Research article

Optimization of selected casting parameters on the mechanical behaviour of Al 6061/glass powder composites

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ABSTRACT

Aluminum alloy and its composites have versatile applications and can be produced via a cost-effective stir casting technique. However, stir casting is faced with some challenges including segregation, occurrence of intermetallic phases, agglomeration, and inducement of residual stress. In view of minimizing these defects, casting should be done applying optimal parameters that will yield the desired outcome. The present study focused on the optimization of stirring parameters of temperature, speed, and time in the production of Al 6061/glass powder composite. Evaluated responses are tensile strength, compressive strength, impact strength, and hardness. The results showed that the process parameters had statistical significance on all properties at 95 % confidence level. Combined interactions of these parameters also presented significant effects on the property responses. Optimum setting for process factors as regards tensile strength were evaluated to be 600 °C, 400 rpm, and 30 min for temperature, speed, and time, respectively. For compressive strength, it is 600 °C, 500 rpm, and 30 min; for hardness, the optimum settings are 700 °C, 400 rpm, and 30 min, while in the case of impact strength, the optimum settings are 500 °C, 400 rpm, and 30 min respectively. Optimization of the combined characteristics was obtained at the optimum conditions of 500 °C, 400 rpm, and 30 min for stirring temperature, speed, and time. Moreover, the significance of the parameters on the composite in descending order is temperature, time, and speed.

1. Introduction

Aluminum alloy composites are very recent advanced materials used extensively in aerospace, automobile, shipbuilding, and other engineering applications. Their advantages cover high strength to weight ratio, resistance to corrosion, and low thermal expansion. The composites are mainly produced through different metallurgical routes including stir casting, squeeze casting, spark plasma sintering, spray condensation, friction stir processing, and other processes [1]. Stir casting, a common approach in the development of these composites allows particulate reinforcement in aluminum melt via a stirrer. The composite melt is thereafter cast into molds and allowed to solidify. The process has some shortcomings including the tendency for segregation [2], formation of intermetallic phases owing to high-temperature reactions [3], agglomeration as a result of density difference [4] and inducement of residual stress due to thermal mismatch [5], amidst others. The defects earlier mentioned could occur owing to high or low stirring temperature, high or low stirring speed, or other likely reasons.

According to Aynalem [1], a way of minimizing these defects is by the setting of optimum processing factors such as stirring speed, temperature, time, blade angle, and reinforcement content. Diverse investigations have been embarked on in optimizing the process parameters of aluminum alloy. Arulraj et al’s work [6] reinforced Al LM 25 with silicon carbide and boron carbide. Stirring speed was varied between 400 and 800 rpm, stirring time between 1 and 5 min, and preheating temperature between 200 and 400 °C. Taguchi method was employed in the design of experiment and optimization of parameters. From the result, via signal-to-noise ratio approach, the optimum parameters were 800 rpm for speed, 5 min for time, and 400 °C for temperature. The same method was implemented by Sylvester et al [7] in...
optimizing the process parameters of stirring speed, time, and temperature on hardness properties of Al 6061 reinforced with chopped carbon fibers. Outcome of the optimization process revealed that the stirring parameters 500 rpm, 5 min, and 740 °C have the highest impact in optimizing hardness of the composite. In the same manner, SiC was employed in the reinforcement of Al-Si alloy by Sadi et al [8]. Optimization carried out employing Taguchi method presented 15 wt. % SiC, melting temperature of 740 °C, stirring speed of 300 rpm and time of 10 min as optimal parameters in optimizing the wear resistance of the composite. Graphene nanocomposite of Al 7050 was developed via stir casting process [9]. Major property analyzed in the study was the tensile strength of the composite while stirring temperature, speed, and graphene content were the process variables. Parameter optimization was accessed through signal to noise ratio and optimum parameters were identified as 825 °C, 500 rpm, and 0.3 wt. % for temperature, speed, and graphene content respectively. Parameters were ranked in descending order of graphene content, stirring speed, and stirring temperature. Kumar and Kumar [10] applied Taguchi technique in the optimization of stir casting process parameters of AA 6063 aluminum composite reinforced with SiC particulate. Process variables are SiC content, pouring temperature, stirring speed and time. Properties studied are hardness, tensile strength, and impact energy. The findings revealed SiC content to be the most important variable. For hardness, SiC had 96.68 % contribution followed by pouring temperature (1.82 %) while stirring speed and time contributed 0.49 and 0.35 %, respectively. SiC also contributed 99.68 % to tensile strength while temperature, time, and speed had 0.17, 0.07, and 0.003 % in that order. As regards impact energy, SiC shared 99.09 % of the total effect, while temperature, time, and speed contributed 0.47, 0.25, and 0.12 % accordingly.

Silica (SiO₂) particles have been employed in a series of literatures in the reinforcement of aluminum alloy, presenting compelling outcomes [11, 12, 13]. Waste glass are found in landfills degrading the environment, and the recycling of such waste glass as a form of reinforcement for aluminum is worth investigating. Moreso waste glass contains high content of silica as reported in our previous works [14, 15, 16, 17]. This therefore motivated Adediran et al [18] to experiment on the effect of waste glass particles (average size of 23 μm) on the properties of Al 6061. Waste glass was considered as a form of replacement to pure and more expensive silica particles.

In the study, glass powder (average size of 23 μm) was employed in reinforcing Al 6061 in varying proportion of 2, 4, 6, 8, and 10 wt. % and the production process was carried out via mechanical stir casting method. Examined properties were density, porosity, tensile, hardness, compressive, and impact. The outcome revealed glass powder (GP) as a significant contributor to property enhancement of the composite. Yield strength and ultimate tensile strength improved with GP proportion and peak values were attained at 6 wt. % GP. Proportional increase in GP resulted in an enhancement of hardness up to 10 % while the optimum yield and ultimate compressive strength were realized at 8 wt. % GP loading. Nevertheless, the optimum stir casting parameters in maximizing the overall properties was not assessed. The present study was aimed at accessing the contributions of the process variables of temperature, speed, and time on the properties of developed Al 6061 reinforced with 6 wt. % GP, with the view to optimize the parameters for optimal performance. Taguchi method for the design of experiment was employed. 6 wt. % GP is adopted in this study owing to the optimum tensile properties’ enhancement experienced in [16].

### 2. Materials and methods

#### 2.1. Material preparation

Aluminum alloy AA 6061-T6 was employed in this study. Result of the composition analysis carried out through a spectrometer is presented in Table 1. Meanwhile, the properties of the alloy are portrayed in Table 2. Mechanical stir casting procedure was carried out using a graphite crucible employing the stirring parameters of the experimental runs (Table 3). Particulates employed are glass powder microparticles of average size 23 μm at 6 wt. % proportion. The particulates were pre-heated to 600 °C for 2 h before been dispersed in the melt. 1 wt. % magnesium was added into the melt for enhancing wettability of the matrix as carried out in [9, 19].

#### 2.2. Methods

In accordance with ASTM E 8/ ESM-21 [20] procedure, machined tensile specimen (dog-boned shape) of dimension; 120 mm specimen length, gauge length 60 mm, and gauge diameter 10 mm were tested for tensile strength employing a universal testing machine (Instron 3369 Series). To ensure the reproducibility of test samples, three repetitive tests were carried out for the tensile strength and the average results were recorded. Load of 10 kN was applied at a rate of 10⁻⁴/s and a cross head speed of 3.0 mm/min. Cylindrical specimens of 15 mm diameter and length 30 mm were subjected to quasi-static compressive loading with the use of the universal testing machine. The test was effected according to ASTM E09-9 [21] protocol at a cross speed of 1 mm/min applying a load of 100 kN. For the compressive tests, triplicate samples were used for repeatability purpose and the average results were recorded. Molybdenum disulfide lubricant was applied on the surface between the specimen to reduce friction and promote uniform deformation. Vickers microhardness test was done on specimens (40 mm diameter and length 20 mm) with a smooth surface using a load of 10 N applied for 10 s for eight different indentation points and the average value recorded (ASTM E 384-11) [22]. Samples in triplicates were used for the impact toughness, they were dimensioned to 50 × 10 (mm²), initially notched at 60° and to impact by a pendulum of mass 30 kg. Thereafter, the energy absorbed to failure was recorded. Following the recommendation by ASTM E 384-17 [23], a field emission scanning electron microscope (JSM-7610 E) was employed in accessing the microstructure of the composites developed. An overview of the experimental set up is as shown in Figure 1.

Figure 2 presents the element presence majorly in the base Al 6061 with peak of Al and minor traces of silicon, titanium, magnesium, molybdenum, (inclusion) and iron. Aluminum has the highest peak indicating Al is the most occurring element in the alloy (Table 1). The inherent properties of the alloy are depicted in Table 2 as regards tensile strength (225.6 MPa), relative density (2.71 g/cm³), and yield strength (192 MPa).

| Table 1. Elemental composition of Al 6061 alloy used in the study. |
|--------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Element | Zn | Mg | Cu | Si | Fe | Ti | Cr | Mo | Al |
| Amount (%) | 0.03 | 0.85 | 0.01 | 0.48 | 0.32 | 0.15 | 0.06 | 0.1 | balance |

Table 2. Properties of Al 6061 metal.

| Properties | Tensile strength | Poisson ratio | Density | Yield strength |
|------------|-----------------|--------------|---------|----------------|
| Value      | 225.6 MPa        | 0.32          | 2.71 g/cm³ | 192 MPa         |

In Table 2 as regards tensile strength (225.6 MPa), relative density (2.71 g/cm³), and yield strength (192 MPa).
2.3. Mix design

2.3.1. Taguchi method of design of experiment

Three factors are considered, namely: stirring speed (A), stirring temperature (B), and stirring time (C). As displayed in Table 3, Taguchi method of the design of experiment and the experimental runs are tabulated. Taguchi analysis was used to determine the optimum parameters which will yield the best results for the properties under investigation. 18 mix proportions (L18) were initially determined as presented in an orthogonal array (Table 3) with the view of limiting number of variables.
experiments [24]. Taguchi method is implemented to determine the control factors and minimize noise factor. The S/N ratio for multi responses were calculated following the procedures stated Ramon et al. [25] and Surajit & Susanta [26] respectively. The higher the signal-to-noise ratio (S/N), the minimal the noise.

2.3.2. Analysis of variance (ANOVA)

ANOVA was conducted on the obtained results to evaluate the significance of the experimental factors at 95% confidence level and 5% significance. In ANOVA analysis, a measure of the probability depicting if an observed parameter could have occurred under the null hypothesis is indicated as p-value or probability value. The lesser the value from 0.05 with regard to 95% level, the more significant the parameter. This test was conducted on the response values of tensile strength, compressive strength, impact strengths, and hardness. The input properties which are the dependent variables are represented with A for temperature, B for speed, and C for time. Minitab 19 was employed in the analysis of result at a confidence level of 95%. Equally, the same software was used in analyzing for the normal plot and Pareto chart for standardized effects on each property. Results were interpreted and discussed in relation to each response.

2.3.3. Pareto chart

Pareto charts reflect the order of significance of the experimental variables and their interactions by which process, variables with the highest or lowest effect on the response can be clearly observed. Therefore, the plot represents the standardized effects revealing the order of significance of the experimental factors and interactions on the property responses. The red line (pointing to 2.262 in the pareto plots) indicates the 95% confidence level. In that case, the bars above 2.262-line outline the process factors and interactions which contributed significantly to the responses while the ones below had insignificant contributions.

2.3.4. Normal, interaction and main effect plots

Pareto plot often highlights the order of significance of the parameters, meanwhile the normal plots depicts which of the factors or parameters has a positive or negative effect on the response. Interaction plot reflects how the parameters interact with one another and the influence of the interactions on the responses. Main effect plots present the interaction profile of the line of best fit for each response with regards to the fitted means and data means. Data means are means of the observed/experimental data responses while the fitted means are predicted response means of a balanced design derived from the least squares’ regression. If the two mean types are identical, it shows a balanced design, but if different, the design is unbalanced.

3. Results and discussion

3.1. Tensile strength

3.1.1. Analysis of variance on tensile strength

Table 4 shows the table of analysis of variance for tensile strength. The model is significant with p value less than 0.05. In the same way, the effects of temperature (A), speed (B), and Time (C) on the tensile strength response were considered significant as the p values are less than 0.05. Square interaction A*A is statistically significant while interactions B*B and C*C are insignificant owing to p value >0.05. Evaluation of the cross interactions A*B is significant while those of A*C and B*C are insignificant. Contributions of each of the factors are 21.90, 13.80, and 28.09% for temperature, speed, and time respectively.

| Source               | DF | Seq SS | F-Value | P-Value | Contribution |
|----------------------|----|--------|---------|---------|--------------|
| Model                | 8  | 11307.4| 39.27   | 0.002   | 98.18%       |
| Temperature          | 1  | 2523.0 | 16.55   | 0.003   | 21.90%       |
| Speed                | 1  | 1496.3 | 9.81    | 0.012   | 13.80%       |
| Time                 | 1  | 3307.6 | 21.69   | 0.001   | 28.09%       |
| Temperature*Speed    | 1  | 2738.8 | 17.96   | 0.002   | 23.60%       |
| Temperature*Time     | 1  | 413.4  | 2.71    | 0.134   | 3.26%        |
| Time*Speed           | 1  | 828.3  | 5.18    | 0.015   | 5.23%        |
| Temperature*Time     | 1  | 800.0  | 5.25    | 0.068   | 6.60%        |
| Temperature*Speed    | 1  | 27.0   | 0.18    | 0.684   | 0.21%        |
| Speed*Time           | 1  | 1.3    | 0.01    | 0.928   | 0.01%        |
| Error                | 9  | 172.3  | 1.82    |          |              |
| Total                | 17 | 11480.8| 100.00% |         |              |

Table 4. ANOVA on tensile strength.

Table 3. Orthogonal array of the experimental runs.

| Experimental runs | Factors level | Input Variables | Response |
|-------------------|---------------|-----------------|----------|
|                   | (A)           | (B rpm)         | (C mins) |
|                   | (A)           | (C)             | TS (MPa) | CS (MPa) | Hd (HV) | IM (KJ/m²) |
| 1                 | 1             | 1               | 500      | 300      | 15      | 240       | 641.2   | 104   | 4.54   |
| 2                 | 1             | 2               | 500      | 400      | 15      | 257       | 662.8   | 115   | 4.00   |
| 3                 | 1             | 3               | 500      | 500      | 15      | 251       | 675.1   | 126   | 3.68   |
| 4                 | 2             | 1               | 600      | 300      | 15      | 252       | 656.4   | 118   | 4.82   |
| 5                 | 2             | 2               | 600      | 400      | 15      | 269       | 682.1   | 122   | 4.55   |
| 6                 | 2             | 3               | 600      | 500      | 15      | 258       | 697.3   | 131   | 4.15   |
| 7                 | 3             | 1               | 700      | 300      | 15      | 248       | 645.9   | 111   | 4.79   |
| 8                 | 3             | 2               | 700      | 400      | 15      | 261       | 668.7   | 118   | 4.50   |
| 9                 | 3             | 3               | 700      | 500      | 15      | 247       | 688.0   | 124   | 4.11   |
| 10                | 1             | 1               | 500      | 300      | 30      | 258       | 657.0   | 122   | 4.97   |
| 11                | 1             | 2               | 500      | 400      | 30      | 274       | 686.8   | 131   | 4.66   |
| 12                | 1             | 3               | 500      | 500      | 30      | 268       | 703.1   | 140   | 4.24   |
| 13                | 2             | 1               | 600      | 300      | 30      | 268       | 682.1   | 130   | 5.46   |
| 14                | 2             | 2               | 600      | 400      | 30      | 283       | 714.8   | 142   | 5.09   |
| 15                | 2             | 3               | 600      | 500      | 30      | 274       | 728.8   | 151   | 4.74   |
| 16                | 3             | 1               | 700      | 300      | 30      | 260       | 644.0   | 122   | 5.40   |
| 17                | 3             | 2               | 700      | 400      | 30      | 277       | 696.1   | 128   | 5.00   |
| 18                | 3             | 3               | 700      | 500      | 30      | 269       | 715.4   | 134   | 4.68   |

A is stirring temperature, B is stirring speed, C is stirring time, TS is tensile strength, CS is compressive strength, Hd is hardness and IM is impact strength.
indicating that stirring time posed the highest contribution to tensile strength. Interaction A*A portrayed a contribution of 23.60% indicating that the stirring temperature is a significant contributory factor to the response. The model for tensile strength (TS) is presented in Eq. (1). From the equation, A, B, and C stands for temperature, speed, and time respectively. From the model, parameters with positive coefficient indicate factors with resultant positive (synergetic) effect on the response while the ones with negative coefficient depict resultant negative (antagonistic) influence. As observed, factors A, B, and C had synergistic effect on the response, similar trend was observed with interaction AC and BC. Interactions AA, BB, and CC portrayed negative effect on the response.

\[
TS = -295.4 + 1.062A + 1.1025B + 0.830C - 0.817AA - 0.0001242BB - 0.0000CC - 0.0162AB + 0.000222AC + 0.001000BC
\]  

(1)

3.1.2. Pareto chart and normal plot

Figure 3a presents the parameters that are significant, and these include factors A, B, and C and interactions A*A, and A*B. With respect to the normal plot (Figure 3b), factors on the positive side of the line had resultant positive contributions on the response, while the ones on the negative side had resultant negative contributions. On account of that, factors A, B, and C, which are stirring temperature, speed, and time respectively, reflect resultant positive contributions to the response, while interactions AA and AB show resultant negative contributions.

Therefore, stirring temperature, speed, and time have resultant positive contributions on tensile strength. Conversely, interactions A*A, and A*B had resultant negative contributions on tensile strength. B*B follows the same trend as factor A. Inputs A (stirring temperature), B (stirring speed), C (stirring time), and interaction A*B (temperature x speed) are statistically significant as confirmed in Table 4 and Figure 3a.

From Figure 3b, Factor A (stirring temperature) is the farthest from the line on the positive side, reflecting the highest positive contribution. Meanwhile, interaction AA is the farthest from the negative side of the line, means AA has the highest negative contribution.

3.1.3. Main effects of fitted and data means

The main effect plot (fitted means) of the process parameters on each property as represented by the mean values of the response is presented in Figure 3c. The figure shows the main effect plots for tensile strength representing the fit lines for the mean values of tensile strength. It is revealed that temperature below 600 °C had a positive effect on the response, that is, as the temperature increased between 500 and 600 °C,
the mean tensile strength increased. Beyond 600 °C, the strength decreased progressively down to 700 °C. The profile based on the line of fit for temperature as it affects tensile strength is parabolic with the end points tending downwards. Therefore, the point of inflection is attained at 600 °C, value of 277 MPa for the tensile strength. Likewise, as the stirring speed increased to 400 rpm, the strength was enhanced at the mean level. However, beyond that, the strength reduced, thereby depicting a parabolic profile (line of fit for means) as the end point downwards. The point of inflexion occurred at 400 rpm yielding a strength of 275 MPa. The profile of stirring time relative to mean tensile strength is linear with a positive gradient indicating that increasing time between 15 and 30 min reflects a positive and increasing effect on mean tensile strength (optimum yield of 284 MPa). The main effect plot (data means) in Figure 3d confirms the profiles of each parameter as regards tensile strength, the optimum mean tensile strength is attained at 600 °C, 400 rpm, and 30 min.

3.2. Compressive strength

3.2.1. Analysis of variance of compressive strength

Results of the ANOVA presented in Table 5 show that the model is significant with p value less than 0.05. Equally, the input factors A, B, and C had significant influence on the compressive strength response, hence are statistically significant.

Additionally, the interactions A*A, B*B and A*B significantly contributed to the enhancement of the strength while C*C, A*C and B*C are insignificant. Table 5 further reflects factor B (stirring speed) to be the highest contributor based on the contribution value of 30.79 %, factor A (stirring temperature) is 8.04 %, while factor C (stirring time) shares 22.37 % of the contributions. Interactions A*A, B*B, and C*C contributed 18.02, 7.41, and 2.76 %, respectively, while cross interactions A*B, A*C, and B*C have contributions of 5.43, 0.94 and 1.03 %. From the contributions, the stirring speed had the highest impact on the compressive strength. The second in rank is the stirring time while the third is interaction A*A. The model for compressive strength (CS) is as presented in Eq. (2). From the equation, A, B, and C stands for temperature, speed, and time respectively. Parameters with positive coefficient in the model are the positive terms of the model depicting synergetic effect of the parameter on the response. However, parameters with negative sign had antagonistic influence on the response and are negative terms of the model. It is noteworthy that factors A, B, and C exhibited synergetic effect on the response, ditto interactions CC, AB and BC. Meanwhile, interactions AA, BB, and AC are antagonist to compressive strength.

\[
CS = -155 + 2.285A + 0.453B + 0.45C - 0.01991AA - 0.00736BB + 0.000419CC + 0.211AB - 0.000166AC + 0.000526BC
\]

(2)

3.2.2. Pareto chart and normal plot

As reflected in Figure 4a, factors A, B, and C are significant, likewise, interactions A*A, B*B and A*B are significant. On the other hand, the interactions A*C, C*C, and B*C are insignificant. It was found that Pareto charts confirm the ANOVA result, thus highlighting the order of significance of the parameters. The trend showing the normal plot is as shown in Figure 4b, while the main effect plot for fitted means and the main effect plot for data means are displayed in Figure 4c,d, respectively.

From the result, factor B has the highest significance, that is, the stirring speed has the highest significant effect on the compressive strength. Factor C (stirring time) is the second while 3rd, 4th, and 5th in terms of contribution to compressive strength are interaction AA, factor A, and interaction BB, respectively. These results agree with the ANOVA result in terms of contribution of each parameter as seen in Table 5.

Figure 4b shows the factors A, B, and C which are on the positive side of the line, reflecting a positive contribution. The same goes with interaction AB whereas interactions AA and BB are on the negative side, depicting negative contributions.

3.2.3. Main effect of fitted and data means

Evidently, from Figure 4c, the profile for that of temperature is parabolic as increasing temperature resulted in increasing mean compressive strength, with a peak at 700 °C. This corresponds to a value of 715 MPa compressive strength. By contrast, for stirring speed, the profile is concave as the value rose from 300 to 500 rpm. The stirring time presented a linear profile with a positive gradient, indicating that increasing time resulted in a progressive increase in strength between 15 and 30 min. As presented in Figure 4d, an optimum mean compressive strength was attained at 600 °C, 500 rpm, and 30 min, respectively.

3.3. Hardness

3.3.1. Analysis of variance on hardness

Table 6 shows the trend in the analysis of variance for hardness. The model is significant with p value less than 0.05. Likewise, the effects of temperature (A), speed (B), and Time (C) on the response of hardness are considered significant as the p values are less than 0.05. Square interactions A*A, B*B, and C*C are statistically insignificant owing to p value >0.05.

Evaluation of the cross interactions A*B, A*C, and B*C shows that their contributions are significant. Contributions of each of the factors are 18.69, 8.74, and 30.36 % for temperature, speed, and time respectively, indicating that stirring time posed the highest contribution on hardness. Interaction A*B, A*C, and B*C reflected contribution of 12.59, 15.75, and 5.23 %, respectively. It is deduced that stirring time is revealed to be the highest contributory factor to the response. The model for hardness (Hd) is as presented in Eq. (3). Evidently, A, B, and C stands for temperature, speed, and time respectively. Positive and negative coefficient of factors and interactions are observed in the model. Factors A, B, and C depicted synergetic effect on hardness while interactions AA, BB, AB, AC, and BC portrayed antagonistic effect on hardness.

\[
Hd = -327.2 + 1.247A + 1.97C - 0.01991AA - 0.00736BB + 0.000419CC - 0.00166AC + 0.000526BC
\]

(3)

3.3.2. Pareto chart and normal plot

Figure 5a,b illustrate the Pareto chart and normal plot, respectively, for the standardized effects regarding microhardness. It is evident from Figure 5a that the Pareto charts for microhardness portray factors C (time), A (temperature), and B (speed) as significant.

In the same manner, the interactions between AC, AB, and BC are significant. However, interactions BB and AA are insignificant. Pareto charts confirm ANOVA as order of significance is highlighted linkable to contributions of the parameters outlined by the ANOVA in Table 6. From

| Source     | DF | Seq SS  | F-Value | P-Value | Contribution |
|------------|----|---------|---------|---------|--------------|
| Model      | 8  | 13528.1 | 233.91  | 0.000   | 96.79%       |
| Temperature| 1  | 988.0   | 63.88   | 0.000   | 8.04%        |
| Speed      | 1  | 2785.0  | 186.22  | 0.037   | 30.79%       |
| Time       | 1  | 2206.7  | 119.90  | 0.000   | 22.37%       |
| Temperature*Temperature| 1 | 1769.3  | 87.41   | 0.524   | 18.02%       |
| Speed*Speed| 1 | 861.1   | 56.78   | 0.017   | 7.41%        |
| Time*Speed | 1 | 188.0   | 5.89    | 0.080   | 2.76%        |
| Temperature*Speed| 1 | 670.0   | 44.26   | 0.002   | 5.43%        |
| Temperature*Time| 1 | 32.9    | 1.66    | 0.670   | 0.94%        |
| Speed*Time  | 1 | 115.0   | 2.83    | 0.550   | 1.03%        |
| Error      | 9  | 448.7   | 3.21%   | 0.31    |              |
| Total      | 17 | 13976.8 | 100.00% | 0.74%   |              |
the result obtained, factor C, stirring time has the highest significant effect on hardness. Factor A is the second, interactions AC, AB are 3rd and 4th respectively. Factor B is the 5th in terms of contribution to hardness.

As shown in Figure 5b, factors C, A, and B, indicated on the positive side of the line, suggest a positive contribution to the hardness response. Interactions BC, AB, and AC are on the negative side of the lines indicating an inverse relationship (antagonistic effect) with the response.

### 3.3.3. Main effect of fitted and data means

**Figure 5c** displays the main effect plot for hardness from where it is disclosed that temperature between 500 and 700 °C has a positive linear effect on the response, that is, as the temperature increased between 500 and 700 °C, the hardness increased. The profile of stirring speed as it affects mean hardness is parabolic with the end points tending downwards. Therefore, the point of inflection is attained at 400 rpm, with a value of 132 HV for hardness. The profile of stirring time as it affects the mean tensile strength is linear with a positive gradient. This indicates that increasing time between 15 and 30 min reflects a positive and increasing effect on mean hardness with an optimum yield of 140 HV. From **Figure 5d**, the optimum mean hardness is realized at 700 °C, 400 rpm, and 30 min.

### 3.4. Impact strength

#### 3.4.1. Analysis of variance on impact strength

The ANOVA for impact strength (**Table 7**) confirmed that the model is significant with p value being lower than 0.05, and the error is minimized.

| Source       | DF | Seq SS | F-Value | P-Value | Contribution |
|--------------|----|--------|---------|---------|--------------|
| Model        | 8  | 24609.7| 14.44   | 0.000   | 95.77%       |
| Temperature  | 1  | 3366.7 | 15.81   | 0.003   | 18.69%       |
| Speed        | 1  | 2054.1 | 9.64    | 0.013   | 8.74%        |
| Time         | 1  | 11501.4| 54.00   | 0.000   | 30.36%       |
| Temperature*Temperature | 1  | 240.3  | 1.13    | 0.316   | 2.91%        |
| Speed*Speed  | 1  | 930.3  | 4.37    | 0.266   | 3.61%        |
| Time*Time    | 1  | 217.0  | 3.20    | 0.063   | 3.12%        |
| Temperature*Speed | 1  | 2278.1 | 10.70   | 0.010   | 12.59%       |
| Temperature*Time | 1  | 2852.1 | 13.39   | 0.005   | 15.75%       |
| Speed*Time   | 1  | 1686.8 | 8.51    | 0.031   | 5.23%        |
| Error        | 9  | 1016.8 | 4.23    |         | 4.23%        |
| Total        | 17 | 25626.5|         |         | 100.00%      |

**Figure 4.** Analysis of compressive strength as per (a) Pareto chart (b) Normal plot (c) Main effect plot for fitted means (d) Main effect plot for data means.

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**Table 6.** ANOVA on hardness.

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Equally, the experimental factors; temperature (A), speed (B), and time (C) had significant contribution on response of the composites as regards impact strength. However, the square relations of A*A and C*C are insignificant while interaction B*B is statistically relevant. Cross interactions between the parameters are statistically insignificant as their p value were >0.05. Contributions of the process variables are further revealed in Table 7. Stirring temperature has the highest contribution of 41.00 %, followed by the stirring time (30.96 %). Speed also contributed 12.50 % in enhancing impact strength. For the interaction’s, interaction B*B displayed a contribution of 10.79 % while others had little or no contribution since there value is less than 5 %. Table 7 further depicts temperature, speed, and time as significant parameters which affect response of the composites at high strain rate.

The model for impact strength (IM) is presented in Eq. (4). A, B, and C stands for temperature, speed, and time respectively. Parameters with positive coefficient in the model are the positive terms of the model presenting synergetic effect of the parameter on the impact strength. Contrarily, the parameters with negative coefficient had antagonistic influence on the response and are negative terms of the model. Therefore, factors A, B, and C and interactions AB, AC, and BC had synergetic effect on the response while interaction AA, BB, and CC showed antagonistic contributions on impact strength.

\[
IM = -4.3 - 0.03147A + 0.00504B + 0.0304C - 0.000025AA - 0.00270BB - 0.00000CC + 0.000002AB + 0.000003AC + 0.000004BC
\]

### Table 7. ANOVA on impact strength.

| Source     | DF | Seq SS | F-Value | P-Value | Contribution |
|------------|----|--------|---------|---------|--------------|
| Model      | 8  | 3.78284| 178.30  | 0.000   | 99.37%       |
| Temperature| 1  | 1.59870| 602.83  | 0.000   | 41.00%       |
| Speed      | 1  | 0.47601| 179.49  | 0.000   | 12.50%       |
| Time       | 1  | 1.44500| 544.87  | 0.000   | 30.96%       |
| Temperature*Temperature | 1 | 0.00001 | 0.00 | 0.950 | 0.00% |
| Speed*Speed | 1 | 0.25840 | 97.44 | 0.000 | 10.79% |
| Time*Time | 1  | 0.00472| 0.59    | 0.635   | 1.12%        |
| Temperature*Speed | 1 | 0.00451 | 1.70 | 0.224 | 1.12% |
| Temperature*Time | 1 | 0.00013 | 0.05 | 0.828 | 1.00% |
| Speed*Time | 1  | 0.00007| 0.03    | 0.870   | 1.00%        |
| Error      | 9  | 0.02387|         | 0.63%   |              |
| Total      | 17 | 3.80671|         |         | 100.00%      |

### 3.4.2. Pareto chart and normal plot

Figure 6a revealed the parameters that are significant, including factors A, B, and C and interaction BB. Factors B and C depict positive contributions on impact strength, while factor A and interaction BB show negative contribution on the property (Figure 6b).
Therefore, the stirring time and speed have a resultant positive contribution on impact strength. Conversely, factor A (stirring temperature) has a resultant negative contribution on impact strength in that increasing temperature amounted to decrease in impact strength. Interaction BB follows the same trend as factor A. Inputs A (stirring temperature), B (stirring speed), C (stirring time), and interaction A*B (temperature x speed) are statistically significant as confirmed in Table 7 and Figure 6a respectively.

3.4.3. Main effect of fitted and data means

The main effect plot for the fitted means of impact strength (Figure 6c) revealed that temperature demonstrated a negative linear response on the strength. Increasing the temperature from 500 to 700 °C led to a progressive reduction in mean strength. As for the stirring speed, speed below 400 rpm had a positive contribution on the strength parameter. Indicating that, below 400 rpm, impact strength is enhanced. Meanwhile, beyond 400 rpm, the strength is on the decline. The profile of speed is therefore a half-parabola with the two ends pointing downwards. The profile of stirring speed is linearly upward with a positive gradient, illustrating that as time increases between 15 and 30 min, impact strength increased progressively. According to Figure 6d, optimum mean impact strength is realized at 500 °C, 400 rpm, and 30 min.

3.5. Interaction plot for properties

3.5.1. Tensile strength

Figure 7 illustrates the interaction plot for tensile strength which elucidates on how the parameters interacted. The (a) portion evinces the interaction temperature against speed and time as it affects the response. At a temperature of 500 °C, increasing speed between 300 and 400 rpm yielded an enhancement in tensile strength even as the same experienced goes for 600 and 700 °C. In addition, at temperatures of 500, 600, and 700 °C, the tensile strength improved with increasing time between 15 and 30 min.

Maximum tensile strength was attained at 276 MPa for temperature against speed when temperature and speed were 600 °C and 400 rpm, respectively, while 278 MPa was actualized for temperature against time at 600 °C and 30 min respectively.

The (b) portion delineates the interaction between stirring speed against temperature and time as the interplay plays a major role in determining the response. Stirring speed of 300–400 rpm results in a significant improvement in tensile strength at temperatures of 500–600 °C, while beyond 600, the strength depreciated. Speed of 300, 400, and 500 rpm amounted to progressive strength enhancement between 15 and 30 min. Maximum tensile strength of 276 MPa is attained for speed

Figure 6. Analysis of impact strength as par (a) Pareto chart (b) Normal plot (c) Main effect plot for fitted means (d) Main effect plot for data means.
against temperature interaction at 600 °C and 30 min respectively, while 275 MPa was actualized for speed against time at 400 rpm and 30 min respectively. Equally in the (c) portion of the plot, the interaction stirring time against temperature, and speed is revealed. Stirring time of 15–30 min engendered strength enhancement at temperatures of 500–600 °C, while beyond 600, the strength depreciated. Stirring time of 15–30 min had a strength improvement between 300 and 400 rpm. Maximum tensile strength of 278 MPa was attained for time against temperature interaction at 600 °C and 30 min respectively, while 275 MPa was actualized for time against speed interaction at 400 rpm and 30 min respectively.

3.5.2. Compressive strength

Figure 8 portrays the interaction plot for compressive strength revealing how the parameters interacted. Portion labeled (a) reflects the relation existing between temperature against speed and time as it affects compressive strength.
At temperatures of 500, 600, and 700 °C, increasing speed of 300–500 rpm resulted in strength enhancement. Moreover, at temperatures of 500, 600, and 700 °C, the compressive strength increased with an increment in time between 15 and 30 min. Maximum compressive strength of 727.26 MPa was attained for temperature against speed at 600 °C and 500 rpm, respectively, while 731.6 MPa was actualized for temperature against time interaction at 600 °C and 30 min respectively.

The (b) portion showcases the interaction between stirring speed against temperature, and time as the activity plays a major role in defining the compressive strength response. Stirring speeds of 300, 400, and 500 rpm resulted in an improvement in the compressive strength at temperatures of 500–600 °C, of which between 600 and 700 °C, the strength reduced. Equally, the stirring speed of 300, 400, and 500 rpm led to an enhancement in compressive strength between 15- and 30-min. Maximum compressive strength of 727.27 MPa were attained for speed against temperature interaction when the values were attaining 600 °C and 500 rpm, respectively, while 730.94 MPa was realized for speed against time upon 500 rpm and 30 min respectively.

In the (c) portion of the plot, the interaction stirring time against temperature and speed is revealed. 15–30 min engaged strength enhancement at temperatures between 500 to 600 °C beyond which there was strength reduction. 15–30 min amounted to strength improvement between 300 and 500 rpm. Maximum compressive strength of 731.6 MPa were attained for time against temperature interaction at 600 °C and 30 min, respectively, while 730.94 MPa was actualized for time against speed interaction at 500 rpm and 30 min respectively.

3.5.3. Hardness

The interaction plot for the hardness is displayed in Figure 9. It shows how the interactions between the parameters affect the response (hardness). Portions labeled (a) depicts the relationship between temperature versus speed and time with regards to hardness.

At temperatures of 500, 600, and 700 °C, an increasing speed of 300–400 rpm amounted to an improvement in the response. Beyond 400 rpm, the hardness reduced for temperatures of 500, 600, and 700 °C. Meanwhile, at temperatures of 500, 600, and 700 °C, the hardness increased with time between 15 and 30 min. Maximum hardness of 141 HV was realized for temperature against speed at 700 °C and 400 rpm, respectively, while 142 MPa was actualized for temperature against time interaction at 700 °C and 30 min respectively.

The (b) portion displays the interaction between stirring speed against temperature and time as the interplay affects hardness. Stirring speed of 300, 400, and 500 rpm led to an improvement in hardness at temperatures of 500–700 °C. Speed of 300, 400, and 500 rpm achieved an improvement in hardness between 15 and 30 min. Maximum hardness value of 141 HV is attained for speed against temperature interaction upon 700 °C and 400 rpm respectively. By contrast, 141 HV was obtained for speed against time interaction when speed and time were 400 rpm and 30 min, respectively.

In the (c) portion of the plot, the interaction stirring time against temperature, and speed is displayed. The stirring time of 15–30 min gave an enhancement in hardness at temperatures of 500–700 °C. Thus, the stirring time of 15–30 min showed a boost in hardness between 300 and 400 rpm, while beyond 400 rpm, there was reduction. The maximum hardness of 142 HV is attained for time against temperature interaction at 700 °C and 30 min, respectively, while 141 MPa was actualized for time against speed interaction at 400 rpm and 30 min respectively.

3.5.4. Impact strength

Figure 10 displays the interaction plot for impact strength. The (a) portion revealed the interactivity, temperature against speed and time with regard to impact strength. At a temperature of 500 °C, increasing speed between 300 and 400 rpm yielded an enhancement in tensile strength even as the same experienced goes to 600 and 700 °C.

Furthermore, temperatures of 500, 600, and 700 °C amounted to an improvement in impact strength with increasing time between 15 and 30 min. Maximum impact strength is attained at 5.14 KJ/m² for temperature against speed at 500 °C and 400 rpm respectively while 5.28 KJ/m² was actualized for temperature against time interaction at 500 °C and 30 min respectively.

The (b) portion showcases the interaction between stirring speed against temperature, and time as the interplay plays a major role in determining the impact response. Stirring speed of 300-500 rpm results in a consistent fall in impact strength at temperatures of 500–700 °C. Speed of 300, 400, and 500 rpm amounted to progressive strength

![Interaction Plot for Hardness](Image)
enhancement between 15 and 30 min. Maximum impact strength of 5.14 KJ/m² is attained for speed against temperature interaction at 400 rpm and 500 °C respectively, while 5.10 KJ/m² was actualized for speed against time at 400 rpm and 30 min respectively.

The (c) portion of the plot, interaction stirring time against temperature, and speed is revealed. Stirring time of 15–30 min evoked strength reduction at temperatures of 500–700 °C. Stirring time of 15–30 min ensued with strength improvement between 300 and 400 rpm and beyond 400 rpm, the strength reduced. Maximum impact strength of 5.28 KJ/m² is attained for time against temperature interaction at 500 °C and 30 min respectively while 5.10 KJ/m² was actualized for time against speed interaction at 400 rpm and 30 min respectively.

3.6. Single objective optimization by signal-to-noise ratio
Taguchi design has been proved to be an effective optimization tool in experimental procedures [27]. Signal-to-noise ratio (S/N) is a measure of soundness employed to indicate the process factor that has the lowest noise on the response. The method uses a loss function to evaluate the variation between experimental outcomes and desired results. There exist three approaches to evaluating signal-to-noise ratio (S/N), which are the lower the better, the higher the better, and the nominal is best. The choice of any of the approach settings depends on the characteristics, based on the kind of goal target; whether to maximize or minimize.

The S/N ratio was appraised using Eq. (5) for the ‘larger the better’ option which goal is to maximize all responses.

\[
SN_f = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right)
\]  

where \( n \) is the number of observations and \( y \) the measured value.

3.6.1. Tensile strength
The variations in the mean signal to noise ratio for tensile strength for all factors are as presented in Table 8.

As observed in Figure 11a, for tensile strength, signal-to-noise ratio is maximum at 700 °C as regards temperature. Also observed is the high difference in SN ratio (+0.6104 dB) between 500 to 600 °C as compared to SN ratio between 600 and 700 °C (−0.4315 dB). It showed higher impact of temperature in enhancing tensile strength when the temperature is between 500 and 600 °C compared to when the tensile is reduced from 600 to 700 °C. Therefore, the stirring temperature demonstrated a higher contribution in enhancing the tensile strength between 500 to 600 °C than the decreasing effect of temperature between 600 and 700 °C.

Stirring speed had the highest SN ratio at 400 rpm. The SN ratio difference of +0.5252 dB experienced at the increasing trend between 300 and 400 rpm is higher than that at the reducing trend between 400 and 500 rpm. It therefore indicates that the speed exhibited higher contribution in enhancing the tensile strength between 300 and 400 rpm than the strength reduction between 400 and 500 rpm.

Stirring duration/time demonstrated the highest difference in SN ratio for all factors between 15 and 30 min (+0.5467 dB) as the strength increased from 15 to 30 min. This affirms the result presented in Figure 4a as regards the stirring time showing the highest impact on the strength. With longer stirring duration, the particulates have enough time to be dispersed evenly within the matrix, enhancing the micro-structural features. The effect ensues an enhancement of properties. From Figure 11a, the optimum tensile strength can be achieved at stirring parameters of 600 °C, 400 rpm, and 30 min for temperature, speed, and time respectively. From Table 8, the values at level 1, 2, and 3 for temperature and speed and level 1,2 for time are presented. Corresponding delta value, ranking of the parameters was made depicting stirring time to be most significant. The 2nd and 3rd in rank are temperature and speed respectively. Hence, the order of importance of the factors for tensile strength is stirring time, stirring temperature, and stirring speed.

| Table 8. Mean signal to noise ratio (dB) for tensile strength. |
|---------------|-----------|-----------|-----------|
| Levels | Temperature | Speed | Time |
| Level 1 | 48.2244 | 48.1026 | 48.0808 |
| Level 2 | 48.8348 | 48.6278 | 48.6275 |
| Level 3 | 48.4033 | 48.3321 | - |
| Delta | 0.6104 | 0.5252 | 0.5467 |
| Rank | 2 | 3 | 1 |
Figure 11. Plot for signal to noise ratio for (a) tensile strength (b) compressive strength (c) hardness (d) impact strength (e) combined optimization.
Table 9. Mean signal to noise ratio (dB) for compressive strength.

| Levels | Temperature (°C) | Speed (rpm) | Time (min) |
|--------|------------------|-------------|------------|
| Level 1 | 56.7305          | 54.5154     | 56.5004    |
| Level 2 | 57.2169          | 56.8138     | 578594     |
| Level 3 | 56.5970          | 57.2152     | -          |
| Delta   | 0.6199           | 2.6998      | 1.3590     |
| Rank    | 3                | 1           | 2          |

Table 10. Mean signal to noise ratio (dB) for micro hardness.

| Levels | Temperature (°C) | Speed (rpm) | Time (min) |
|--------|------------------|-------------|------------|
| Level 1 | 41.2595          | 41.4030     | 41.1761    |
| Level 2 | 42.1555          | 42.5442     | 42.4792    |
| Level 3 | 42.8514          | 41.9857     | -          |
| Delta   | 1.5919           | 1.1412      | 1.3031     |
| Rank    | 1                | 3           | 2          |

Table 11. Mean signal to noise ratio (dB) for impact strength.

| Levels | Temperature (°C) | Speed (rpm) | Time (min) |
|--------|------------------|-------------|------------|
| Level 1 | 13.9560          | 12.2912     | 12.7366    |
| Level 2 | 13.4967          | 13.5546     | 13.8076    |
| Level 3 | 12.7236          | 13.2912     | -          |
| Delta   | 1.3859           | 0.9842      | 1.071      |
| Rank    | 1                | 3           | 2          |

Table 12. Mean signal to noise ratio (dB) for combined characteristics.

| Levels | Temperature (°C) | Speed (rpm) | Time (min) |
|--------|------------------|-------------|------------|
| Level 1 | 19.9436          | 18.7562     | 18.7497    |
| Level 2 | 19.4500          | 19.6144     | 19.8204    |
| Level 3 | 18.8371          | 19.4753     | -          |
| Delta   | 1.1065           | 0.8582      | 1.0710     |
| Rank    | 1                | 3           | 2          |

3.6.2 Compressive strength

The variations in the mean signal to noise ratio for the compressive strength for all factors are as presented in Table 9.

Figure 11b, for compressive strength, signal-to-noise ratio is maximum at 600 °C as regards temperature. Also observed is the high difference in SN ratio (+0.6199 dB) from 600 to 700 °C compared to SN ratio between 500 and 600 °C (+0.4864 dB). It showed that the contribution of temperature in lowering the compressive strength is higher between 600 and 700 °C than enhancing compressive strength between 500 and 600 °C.

Stirring speed had the highest SN ratio when the speed was 500 rpm with SN ratio difference of +2.2984 as the trend increased between 300 and 400 rpm, higher than what was obtained when the speed rose between 400 and 500 rpm. Implication: the speed depicted a higher contribution in enhancing the compressive strength between 300 and 400 rpm than the strength increases between 400 and 500 rpm (with SN difference of +0.4014 dB).

The mean SN ratio for stirring time between 15 and 30 min is +1.3590 dB confirming longer stirring temperature contributes significantly to the compressive strength of the composite. From Figure 11b, the optimum compressive strength can be achieved at stirring parameters of 600 °C, 500 rpm, and 30 min for temperature, speed, and time respectively. From Table 9, the values at level 1, 2, and 3 represent temperature and speed, while level 1, 2 for time are displayed. The corresponding delta value ranks the parameters as speed, temperature and time as 1st, 2nd, and 3rd respectively. Therefore, order of importance of the factors for compressive strength is stirring speed, stirring time, and stirring temperature.

3.6.3 Hardness

The variations in the mean signal to noise ratio for the micro hardness for all factors are as presented in Table 10.

Main effect plot for the mean signal-to-noise ratio for hardness is presented in Figure 11c. With regard to temperature as a process parameter, the stirring temperature between 500 and 600 °C shows equal SN difference as that of between 600 and 700 °C with a value of ±0.6959 dB. This depict an almost equal contribution of temperature between 500 and 600 °C and 600 and 700 °C. Stirring speed as a process factor exhibited SN difference +1.1412 dB for speed between 300 and 400 rpm which reflected in the enhancement in hardness. Between 400 and 500 rpm, there was a reduction in hardness with SN difference of -0.5585 dB. Consequence of this is that the proportion of the contribution of speed in enhancing the hardness of aluminum composite between 300 and 400 rpm is the same proportion in lowering the hardness between 400 and 500 rpm. 30 min exhibited a significant impact in enhancing hardness as its shows SN ratio difference of +1.0031 dB Table 10 reveals the values of the mean signal to noise ratio for hardness as illustrated in Figure 11c for the factors. The values at level 1, 2, and 3 for temperature and speed and level 1, 2 for time are presented. Corresponding delta value ranks the parameters as temperature, time and speed as 1st, 2nd, and 3rd respectively. Therefore, order of importance of the factors for hardness is stirring temperature, stirring time, and stirring speed.

3.6.4 Impact strength

The variations in the mean signal to noise ratio for the impact strength for all factors are as presented in Table 11.

Figure 11d, for impact strength, signal-to-noise ratio with respect to temperature trended downwards from 13.9560 at 500 °C to 12.7236 at 700 °C (SN ratio difference of -1.3856 dB) indicating that temperature has a negative influence on impact. Implication of this exhibited increasing temperature from 500 °C is detrimental to the impact strength of the composite developed. Also observed is the high difference in SN ratio (+0.7731 dB) between 600 to 700 °C as compared with SN ratio between 500 and 600 °C (-0.4593 dB). It showed that the contribution of temperature in lowering the impact strength is more pronounced between 600 and 700 °C than between 500 and 600 °C.

Stirring speed had the highest SN ratio when the speed was 400 rpm with SN ratio difference of +1.26234 dB at the increasing trend between
Figure 12. Microstructural image of selected composite.
The mean SN ratio for stirring time between 15 and 30 min is +1.0710 dB confirming longer stirring duration contributes significantly to impact strength of the composite owing to adequate time for particle distribution within matrix. From Figure 11d, the optimum impact strength was attained at stirring parameters of 500 ºC, 400 rpm, and 30 min for temperature, speed, and time respectively. Table 11 shows the values of the mean signal to noise ratio for impact strength as featured in Figure 11d for the factors. The values at level 1, 2, and 3 for temperature and speed and level 1, 2 for time are showcased. Corresponding delta value ranks the parameters; temperature, time and speed as 1st, 2nd and 3rd in that order. Evidently, the order of importance of the factors for impact strength is stirring temperature, stirring time and stirring speed.

3.6.5. Signal to noise ratio for the combined characteristics

The variations in the mean signal to noise ratio for the combined characteristics of all factors are as presented in Table 12.

In the overall (Figure 11c), the effect of the temperature is downwards, that is, increasing the temperature between 500 and 700 ºC amounts to a lowering of the resultant response. Temperature between 600 and 700 ºC is more detrimental than temperatures between 500 and 600 ºC owing to SN ratio difference of -0.6129 dB for temperatures between 600 to 700 ºC as compared with -0.4936 dB for temperatures between 500 and 600 ºC. Resultant performance is affected by the stirring speed in two ways in that between 300 and 400 rpm, the performance is enhanced while between 400 and 500 rpm, the resultant performance depreciates. Furthermore, between 300 and 400 rpm, SN ratio difference is +0.8582 dB while between 400 and 500 rpm, it is -0.1391 dB. This points to the fact that speed contributes more to the enhancement of resultant performance between 300 and 400 rpm than it does in reducing the performance when stirring is between 500 and 600 rpm. Stirring temperature as its resultant performance is on the upward implying increasing stirring time between 15- and 30-min achieving improvements in mechanical strength with SN ratio difference of +1.0710 dB. In overall, as regards tensile, compressive, and impact strengths and hardness of the developed Al 6061/GP, the stirring temperature, stirring time and stirring speed take first, second, and third in that order respectively.

As shown in Table 12, the values at level 1, 2, and 3 are for temperature and speed, and level 1, 2 for time are evident. The corresponding delta value ranks the parameters; temperature, time and speed as 1st, 2nd, and 3rd in that order. However, the order of importance of the factors for the combined characteristics is stirring temperature, stirring time, and stirring speed respectively.

3.7. Confirmation of result

Confirmation experiment was carried out by preparing samples at optimum conditions of 600 ºC, 400 rpm and 30 min for temperature, speed, and time respectively. Also, random experiment was carried out at conditions of 550 ºC, 450 rpm, and 20 min for random R1 and 600 ºC, 550 rpm, and 20 min for random R2. Tensile strength, compressive strength, hardness, and impact strength were evaluated in triplicates for the stipulated conditions and the mean value recorded. Confirmation values and predicted values (obtained from the model expression) are presented in Table 13 for the properties. The corresponding error were calculated and for all values, the error was observed to be <5% thereby validating the model and the process.

3.8. Microstructural analysis

Figure 12 presents the microstructural images of selected samples developed at different stirring parameters. Evidently, in Figure 12a, intermetallic phases, blow holes, expanded voids, and induced cracks are observed. These are defects associated with high temperature casting and high-speed stirring. At high temperature, there is low viscosity allowing gas entrapment causing voids and blow holes [28, 29]. High speed stirring ensue turbulence promoting gas entrapment and pores within matrix. In Figure 12b, c, and d, expanded voids, inclusions, blow holes, and intermetallic phases are noted. These are observed to be defects of high temperature stirring, owing to intermetallic reactions. Intermetallic phases were observed in Figure 12d, associated with high temperature reaction. In effect, the phases impact brittleness with lower strength and machinability. Figure 12e displays regions of segregation caused by low temperature and speed casting. At lower temperature, the viscosity is high limiting particle dispersion in the matrix which may lead to agglomeration [30, 31]. Additionally, dense impurities condense at the base of the crucible and at lower speed, adequate dispersion is inhibited amounting to segregation and agglomeration. As shown in Figure 12f, cracks were evident, attributed to the slow segregation caused at the onset, thus leading to induced stress around that region and lower adhesion to matrix. Upon solidification, there is a forced detachment thereby leading to crack. In Figure 12g, particles are observed to be distributed within the matrix, however, it is observed that particle agglomeration is present. This can be associated with the limited stirring times invariably preventing uniform dispersion. Figure 12h shows the uniform dispersion of particles and strong adherence to the matrix yielding improved properties of the composite.

4. Conclusion

Taguchi technique was employed in analyzing the stir casting parameters and optimizing the mechanical performance of Al 6061/GP composite. The following conclusions were arrived at;

i. normal plot and ANOVA analysis showed that the three parameters; stirring temperature, speed, and time had significant effect on tensile strength, compressive strength, hardness, and impact strength as p value is <0.05 in each case.

ii. interaction plot analyzed showed that the combined interaction of the effects had significant effects on the properties.

iii. the four properties analyzed were observed to be dependent on the process parameters, with stirring temperature being the most important of the three.

iv. the three variables were confirmed to have positive influence on the tensile strength response in the descending order of contribution as time, temperature, and speed. Optimum tensile strength was then achieved when temperature, speed, and time were 600 ºC, 400 rpm, and 30 min, respectively.

v. for the compressive strength, the process parameters had positive influence on the response in descending order of temperature, time, and speed. Optimum compressive strength was achieved when the temperature, speed, and time were 600 ºC, 500 rpm, and 30 min in that order.

vi. contribution of the parameters as regards hardness is also positive in the order of time, temperature, and speed. Optimum hardness was attained when temperature, speed and time were 700 ºC, 500 rpm, and 30 min in that order.

vii. as regards impact strength, temperature had negative influence on the response, while speed and time had positive influence in the descending order of temperature, time, and speed. Optimum impact strength was achievable when the temperature, speed, and time were 500 ºC, 400 rpm, and 30 min respectively.

viii. Taguchi optimization showed stirring parameters of 500 ºC, 400 rpm, and 30 min for temperature, speed, and time, respectively, yielding optimum performance as these parameters enhanced the dispersion of the particulates as well as promoted interfacial adhesion with matrix. In the overall, significance of the input parameters are stirring temperature, stirring time and stirring speed.
speed in that order, respectively. Validation procedure carried out affirmed that the models are significant and Taguchi method was capable for optimization procedure.

**Declarations**

**Author contribution statement**

Abayomi A. Akinwande: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Adeolu A. Adediran: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Oluwatosin A. Balogun: Analyzed and interpreted the data; Wrote the paper.

Moses Ebiowei Yibowei, Abel A. Barnabas, Henry K. Talabi, Bayode J. Oluwatosin A. Balogun: Analyzed and interpreted the data; Wrote the paper.

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**Data availability statement**

Data will be made available on request.

**Declaration of interests statement**

The authors declare no conflict of interest.

**Additional information**

No additional information is available for this paper.

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