minutes of stirring. The frequency of Ultrasonic vibrator used is 20 KHz and power is 2500 watts. Finally pour the melt into the preheated (400 deg C) mould, allow the cast material to cool and solidify inside the mould before removing it for further analysis. Taguchi L16 orthogonal array design was used to create 16 unique combinations of stirring speed, stirring time, temperature, and $ZrO2/Al_2O_3$ composition.

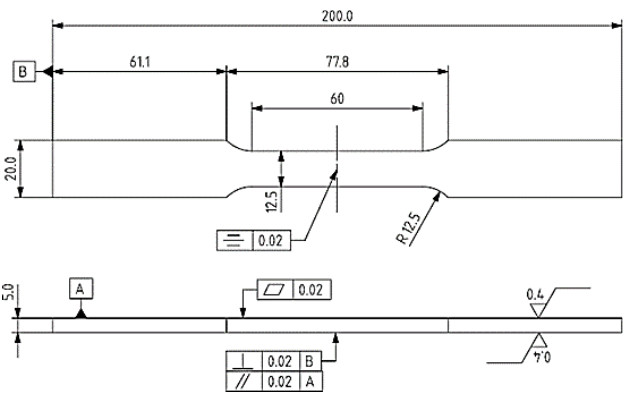


Fig. 3. Tensile specimen specification

The tensile specimens were prepared according to the ASTM E8-22 standard [22, 23]. The specimens were manufactured according to the procedure depicted in Figure 3. The tensile test was conducted using a servo hydraulic universal testing machine (Make: BISS) with a load capability of 25KN.The testing machine is equipped with a load cell to measure the applied force and an extensometer to measure the deformation. The load and displacement data is converted into stress-strain values, which are subsequently used to calculate mechanical properties (i.e., such as Young's modulus, yield stress, and UTS).

3. Results and Discussion

Table 3 displays the experimental design and the associated levels for the different parameters examined in the study. Five criteria were taken into account, with each factor having four levels. The five factors and their respective levels were systematically varied to investigate their individual and combined effects on the properties of the fabricated material. Such a design allows for a comprehensive exploration of the parameter space and facilitates the identification of optimal conditions for desired material properties.

The Table 4 provides a detailed overview of the experimental runs conducted, along with the corresponding values of the factors and the resultant UTS of the fabricated material. Each row represents a distinct experimental run, while the columns depict the weight percentage of reinforcement, stirring time, stirring speed and temperature respectively. Each combination of factor levels resulted in a unique set of ultimate tensile strength and S/N ratio, as reflected in table 4. The table provides a comprehensive dataset that enables the analysis of the effects of individual factors as well as their interactions on the UTS of the material. These experimental data are valuable for optimizing the fabrication process to achieve desired mechanical properties and overall performance characteristics of the material.

Table 3. Design of Factors for Stir Casting Process

Factor	Levels	Values
Zirconia	4	0.50, 0.75, 1.00, 1.25
Alumina	4	0.50, 0.75, 1.00, 1.25
Temperature	4	700, 725, 750, 775
Speed	4	400, 450, 500, 550
Time	4	6, 8, 10, 12

Table 4. Design matrix and experimental observations

Runs	ZrO_2	Al_2O_3	Time	Speed	Temperature	UTS	S/N Ratio
1	0.50	0.50	6	400	700	149.3	43.48
2	0.50	0.75	8	450	725	155.2	43.82
3	0.50	1.00	10	500	750	170	44.61
4	0.50	1.25	12	550	775	167.1	44.46
5	0.75	0.50	8	500	775	165.5	44.38
6	0.75	0.75	6	550	750	168	44.51
7	0.75	1.00	12	400	725	169.7	44.59
8	0.75	1.25	10	450	700	167	44.45
9	1.00	0.50	10	550	725	172.1	44.72
10	1.00	0.75	12	500	700	171	44.66
11	1.00	1.00	6	450	775	183.7	45.28
12	1.00	1.25	8	400	750	184.9	45.34
13	1.25	0.50	12	450	750	173	44.76
14	1.25	0.75	10	400	775	174.3	44.83
15	1.25	1.00	8	550	700	177	44.96
16	1.25	1.25	6	500	725	180.5	45.13

The stress-strain relationship of the composites that were created with varying weight fractions is displayed in Figure 4. Because the presence of nano-alumina and nano-ZrO_2 reinforcing particles inhibits the matrix material's ability to flow plastically, the weight fraction of n-Al_2O_{3p} and n- ZrO2 increased while the fracture strain and ductility of the resulting composites dropped gradually.

The findings from Tables 5 and 6 illustrate the responses concerning the S/N ratio and means, respectively. These tables collectively identify key factors significantly influencing the UTS of the composite material under investigation. Notably, among the five parameters analyzed, ZrO_2, Al_2O_3 percentage and temperature emerges as particularly noteworthy, as indicated by its high delta value. Following this, stirring speed, and stirring time also exhibit notable impacts on the UTS behavior of the Al6061 composite with ZrO_2 and Al_2O_3 content. This influence can be attributed to the enhancement of composite strength facilitated by the inclusion of ZrO_2 and Al_2O_3 nanoparticles in the matrix. These nanoparticles play a crucial role in refining the grain structure of the composite, thereby contributing to the observed improvement in mechanical properties.

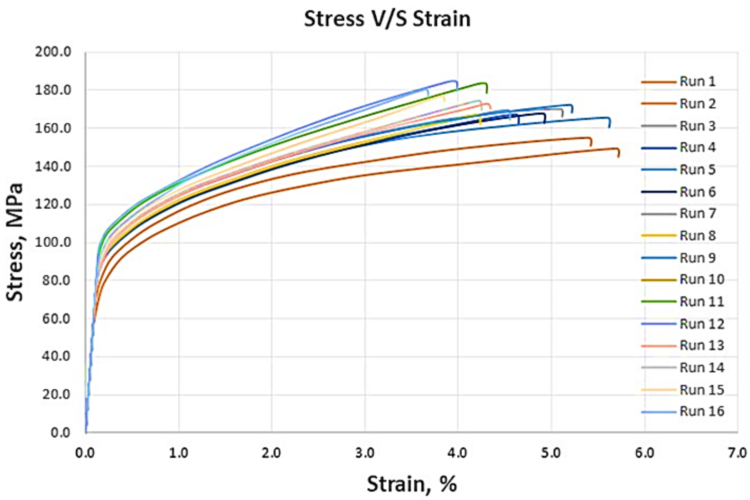


Fig. 4. Stress-strain curve of the produced composites at different runs

Table 5 displays the response table for signal to noise ratios.

Level	ZrO_2	Al_2O_3	Time	Speed	Temperature
1	44.09	44.33	44.6	44.56	44.39
2	44.48	44.45	44.62	44.58	44.56
3	45	44.86	44.65	44.69	44.8
4	44.92	44.85	44.62	44.66	44.74
Delta	0.91	0.53	0.05	0.13	0.41
Rank	1	2	5	4	3

Figures 5 and 6 display the primary effect graphs, illustrating the impact of different settings on the S/N ratio and data means, respectively. After careful investigation, it has been determined that the ideal conditions for producing the highest ultimate tensile strength (UTS) are as follows: a composition consisting of 1% weight percent, a melt temperature of 750°C, a stirring speed of 500 RPM, and a stirring period of 10 minutes.

Table 6. displays the response table for means

Level	ZrO_2	Al_2O_3	Time	Speed	Temperature
1	160.4	165	170.4	169.6	166.1
2	167.6	167.1	170.7	169.7	169.4
3	177.9	175.1	170.9	171.8	174
4	176.2	174.9	170.2	171.1	172.6
Delta	17.5	10.1	0.7	2.2	7.9
Rank	1	2	5	4	3

Notably, the UTS demonstrates its highest values at a moderate stirring speed of 500 RPM, with a decrease in tensile properties observed upon further increases in stirring speed. Additionally, it is observed that a moderate stirring time yields superior tensile strength, whereas an excessive increase in stirring time leads to a reduction in tensile strength.

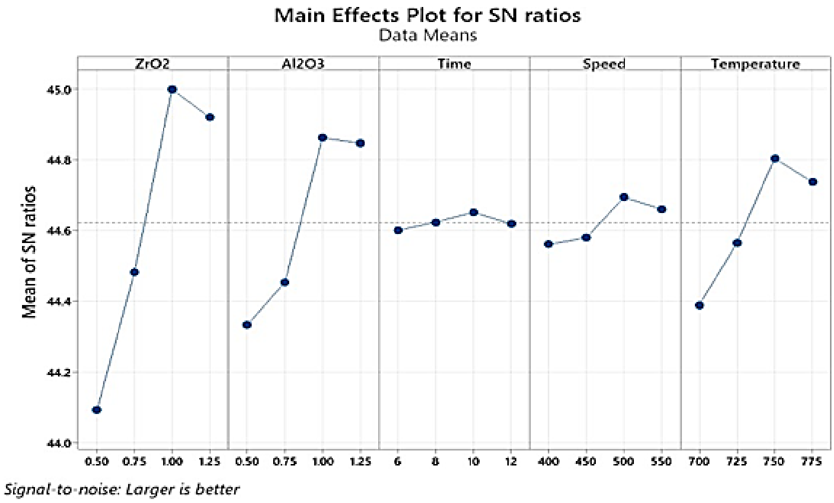


Fig. 5. Main effects plot for S/N ratios

Fig. 7 illustrates the interaction plot concerning tensile strength, revealing notable interactions primarily among filler percentage followed by temperature, stirring speed, and stirring time. Among these factors, ZrO2 and Al_2O_3 emerge as the most influential and highly interacting parameter affecting ultimate tensile strength (UTS). Specifically, the interaction between stirring speed and stirring time indicates a pattern wherein an increase in stirring time initially boosts strength before exhibiting a subsequent decline.
The observed enhancement in strength when the filler content increases by 1% can be ascribed to mechanisms such as particle reinforcement and grain refining. Moreover, the increase in stirring speed first improves the strength of the composite, but then it decreases. Appropriate stirring speeds are essential for achieving a uniform dispersion of reinforcement inside the matrix. The contour plots in Figure 8 depict the correlation between the process parameters and ultimate tensile strength (UTS) in relation to the weight percentage (wt %) of ZrO2.

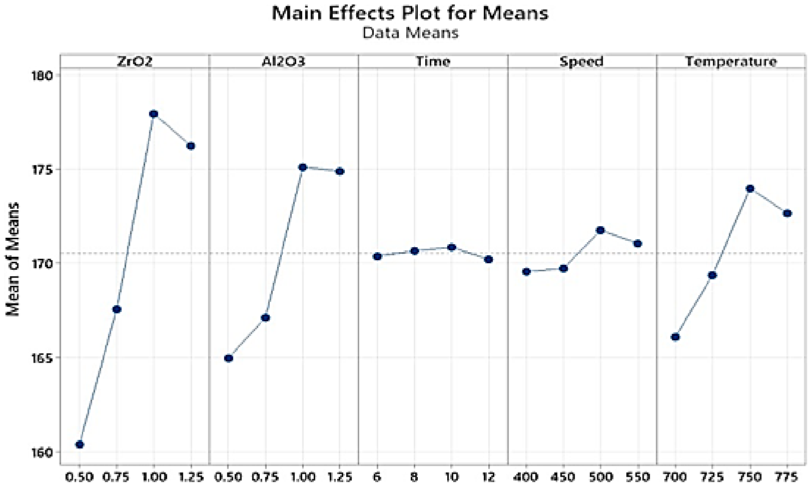


Fig. 6. Main effects plot for means

The weight percentage of ZrO2 is a crucial factor that can impact the ultimate tensile strength (UTS). Experimental evidence demonstrates that increasing temperatures, while decreasing the weight percentage of ZrO2 and increasing the weight percentage of Al_2O_3, lead to increased ultimate tensile strength (UTS). On the other hand, low stirring time and high ZrO_2 wt % yield maximum UTS, however high stirring speed and high ZrO_2 wt % can also yield the highest UTS. Likewise, Fig. 12 shows the contour plots of UTS relative to wt % of Al_2O_3. It is evident that the low stirring time, stirring speed and wt % of Al_2O_3 increases the UTS. Additionally, the low wt% of Al_2O_3 with high temperature also attains maximum UTS.

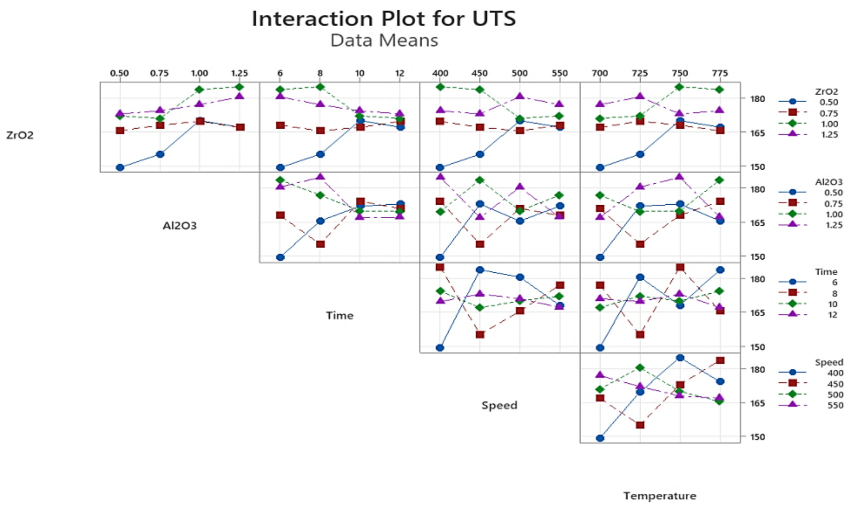


Fig. 7. Interaction plot for UTS of Al6061/ZrO_2/ Al_2O_3

ANOVA Table 7 summarizes regression analysis results to determine how factors affected the dependent variable. ZrO2, Al2O3, Time, Speed, and Temperature are considered. The regression model is significant with an F-value of 10.35 and a p-value of 0.001. The p-values for ZrO2, Al_2O_3, and temperature are 0.000, 0.004, and 0.038, respectively. These low p-values indicate a substantial relationship with UTS, as they are all below the threshold of 0.05. The high p-values of 0.975 and 0.537 for stirring duration and speed indicate that they do not affect the dependent variable.

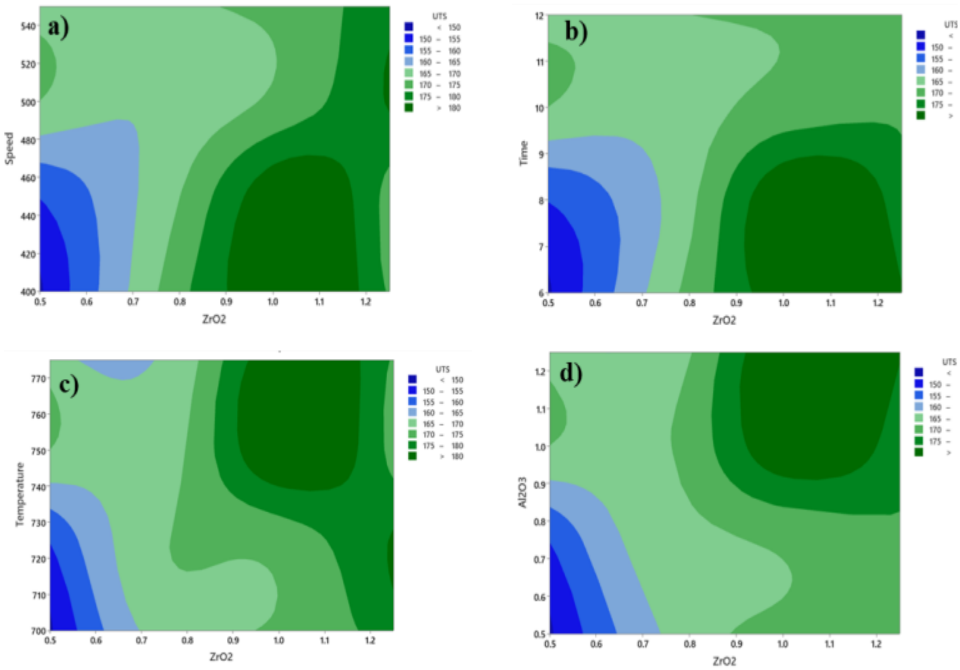


Fig. 8. Contour plots of UTS for various process parameters with respect to wt% of ZrO_2

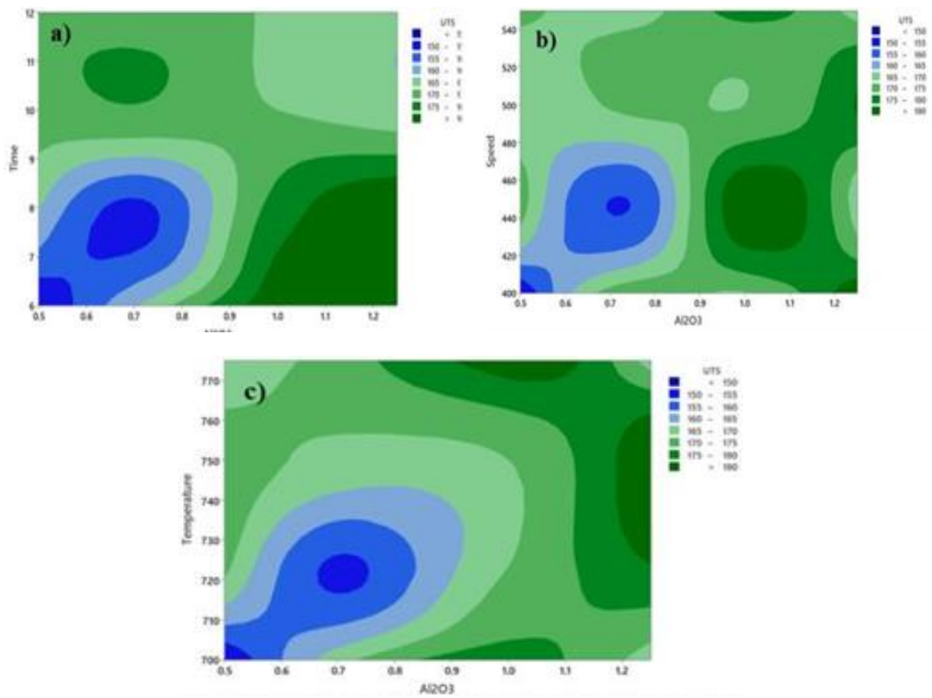


Fig. 9. Contour plots of UTS with various process parameters with respect to wt% of Al_2O_3

Table 7. Summary of Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	5	1078.35	215.67	10.35	0.001
ZrO_2	1	667.59	667.59	32.02	0.000
Al_2O_3	1	283.88	283.881	13.62	0.004
Time	1	0.02	0.021	0	0.975
Speed	1	8.52	8.515	0.41	0.537
Temperature	1	118.34	118.341	5.68	0.038
Error	10	208.48	20.848		
Total	15	1286.82			

- Regression Equation

$$UTS = 59.3 + 23.11\ ZrO2 + 15.07\ Al_2O_3 - 0.016\ Time + 0.0130\ Speed + 0.0973\ Temperature$$

Regression equation is a mathematical representation of the relationship between the predictor variables (ZrO_2, Al_2O_3, Time, Speed, and Temperature) and the response variable (UTS). It can be used to predict the Ultimate Tensile Strength for given values of the predictor variables.

- Model Summary

These data provide a comprehensive understanding of the regression model's accuracy and predictive capabilities. The regression's standard error, shown as S, is precisely 4.566. The provided value is the standard deviation of the residuals, which indicates the average difference between the actual values and the expected values. An R-squared value of 83.80% shows that the model successfully explains a substantial portion of the variability seen in the dependent variable (ZrO_2, Al_2O_3, Time, Speed, and Temperature). Overall, the high R-squared value shows that the model fits the data well.

Table 8. Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
4.566	83.80%	75.70%	51.15%

3.1 Outcome of Taguchi and ANOVA Analysis

Table 4 summarizes the average UTS of the runs. The Ultimate tensile strength for Al6061/Al_2O_3/ZrO_2 composite was higher when compared to base alloy. Figures 5 and 6 demonstrate that the combination of 1 weight % of ZrO2 and 1 weight % of Al_2O_3 exhibits the highest Ultimate tensile strength when subjected to a melt temperature of 750 deg C, speed of 500 RPM, and time of 10 minutes. The quality qualities are assessed by converting the experimental values into S/N ratio. An analysis has been conducted on the impact of parameters such as composition, melt temperature, stirring speed, and stirring time on the ultimate tensile strength. This analysis was performed utilizing a signal-to-noise response table. The signal-to-noise ratio (S/N ratio) is a single value that represents the level of variation in a set of iterations. Table 5 provides the ranking of process parameters for Ultimate tensile strength based on the signal to noise ratio achieved for different parameter values. The control factors have been found to be statistically significant in influencing the signal to noise ratio. It has been noted that the composition is the most influential parameter in improving the Ultimate tensile strength, followed by the Melt temperature, speed, and time of stirring. Figure 10 depicts the graphical representation of the impact of process parameters. The experimental data was analyzed utilizing the signal-to-noise ratio approach to ascertain the optimal conditions that result in an augmentation of the ultimate tensile strength. According to Figure 8, the highest Ultimate tensile strength is achieved at a melt temperature of 750 deg C, speed of stirring is 500 RPM, and duration of 10 minutes when the composition includes 1 weight % of ZrO_2 and 1 weight % of Al_2O_3. Therefore, the most effective configuration of the control variables to enhance the Ultimate tensile strength of HMMC has been determined. Furthermore, the literature survey clearly indicates that these process parameters are quite similar to the optimized parameters [24].

3.2 Confirmation Test

After conducting Taguchi and ANOVA analyses to optimize the fabrication process of Al6061- based composites with nano ZrO_2 and nano Al_2O_3, it is essential to validate the results by performing confirmation tests. These tests provide assurance that the identified optimal parameter settings indeed lead to the desired material properties and consistent performance.

Table 9. Optimized parameters

ZrO_2	Al_2O_3	Time	Speed	Temperature
1	1	10	500	750

The main goal of the confirmation test is to verify the outcomes of the Taguchi and ANOVA analyses. By implementing the optimized parameter combinations, as determined by these analyses, we aim to assess whether the predicted improvements in mechanical properties are reproducible and consistent.

Table 10. Predicted and Experimental Values

S/N Ratio	Predicted UTS	Experimental UTS	Deviation
45.5162	187.52	195.21	4.1%

3.3 SEM/EDAX Analysis of Produced Composites

SEM and EDAX plot indicate the presence of peaks associated with n-Al_2O_3, n-ZrO2, base alloy, and Al6061/1% n-ZrO_2/1% n-Al_2O_3 is depicted in Figures 10, 11, 12 and 14, respectively.

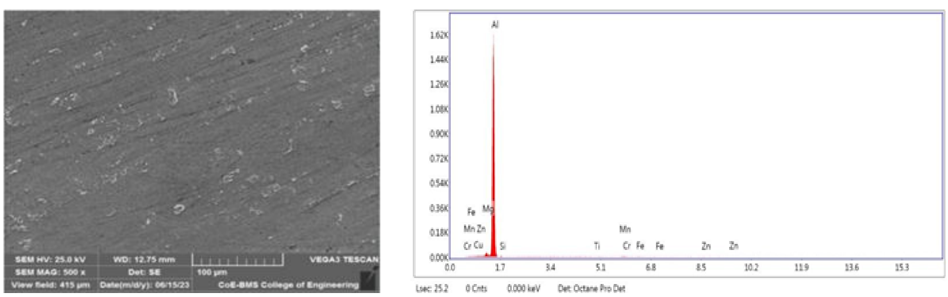


Fig. 10. SEM and EDS Spectrum of Al6061

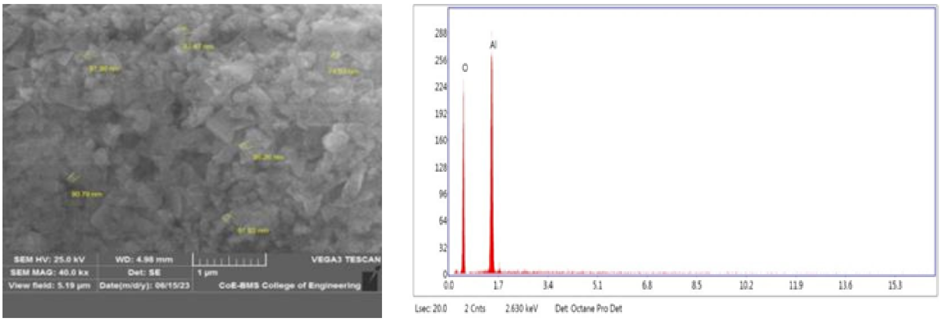


Fig. 11. SEM and EDS Spectrum of n-Al_2O_3

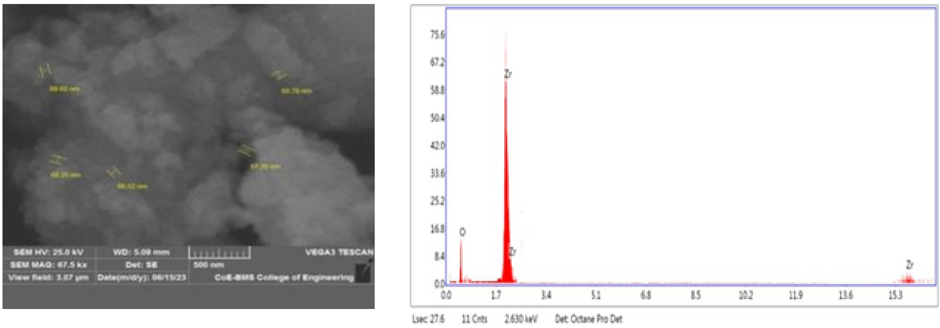


Fig. 12. EDS Spectrum of n-ZrO_2

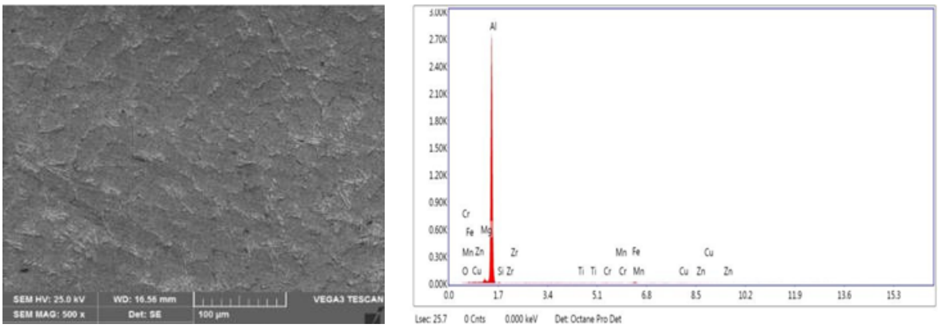


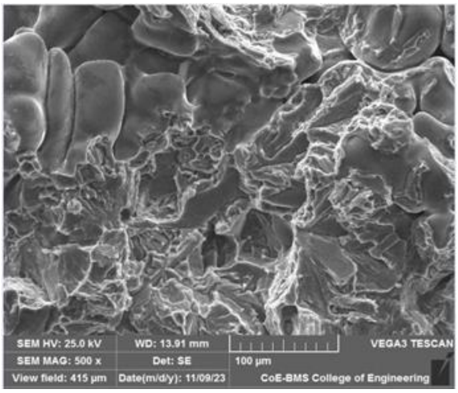
Fig. 13. EDS Spectrum of Al6061/1%ZrO_2/1%Al_2O_3

Table 11. Chemical composition of Al6061/1%ZrO_2/1%Al_2O_3

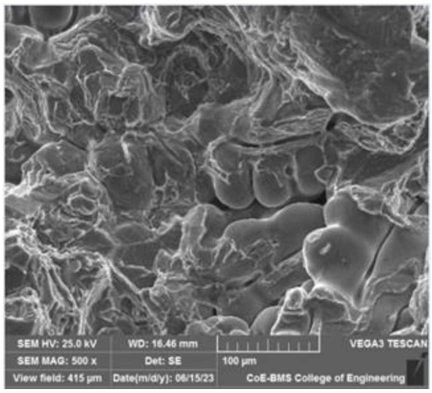
Elements	Mg	Si	Ti	Cr	Mn	Fe	Cu	Zn	O	Zr	Al
Percentage	0.84	0.72	0.12	0.2	0.09	0.34	0.3	0.16	0.52	0.91	Balance

3.4 Fracture Behavior

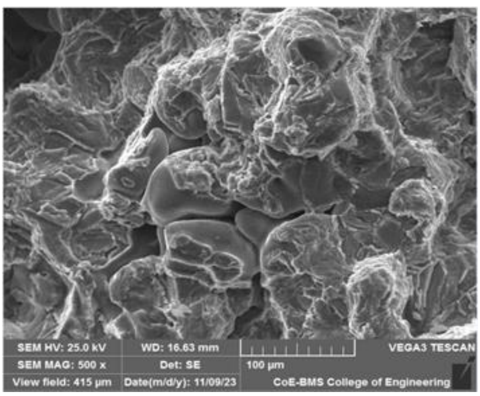
An essential procedure for identifying the cause of material failure involves analyzing the broken surface of the alloys and their composites. When examining fractography, it is crucial to bear in mind two fundamental aspects. Firstly, a ductile material that does not exhibit the formation of small dimples, such as a structural pattern, in the fractured regions. Furthermore, when examining SEM pictures of a failed material, one may notice trans-granular or intergranular fragmentations in the event of fractures occurring. Figure 14 (a-e) shows the fractured surfaces of the Al6061 alloy and Al6061-0.5, 0.75, 1, and 1.25 wt. % n- Al_2O_3 and n-ZrO2 particles in their as-cast state. The base matrix exhibited a smooth and consistent surface with shallow and evenly distributed depressions, indicating a fracture that is capable of being stretched without breaking. This can be observed in Figure 14a. On the other hand, the composite material displayed a distribution of depressions in two directions. This means that the larger depressions absorbed the reinforcing particles, while the smaller depressions were caused by the breaking down of the stretchable matrix. Furthermore, the scanning electron microscope (SEM) analysis of the damaged composite surface (Fig. 14b and Fig. 14d) revealed the presence of fine cracks on the n- Al_2O_{3p} and n-ZrO_2 particles, as well as partial separation between the matrix and reinforcement, and even fracture of the matrix itself. Typically, the fracture surfaces displayed smooth particles, suggesting that the particles were broken rather than detached, and that these composites are mainly distinguished by their robust interfacial connections. The fracture surfaces in the Al6061 matrix showed both large and relatively smaller depressions in the composites reinforced with 1.25 and 1.25 wt % n- Al_2O_{3p}/n-ZrO_2 (Figure 14 e). These findings indicate that the failure was caused by the expansion, combination, and eventual collapse of flexible empty spaces. The addition of n- Al_2O_{3p}/n-ZrO_2 resulted in a change in the fracture behavior of the Al6061 matrix. It shifted from being ductile to brittle, and then to an intermediate ductile mode [25]. The n-Al_2O_3 particle displays small depressions, as well as a matrix and a fine crack.



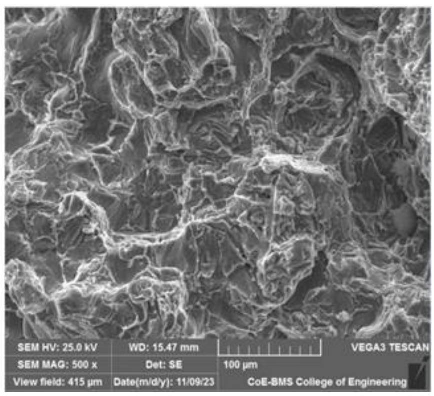
(a)



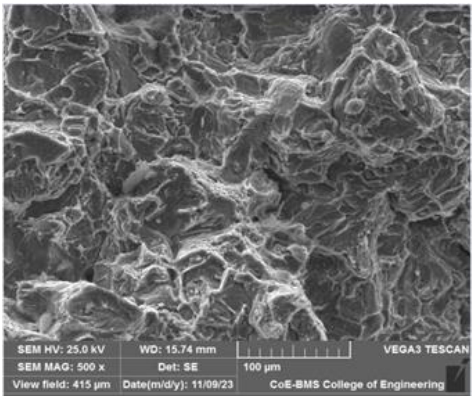
(b)



(c)



(d)



(e)

Fig. 14. (a-e) Fractography of images of (a) Al6061 and (b) Al6061-0.5 wt. % of n-Al_2O_{3p} and n-ZrO_2 (c) Al6061-0.75 wt. % of n- Al_2O_{3p} and n-ZrO_2 and (d) Al6061-1 wt. % of n-Al_2O_{3p} and n-ZrO_2 (e) Al6061-1.25 wt. % of n-Al_2O_{3p} and n-ZrO_2

4. Conclusion

The present experiment produced 16 stir-cast composite samples. Through optimization techniques, the ultimate tensile strength results of Al6061 with ZrO_2 and Al_2O_3 filler content were obtained. The experimental findings are summarized as follows:

- Scanning electron microscopy (SEM) analysis revealed that the ZrO_2 and Al_2O_3 components were evenly distributed throughout the aluminium matrix. Energy-dispersive X-ray spectroscopy (EDS) confirmed ZrO_2 and Al_2O_3 particles in composite materials.
- Among the parameters studied, filler content (ZrO_2 and Al_2O_3) and temperature emerged as the most significant factors influencing the output response (UTS), in contrast to stirring speed and stirring time which exhibited comparatively lesser significance.
- The most effective parameters (i.e., a temperature of 750 deg C, a speed of 500 RPM, and a time of stirring is 10 minutes) determined through stir casting to achieve improved ultimate tensile strength are 1 wt.% ZrO_2, 1 wt.% Al_2O_3
- The interaction plot concerning tensile strength, revealing notable interactions primarily among filler percentage followed by stirring speed, temperature, and stirring time. Among these factors, ZrO_2 and Al_2O_3 emerge as the most influential and highly interacting parameter affecting ultimate tensile strength.
- The control factors have been found to be statistically significant in influencing the signal to noise ratio. It has been noted that the composition is the most influential parameter in improving the Ultimate tensile strength, followed by the Melt temperature, and stirring time and speed.
- The primary objective of the confirmation test is to validate the findings of the Taguchi and ANOVA analyses. The confirmation tests served to corroborate the results obtained.
- Fractography analysis using a SEM was conducted to examine the surfaces that had undergone tensile rupture. This analysis indicated distinct fracture mechanisms between the base alloy Al6061 and the resultant composites. As cast Al6061 alloy exhibits purely ductile mode of fracture, further with the inclusion

of particles like ZrO_2 and Al_2O_3, the combined brittle and ductile fracture mode has been observed.

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