Investigation of Parametric Influence on the Properties of Al6061-SiC\textsubscript{p} Composite

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Abstract. The influence of process parameter in stir casting play a major role on the development of aluminium reinforced silicon carbide particle (Al-SiC\textsubscript{p}) composite. This study aims to investigate the influence of process parameters on wear and density properties of Al-SiC\textsubscript{p} composite using stir casting technique. Experimental data are generated based on a four-factors-five-level central composite design of response surface methodology. Analysis of variance is utilized to confirm the adequacy and validity of developed models considering the significant model terms. Optimization of the process parameters adequately predicts the Al-SiC\textsubscript{p} composite properties with stirring speed as the most influencing factor. The aim of optimization process is to minimize wear and maximum density. The multiple objective optimization (MOO) achieved an optimal value of 14 wt\% reinforcement fraction (RF), 460 rpm stirring speed (SS), 820 °C processing temperature (PT\textsuperscript{emp}) and 150 secs processing time (PT). Considering the optimum parametric combination, wear mass loss achieved a minimum of 1 x 10\textsuperscript{-3} g and maximum density value of 2.780 g/mm\textsuperscript{3} with a confidence and desirability level of 95.5%.

1. Introduction
Light weight composite materials possesses the requirements for structural applications, with aluminium matrix composite (AMC) as the most attractive due to its inherent properties. The major attraction of AMC resulted due to its reduction in mass; improve wear resistance and material properties such as high strength and stiffness. Moreover, AMC has attracted much attention by researchers owing to its low density, high thermal conductivity, low melting point and ability to be reinforced by a wide variety of reinforcement phases such as SiC, Al\textsubscript{2}O\textsubscript{3}, TiC, B\textsubscript{4}C and fly ash [1-3].

Cost effective stir casting process is one of the potential techniques to develop AMC due to its simplicity, flexibility. The properties of cast AMC from stir casting process is majorly influenced by the processing parameters. Sozhamannan et al. [4] examined the influence of PT\textsuperscript{emp} and stirring time (ST) on the mechanical properties of Al-SiC\textsubscript{p}. It was observed that the hardness value increases linearly between 750-800 °C at 20 min processing time. Balasivanandha et al. [5] reported that higher SS and ST influences the hardness of AMC. Furthermore, Naher et al. [6] studied the effect of different SS on uniform distribution of particle in simulated fluids. It is concluded from the study that SS has a significant effect on the particle distribution. Based on majority of studies conducted in the literatures, the processing parameters are examined independently of each other, although a simultaneous evaluation of these parameters is required because of their influence on the processing condition. As a result, several experimental design techniques maybe recommended to investigate the
effect of these processing factors on the properties of AMC. The response surface methodology (RSM) of central composite design (CCD) has been a preferred method for experimental plan because it is a very efficient in reducing the number of experiments with a large number of factors and levels [7]. CCD is also capable of achieving the optimum conditions required to attain the best characteristic properties. Therefore, the aim of this study is to examine the influence of parametric optimization on wear and density properties of AMC using the stir casting technique.

2. Experimental details

2.1. Materials and method

AA6061 alloy is used as the matrix material and silicon carbide particle ($\text{SiC}_p$) as the reinforcement material. Table 1 shows the properties of the matrix alloy and reinforcement materials.

| Table 1. Properties of matrix (AA6061) and reinforced $\text{SiC}_p$ phase. |
| Property | Unit | Al (6061) | $\text{SiC}_p$ |
|------------------|--------|------------|--------------|
|Density           | g/cm$^3$| 2.7        | 3.22         |
|Melting point     | °C     | 660        | 2973         |
|Coefficient of thermal expansion | µm/m°C | 23.4 | 4 |
|Thermal conductivity | W/mK  | 166        | 126          |

The composite is developed using the liquid metallurgy route through the bottom pouring stir casting process. The melting and preheating furnace chamber has a maximum heating capacity of 1000 °C which is sufficient to conduct all the experimental design runs. The $\text{SiC}_p$ powder is treated in the preheating furnace to 900 °C for 2 hrs to make their surfaces oxidized [8]. After melting of the aluminium alloy, dross formation on the surface is extracted using a preheated coated skimmer. Prior to incorporation of the preheated $\text{SiC}_p$ powder, 1wt% magnesium ($\text{Mg}$) is added to improve the wettability between the matrix alloy and reinforcement phase. The presence of Mg not only has the beneficial effect of alloying but also reduces the surface tension of the melt and decreases the solid-liquid interfacial energy. The preheated $\text{SiC}_p$ was gradually injected into the melt as the coated stainless steel stirrer is automatically lowered into the furnace for stirring purpose. This process is conducted for each of the experimental run considering the process parameters in the design plan.

2.2. Wear test condition

High frequency reciprocating wear testing machine is used to conduct the wear test according to ASTM D 6079-97. All AMC samples developed based on the design plan were evaluated at a constant operating condition of 50 N load at 600 rpm for 30 min using a 52100 chrome steel ball as the counter surface. The ball has a diameter of 6mm and hardness value of 60-67 RC. The difference in mass before and after the test is used to evaluate the WML.

2.3. Experimental design

The experiments were planned based on CCD method. It utilized four factor five level design scheme as shown in Table 2. The factors are reinforcement fraction (RF), stirring speed (SS), processing temperature (PT$_{emp}$), and processing time (PT).

| Table 2. Design plan for factors and their levels in CCD |
|------------------|------------|-------------|-------------|
| Factors           | Levels     | -2 | -1 | 0 | +1 | +2 |
|------------------|------------|-----------------|-----------------|
|Reinforcement fraction (wt %) | $X_1$      | 5 | 10 | 15 | 20 | 25 |
|Stirring speed (rpm) | $X_2$      | 200 | 300 | 400 | 500 | 600 |
|Processing temperature (°C) | $X_3$    | 700 | 750 | 800 | 850 | 900 |
|Processing time (secs) | $X_4$    | 60 | 90 | 120 | 150 | 180 |
The CCD consist of $2^k + 2k + n$ runs, where $k$ is the number of factors, $2^k$ is the number of the factorial points at the corners of the cube, $2k$ is the number of the axial points. Thus, the number of experimental runs in this study is $16+8+6=30$. The experimental outcome is presented in Table 3.

### Table 3. Experimental design plan and response based on CCD

| No | a: Reinforcement Fraction (wt %) | b: Stirring speed (rpm) | c: Processing Temperature(°C) | d: Processing Time (secs) | Wear mass loss (g) | Density (g/mm$^3$) |
|----|---------------------------------|-------------------------|-------------------------------|---------------------------|-------------------|-----------------|
| 1  | 15.00                           | 400.00                  | 800.00                        | 120.00                    | 0.001600          | 2.7793          |
| 2  | 20.00                           | 400.00                  | 700.00                        | 150.00                    | 0.001725          | 2.7650          |
| 3  | 15.00                           | 300.00                  | 800.00                        | 120.00                    | 0.002025          | 2.7630          |
| 4  | 10.00                           | 300.00                  | 800.00                        | 90.00                     | 0.002395          | 2.7695          |
| 5  | 10.00                           | 300.00                  | 850.00                        | 150.00                    | 0.001750          | 2.7695          |
| 6  | 25.00                           | 400.00                  | 800.00                        | 120.00                    | 0.001250          | 2.7600          |
| 7  | 10.00                           | 500.00                  | 850.00                        | 90.00                     | 0.001350          | 2.7743          |
| 8  | 20.00                           | 300.00                  | 750.00                        | 90.00                     | 0.002050          | 2.7540          |
| 9  | 15.00                           | 400.00                  | 800.00                        | 120.00                    | 0.001125          | 2.7785          |
| 10 | 10.00                           | 500.00                  | 750.00                        | 150.00                    | 0.001100          | 2.7770          |
| 11 | 15.00                           | 400.00                  | 800.00                        | 120.00                    | 0.001150          | 2.7743          |
| 12 | 15.00                           | 400.00                  | 800.00                        | 120.00                    | 0.001100          | 2.7800          |
| 13 | 15.00                           | 400.00                  | 800.00                        | 120.00                    | 0.001100          | 2.7808          |
| 14 | 10.00                           | 300.00                  | 750.00                        | 150.00                    | 0.001950          | 2.7553          |
| 15 | 20.00                           | 500.00                  | 750.00                        | 90.00                     | 0.001650          | 2.7498          |
| 16 | 10.00                           | 500.00                  | 750.00                        | 90.00                     | 0.001825          | 2.7600          |
| 17 | 20.00                           | 300.00                  | 750.00                        | 150.00                    | 0.001425          | 2.7580          |
| 18 | 15.00                           | 200.00                  | 800.00                        | 120.00                    | 0.002310          | 2.7500          |
| 19 | 20.00                           | 500.00                  | 750.00                        | 150.00                    | 0.001800          | 2.7580          |
| 20 | 15.00                           | 400.00                  | 800.00                        | 120.00                    | 0.002050          | 2.7540          |
| 21 | 20.00                           | 300.00                  | 850.00                        | 90.00                     | 0.001375          | 2.7500          |
| 22 | 15.00                           | 400.00                  | 800.00                        | 60.00                     | 0.002450          | 2.7483          |
| 23 | 5.00                            | 400.00                  | 800.00                        | 120.00                    | 0.000900          | 2.7663          |
| 24 | 10.00                           | 500.00                  | 850.00                        | 150.00                    | 0.001025          | 2.7553          |
| 25 | 15.00                           | 400.00                  | 800.00                        | 180.00                    | 0.001025          | 2.7553          |
| 26 | 15.00                           | 600.00                  | 800.00                        | 120.00                    | 0.001825          | 2.7580          |
| 27 | 20.00                           | 500.00                  | 850.00                        | 90.00                     | 0.001500          | 2.7658          |
| 28 | 15.00                           | 400.00                  | 900.00                        | 120.00                    | 0.001200          | 2.7655          |
| 29 | 10.00                           | 300.00                  | 750.00                        | 90.00                     | 0.002450          | 2.7483          |
| 30 | 20.00                           | 500.00                  | 850.00                        | 150.00                    | 0.001200          | 2.7663          |

### 3. Results and discussion

#### 3.1. Model development

The mathematical relationship between the response and processing factors is expressed in equation 1 by the second order polynomial equation [9].

$$ Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_i X_i^2 + \sum_{i=1}^{k} \sum_{j \neq i} \beta_{ij} X_i X_j + \epsilon $$  \hspace{1cm} (1)
where $Y$ represents the response, $X_i$ and $X_j$ are the equation value of the factors, $\beta_0$ is the constant, $\beta_i$, $\beta_j$ and $\beta_{ij}$ are linear, interaction and quadratic end coefficient respectively, and $k$ is the number of the factors.

3.2. Parametric influence on wear mass loss (WML)

The relationship between the processing parameters and WML is evaluated by regression analysis. It is observed that a quadratic model is suggested as shown in Table 4. The model is associated with p values of < 0.0045, which is < 0.05, indicating that the model is considered to be statistically significant.

| Source      | SS         | df | MS      | F Value | p-value |
|-------------|------------|----|---------|---------|---------|
| Mean        | 7.070E-005 | 1  | 7.070E-005 |         |         |
| Linear      | 3.615E-006 | 4  | 9.037E-007 | 9.02    | 0.0001  |
| 2FI         | 5.743E-007 | 6  | 9.571E-008 | 0.94    | 0.4888  |
| Quadratic   | 1.184E-006 | 4  | 2.960E-007 | 5.94    | 0.0045  |
| Cubic       | 3.858E-007 | 8  | 4.823E-008 | 0.93    | 0.5424  |
| Residual    | 3.614E-007 | 7  | 5.163E-008 |         |         |
| Total       | 7.682E-005 | 30 | 2.561E-006 |         |         |

The adequacy and validity of the model is ascertained using ANOVA in Table 5 by confirming the significant terms with p values < 0.05. However, model terms with p values > 0.05 are considered insignificant. The numerical analysis for WML model equation is therefore obtained based on the significant terms. Moreover, the difference between the adjusted $R^2$ (0.7591) and predicted $R^2$ (0.6171) is > 0.2, which establishes a reasonable agreement as required.

| Source                  | SS         | df | MS      | F Value | p-value |
|-------------------------|------------|----|---------|---------|---------|
| Model                   | 5.053E-006 | 8  | 6.316E-007 | 12.43   | < 0.0001 significant |
| A-Reinforcement Fraction| 5.385E-007 | 1  | 5.385E-007 | 10.59   | 0.0038  |
| B-Stirring speed        | 1.609E-006 | 1  | 1.609E-006 | 31.66   | < 0.0001 |
| C-Processing Temperature| 3.638E-007 | 1  | 3.638E-007 | 7.16    | 0.0142  |
| D-Processing time       | 1.103E-006 | 1  | 1.103E-006 | 21.70   | 0.0001  |
| AB                      | 3.150E-007 | 1  | 3.150E-007 | 6.20    | 0.0213  |
| $A^2$                   | 3.934E-007 | 1  | 3.934E-007 | 7.74    | 0.0112  |
| $B^2$                   | 7.487E-007 | 1  | 7.487E-007 | 14.73   | 0.0010  |
| $C^2$                   | 2.288E-007 | 1  | 2.288E-007 | 4.50    | 0.0459  |
| Residual                | 1.067E-006 | 21 | 5.083E-008 |         |         |
| Lack of Fit             | 7.941E-007 | 16 | 4.963E-008 | 0.91    | 0.6023  |
| Pure Error              | 2.733E-007 | 5  | 5.467E-008 |         |         |
| Cor Total               | 6.120E-006 | 29 |         |         |         |

Based on the confirmation, model equations were developed for WML. Equation 2 is used to recreate the response for any given level of each processing parameters in the experiment.
\[ W_m (g) = + 0.034060 -2.84440E-004a - 1.98811E-005b -6.03196E-005c - 7.14583E-006d + \\
2.80625E-007ab + 4.74107E-006a^2 + 1.63527E-008b^2 + 3.61607E-008c^2 \]  \quad (2)

Moreover, equation 3 is used to identify the relative impact of the processing parameters by comparing their coefficients. It is concluded from the equation that the process parameter with the most influencing impact on WML is SS as illustrated in Figure 1.

\[ W_m (g) = + 1.237E-003 -1.498E-004a - 2.590E-004b - 1.231E-004c - 2.144E-004d + 1.403E-004ab \\
+ 1.185E-004a^2 + 1.635E-004b^2 + 9.040E-005c^2 \]  \quad (3)

From the quadratic influence, it is observed from Figure 2a that WML decreases as both SS and RF gradually increases. However, the WML did not show any obvious decrease beyond 500 rpm and 18 wt%, rather a further tendency of an increase in WML may be observed. Higher SS beyond 500 rpm initiates an increase in WML due to vigorous stirring which gives rise to vortex phenomenon leading to porosity formation as a result of gas entrapment in the melt. Therefore, the RF shows little or no obvious effect on the WML beyond 18 wt% due to the influence of further increase in the SS.

![Figure 1. Perturbation plot for wear mass loss](image1.png)

![Figure 2. Surface plot profile of (a) SS and RF (b) SS and PT\text{emp} on WML](image2.png)

Figure 2b shows the simultaneous influence of SS and PT\text{emp} on WML. It is observed that both factors attained minimum WML at 500 rpm and 830 °C respectively. Though, beyond these processing conditions an increase in WML is experienced due to undesirable situation of porosity formation and particle settling due to higher SS and PT\text{emp}.

### 3.3. Parametric influence on density property

A quadratic relationship is suggested between the process parameters and density as indicated in Table 6. The model has a p values of 0.0002 which is < 0.05 (i.e. \( \alpha = 0.05 \) or 95\% confidence) indicating that the model is considered to be statistically significant. The adequacy and validity of the developed model is tested through ANOVA as shown in Table 7. The significant model terms are considered to generate the model and are identified with p values < 0.05. However, model terms with p value > 0.05 are regarded as insignificant. Insignificant lack of fit implies that the model fits the data adequately. The difference between the adjusted \( R^2 \) (0.7257) and predicted \( R^2 \) (0.5755) is within the acceptable limit < 0.2 in order to establish a reasonable agreement.
Table 6. Test for significance of density

| Source     | SS     | df | MS          | F Value | p-value |
|------------|--------|----|-------------|---------|---------|
| Mean       | 229.22 | 1  | 229.22      |         |         |
| Linear     | 1.358E-003 | 4 | 3.395E-004 | 4.12    | 0.0107  |
| 2FI        | 2.235E-004 | 6 | 3.726E-005 | 0.39    | 0.8794  |
| Quadratic  | 1.382E-003 | 4 | 3.456E-004 | 11.37   | 0.0002  |
| Cubic      | 3.696E-004 | 8 | 4.620E-005 | 3.75    | 0.0491  |
| Residual   | 8.615E-005 | 7 | 1.231E-005 |         |         |
| Total      | 229.22 | 30 | 7.64        |         |         |

Based on the validity and adequacy through ANOVA, two model equation developed for density. Equation 4 determines the density value for any given level of each processing parameters in the experiment.

\[
\rho = + 1.49158 + 4.70000E-003a + 4.16042E-004b + 2.65083E-003c + 1.14792E-003d - 1.76667E-004a^2 - 4.63542E-007b^2 - 1.61667E-006c^2 - 4.21296E-006d^2
\]  

(4)

Moreover, equation 5 defines the relative impact of the processing parameters on density.

\[
\rho = + 2.78 - 3.000E-003a + 4.521E-003b + 3.208E-003c + 4.104E-003d - 4.417E-003a^2 - 4.635E-003b^2 - 4.042E-003c^2 - 3.792E-003d^2
\]  

(5)

The perturbation plot in Figure 3 shows that there is interaction among the process parameters and it also describes the SS as the most influential factor on density. The interactions indicate that the factors influences the density property due to their quadratic effect. Figure 4 shows the effects of the process parameters on density and it is observed that density increases as the factors increases. However, an optimum condition is attained as density shows a reverse trend due to further increase in the parameters. In Figure 4(a) and (b), the SS, RF and PT achieved optimum at 500 rpm, 14 wt% and 160 secs respectively. Moreover, in Figure 4(c) the PT_{emp} attained an optimum of 835 °C. With PT_{emp} above 835 °C the reinforced particles gain higher energy which facilitates faster movement and settling of the particles in the melt. This phenomenon of particle settling at higher temperature hinders the effective distribution of the reinforcement thereby influencing an increase in WML.

Figure 3. Perturbation plot for density
The influence of different process parameters was exhibited through the perturbation and surface plots. Models have been developed based on CCD. The developed models has the potential to evaluate WML and density under various process parameter conditions. The multiple objective optimization analysis generates a set of condition that simultaneously optimizes both responses (WML and density) through optimal solutions. Based on the solution analysis in Table 8, the optimum values of input process parameters is achieved with experiment No 1. The conditions are reinforcement fraction 14 wt%; stirring speed 460 rpm; processing temperature 820 °C and processing time 150 secs with a confidence and desirability level of 95.5%.

Table 8. Optimal solution generated for the response

| No | Reinforcement fraction | Stirring speed | Processing Temperature | Processing time | Wear mass loss | Density | Desirability |
|----|------------------------|----------------|------------------------|-----------------|---------------|---------|--------------|
| 1  | 14.030                 | 462.562        | 821.590                | 150.000         | 0.001         | 2.780   | 0.955        | Selected   |
| 2  | 14.428                 | 464.695        | 824.793                | 149.997         | 0.001         | 2.780   | 0.955        |
| 3  | 14.444                 | 464.457        | 824.277                | 149.997         | 0.001         | 2.780   | 0.955        |
| 4  | 14.413                 | 464.853        | 824.280                | 149.998         | 0.001         | 2.780   | 0.955        |
| 5  | 14.457                 | 464.020        | 824.266                | 149.999         | 0.001         | 2.780   | 0.955        |

Figure 5 shows the desirability histogram of WML and density generated for the solutions and multiple (combined) optimum for the stir casting process condition. It is observed that MOO improved the density response as indicated from the desirability histogram.

Figure 5. Desirability histogram of MOO for stir casting process parameters

5. Conclusion
Optimum parametric condition for processing Al-SiC<sub>3</sub> composite was successfully achieved using the bottom pouring stir casting technique. Models have been developed based on CCD. The developed models has the potential to evaluate WML and density under various process parameter conditions. The influence of different process parameters was exhibited through the perturbation and surface plots.
It is described from the response surface plot that WML decreases with an increase in the processing parameter. However, the reinforcement fraction reaches an optimum condition where there is little or no obvious change in WML as other processing parameter initiates an increase in WML at higher processing conditions. For density, the surface plot exhibits an increase in density as the processing parameter increases. Though, an optimum condition is attained after which the density shows a reverse trend as the processing parameter further increases. From the MOO analysis, the set of conditions that simultaneously optimizes both WML and density was found as RF 14 wt%; SS 460 rpm; PT\textsubscript{emp} 820 °C and PT 150 secs. As a result the WML achieved a minimum of 1 x 10\(^{-3}\)g and a maximum density value of 2.780g/mm\(^3\) with a confidence and desirability level of 95.5%.

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