Solid particle erosion studies on SiC reinforced functionally graded aluminium matrix composites

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Abstract. The main objective of this present study is to fabricate functionally graded Aluminium alloy reinforced with silicon carbide composite by horizontal centrifugal casting process and investigate its erosion wear behaviour using Taguchi technique. Microstructural examination confirmed that the gradient structure across the radial direction and maximum particle reinforcement was found at the outer zone of the fabricated functionally graded metal matrix composite. Solid particle erosion wear experiments were carried out on the fabricated functionally graded metal matrix composite using abrasive air jet erosion test rig. Erosion process parameters such as zone distance from outer surface, Erodent velocity and Exposure time were examined using L9 orthogonal array table. The effect of erosion parameters on the erosion rate was investigated by signal-to-noise ratio and Analysis of Variance. Analysis of Variance result concluded that zone distance from the outer surface had 91.46% influence on erosion rate followed by exposure time (2.54%) and erodent Velocity (0.54%). Finally, regression equation was formed to find the optimal erosion rate and that has been validated by confirmatory experiment.

1. Introduction

Functionally graded materials are the newly developing materials and it has been attracted by the researcher because of its better gradient structure. It has two or more material added together with different volume fraction to get continuously varying properties. A component with better wear resistant on the outer surface when compared with the inner surface can be achieved through functionally graded materials [1]. Now a day, solid particle erosion is one of the most considerable obstacles that affect the tribological behaviour of the metal matrix composites. Here the solid abrasive particles move with high impact velocity and strike on the surface with different directions and immediately take away some materials from the surface of the composite. Because of this action, the normal properties of the composite can be altered due to the localized impact of high velocity solid particles [2]. W. Wu et al compared the effect of reinforcement on the mechanical and wear properties of the heat treated aluminium and pure aluminium. They conducted an analysis on the aluminium with...
as-cast, annealed, as-quenched, and T6 conditions. They concluded that lack of ductility was the major problem for erosion rate. Moreover, heat treatment had a little considerable effect on the erosion [3]. Mengyao Dong et al studied the effect of solid particle erosion on the thermoplastic polyurethane nanocomposite reinforced with a different weight percentage of carbon nanotubes fabricated through hot pressing technique. The influence of impact parameters such as impingement angle, impact velocity and size of impact particles on the surface roughness of the fabricated composites was studied. They concluded that the addition of carbon nanotubes improved the erosion resistance and also the increase in impact velocity increased the erosion rate [4]. Mehmet Bagci et al had done a erosion study on the epoxy and glass fibers matrix composite reinforced with 0, 15 and 30% boric acid particles fabricated through hand lay-up technique. The impact of different erosion parameters such as fiber direction, erodent size, percentage boric acid particles, impingement angle and impact velocity were studied. Moreover, Taguchi technique was used to found the combination of erosion parameters which affect the erosion rate of the composite. They concluded that the addition of boric acid particles increased the strong bonding between epoxy composite and also contributed 52.51% on the erosion rate of the composite [5]. M. Pethuraj et al conducted erosion studies on the Aluminum metal matrix composite reinforced with sillimanite fabricated by vacuum assisted stir casting method. They found the effect of different varying operation parameters such as erodent velocity, angle of impingement and weight percentage of the reinforcement on the erosion rate of the composite. The results were revealed that the addition of reinforcement decreased the erosion rate. Moreover, the high reinforced composite had a high erosion rate when compared with pure Aluminum [6]. K. Balamurugan et al carried erosion study on the silicon carbide reinforced magnesium composite. They found the influence of erosion governing parameters such as erodent particle, impact angle, erosion velocity, and discharge rate on the erosion rate and Taguchi technique were used to found the optimal parameters that are affected the erosion rate of the composite. The conclusion stated that erosion velocity has a significant effect on the composite compared with other parameters [7]. S. Vigneshwaran et al had done erosion experimental study on the red mud filled and unfilled sisal fiber reinforced hybrid composites. Taguchi analysis was used to found the factor which is highly affected the erosion rate among various factors such as filler material, fiber concentration, erodent velocity, impact angle and erodent discharge rate. The significant finding shows that erodent velocity had the greatest effect on the erosion rate of the composite [8]. Many researchers have conducted erosion study on the different composite but no one reported the erosion study on the Aluminium functionally graded metal matrix composite. This is the seed for the present study.

The main objective of the present study is to fabricate Aluminum Functionally Graded Metal Matrix Composite reinforced with SiC particles (FGMMC) through stir casting process followed by a vertical centrifugal casting process. Then the erosion wear behavior of FGMMC was found by using air jet erosion tester apparatus using L9 orthogonal array table. Finally, the optimal factors that are influencing the erosion wear are calculated.

2. Experimental Details

2.1. Materials and Methods

The major base material preferred for this study was Aluminium alloy Al6061 as a result of its wide range of automotive applications and reinforcement elected for this study was Silicon Carbide(SiC) with a standard size of 15μm (20 wt%). The Aluminium alloy Al6061 had a lower density of 2.7 g/cm³ compared to SiC particle which had a density of 3.21 g/cm³. Functionally graded metal matrix composites were fabricated through two steps namely stir casting process and vertical centrifugal casting process. Initially, Aluminium alloy was melted in the electrical resistance furnace to 740°C and then SiC particles were added to the molten metal slowly. Mechanical stirring was done on the molten metal to get uniform distribution of SiC. Then the melt was poured into a vertical centrifugal casting machine which was rotating with a speed of 1200 rpm. Because of the centrifugal force, high density SiC particles are thrown to the outer surface of the fabricated disc
during centrifugal casting. Finally, a disc with a diameter of 250 mm and thickness 25 mm was fabricated and is shown in figure 1.

![Figure 1. Al6061-20%SiC functionally graded metal matrix composite disc.](image)

The microstructural examination was performed on the fabricated disc to ensure the distribution of SiC particles towards the inner surface. Based on the microstructural study three regions were selected to erosion study based on the distribution of SiC particles. A cut portion from the fabricated disc with three selected zone is shown in figure 2. A specimen with a dimension of 10 x 10 x 4 mm was cut from the three regions of the disc to erosion study.

![Figure 2. Cut portion from the fabricated disc with three identified zones.](image)

2.2. Solid Particle Erosion

Abrasive air jet erosion tester was used to study the erosion wear performance and the apparatus is shown in figure 3. During erosion, high velocity air mixed with uniform size abrasive erodent. This mixture was made to impact on the target material through a nozzle. Alumina particles with an average size of 50 microns are selected as an erodent. Impingement angle of 90° was maintained throughout the experiment. The erosion study was conducted on the specimen with three erosion control process parameters such as zone distance from the outer surface, erodent velocity and exposure
time with different levels and is consolidated in table 1. L9 orthogonal array table was elected to conduct the erosion experiment.

| S. No | Zone distance from the outer surface (mm) | Erodent velocity (m/s) | Exposure time (min) |
|-------|------------------------------------------|------------------------|---------------------|
| 1     | 15                                       | 100                    | 10                  |
| 2     | 45                                       | 150                    | 15                  |
| 3     | 75                                       | 200                    | 20                  |

**Table 1.** Erosion process parameters and their levels.

Finally, Erosion wear rate was calculated for each combination of erosion parameters using the following formula [9].

$$Erosion\ rate = \frac{W_m}{W_p}$$

Where $W_m$ is the weight loss in the FGMMC specimen and it was found by using a precision weighing machine and $W_p$ is the weight of the impact particles (testing time x feed rate).

3. Results and discussions

3.1. Microstructural Examination

Figure 4 shows the microstructure of the specimen cut from the three regions of the fabricated disc. Figure 4(a) shows the microstructure observed on the specimen cut from the 15 mm distance from the outer surface. This shows a high concentration of SiC particles. Because the high density SiC particles are propelled to the outer surface of the composite during centrifugal casting and this portion is called SiC particle rich zone. Figure 4(b) shows the microstructure observed on the specimen cut from the 45 mm distance from the outer surface. This shows the intermediate concentration of SiC particles.
distribution. This portion is called SiC particle intermediate zone. Figure 4(c) shows the microstructure observed on the specimen cut from the 75 mm distance from the outer surface. This shows a lower concentration of SiC particles. This portion is called SiC particle depletion zone.

![Figure 4(a). Microstructure of SiC particle rich zone; Figure 4(b). Microstructure of SiC particle intermediate zone; Figure 4(c). Microstructure of SiC particle depletion zone.](image_url)

### 3.2. Erosion Test

The major intention of the experiment is to determine the optimum combination of erosion parameters to get a lower erosion rate. Table 2 shows the experimental results of erosion rate with a different combination of erosion parameters and corresponding S/N ratios.

| S. No | Zone distance from the outer surface (mm) | Erodent velocity (m/s) | Exposure time (min) | Erosion rate $10^5$ (g/m²) | S/N ratio (dB) |
|-------|------------------------------------------|------------------------|---------------------|-----------------------------|----------------|
| 1     | 15                                       | 100                    | 10                   | 1.25                        | 7.604          |
| 2     | 15                                       | 150                    | 15                   | 1.16667                     | 8.203          |
| 3     | 15                                       | 200                    | 20                   | 1.225                       | 7.779          |
| 4     | 45                                       | 100                    | 15                   | 1.46667                     | 6.215          |
| 5     | 45                                       | 150                    | 20                   | 1.375                       | 6.776          |
| 6     | 45                                       | 200                    | 10                   | 1.3                         | 7.263          |
| 7     | 75                                       | 100                    | 20                   | 1.785                       | 4.509          |
| 8     | 75                                       | 150                    | 10                   | 2.1                         | 3.098          |
| 9     | 75                                       | 200                    | 15                   | 2.16667                     | 2.826          |
3.3. Taguchi Analysis

Taguchi method was utilized to determine the effect of each erosion parameters on the response. Signal to Noise ratio for the erosion parameters namely zone distance from the outer surface, erodent velocity and exposure time were calculated by feeding the calculated erosion rate to the MINITAB 17 software. “Smaller the Better” quality characteristic was selected to find minimum wear rate. The response table for the signal to noise ratio for the calculated erosion rate is shown in table 3.

**Table 3. S/N ratio response table for erosion rate.**

| Erosion parameters                  | Level-1 | Level-2 | Level-3 | Delta | Rank |
|-------------------------------------|---------|---------|---------|-------|------|
| Zone distance from the outer surface (mm) | -1.680  | -2.791  | -6.064  | 4.384 | 1    |
| Erodent velocity (m/s)              | -3.433  | -3.516  | -3.586  | 0.153 | 3    |
| Exposure time (min)                 | -3.554  | -3.794  | -3.187  | 0.607 | 2    |

From table 3, it was observed that zone distance from the outer surface was found to be the most significant process parameter that is affecting the erosion rate. Moreover, erodent velocity had only a small amount of impact on the erosion rate when compared with zone distance from the outer surface and exposure time. Figure 5 shows the main effect plot that shows the impact of all erosion parameters with different levels. The optimum erosion parameters that are affected the erosion rate can be found from this main effect plot. So the optimum erosion process parameters needed for getting lower erosion rate are 15 mm zone distance from the outer surface, 100 m/s erodent velocity and 20 min exposure time. Moreover, ANOVA analysis was done to confirm the above said optimum erosion parameters.

![Main Effects Plot for SN ratios](image)

**Figure 5.** Main effect plot for erosion parameters on erosion rate.
Analysis of Variance was done by using MINITAB 17 software. The results obtained in the ANOVA analysis are shown in table 4. The ANOVA results reviled that zone distance from the outer surface had a greater impact on the erosion rate when comparing with erodent velocity and exposure time. The zone distance from the outer surface had 91.46% contribution on the erosion rate whereas the exposure time had 2.49% contribution and erodent velocity had only 0.54% contribution on the erosion rate. The error had only a small significant role on the erosion rate which shows the experiment was conducted without missing any erosion parameters.

| Zone distance from the outer surface (mm) | Degree of freedom | Sum of Squares | Mean Sum of Squares | Contribution % | Rank |
|-----------------------------------------|------------------|----------------|---------------------|----------------|------|
| Erodent velocity (m/s)                  | 2                | 0.00647        | 0.003233            | 0.54           | 3    |
| Exposure time (min)                     | 2                | 0.02944        | 0.014720            | 2.49           | 2    |
| Error                                   | 2                | 0.06480        | 0.032400            | 5.49           |      |
| Total                                   | 8                | 1.17917        |                     | 100            |      |

### 3.4 Confirmation Test

Confirmation test has been conducted with optimum erosion parameters. After finding the optimum erosion parameters from taguchi analysis, it is necessary to find the optimum erosion rate with optimum erosion parameters. A regression equation was derived from MINITAB 17 software to find the predicted optimum erosion rate and the equation is shown below.

\[
\text{Erosion rate} = 0.972 + 0.01339 \times \text{Zone distance} + 0.00063 \times \text{Erodent velocity} - 0.0088 \times \text{Exposure time}
\]

The predicted value calculated was 1.05985. The experimental erosion wear was calculated using the abrasive air jet tester and the experimental erosion value was 0.9985. The theoretical and experimental erosion values are less than the values which are already calculated in the erosion experiment. The results of the confirmation erosion test with optimum erosion rate are tabulated in table 5.

| Optimal machining Parameter | Predicted Erosion Rate | Experimental Erosion Rate |
|----------------------------|------------------------|---------------------------|
| Erosion rate               | 1.05985                | 0.9985                    |
4. Conclusion

This study presented the fabrication of Aluminium functionally graded metal matrix composite reinforced with SiC particles through stir casting process followed by vertical centrifugal casting process successfully and the following conclusions are drawn,

Microstructure examination confirmed the gradient distribution of SiC particles along the radial direction from outer surface and erosion test was conducted by using taguchi L9 orthogonal array table. The optimum erosion parameters calculated using the taguchi method to get lower erosion rate was zone distance from the outer surface of 15 mm, erodent velocity of 100 m/s and exposure time of 20 minute.

ANOVA result revealed that the zone distance from the outer surface had the highest amount of contribution on the erosion rate followed by erodent velocity and exposure time.

The confirmation experiment was conducted for the optimum erosion parameters and the confirmation test result showed a lesser amount of erosion rate compared with all the combinations.

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