A6061/B4C MMCs fabrication, experimental investigation and prediction of properties

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Abstract. The growing demand for light composite materials is the new trend in engineering solicitations. The objective is to fabricate light weight composite material through less expensive method. In this work, nine different composites have been fabricated with A6061 as base matrix and reinforced with 3%/6%/9% wt% B4C having particle sizes of 30µm, 40µm and 60µm respectively. The investigation of the actual density and hardness of the fabricated composite is the major task. The densities of the fabricated composites were investigated with Two-way Analysis of Variance (ANOVA). Also the densities of the composites were predicted with Taguchi, regression and Poisson method. From all of these fabricated composites 60µm size, 9% wt B4C particle reinforced A6061/B4C composite shows lighter density and this value were nearest to Poisson predicted value.

1. Introduction

Metal matrix composites (MMCs) [1] shows an essential part in the latest engineering applications. In aluminium metal matrix composites (AMMCs) [2] the base metal is aluminium alloy and the addition of reinforcement makes composites. The commonly used reinforcement particles during the fabrication of AMMCs include boron carbide (B4C), silicon carbide (SiC), titanium carbide (TiC) [2]–[4]. Stir casting method is the liquid state fabrication process in AMMCs [5]. The density [6] of the fabricated composites can be measured using Archimedes [7] test. Also rule of mixture [8] is used for the analysis of theoretical density. Once the actual density and theoretical density obtained, the porosity percentage of the composite can be identified [9]. Micro hardness [10] has been obtained through Brinell Hardness test. Also the hardness is obtained using Rockwell test [11]. The X-ray diffraction (XRD) method is used for the phase analysis [12]. Scanning electron microscopy (SEM) is used for the characterization study [13]. The core aspects of this research paper are divided into the following sections: section 2 focuses on experimentation of A6061 MMCs reinforced with B4C particles. Section 3 explains the result and discussion of mechanical properties of A6061+(wt% B4C) MMCs. Section 4 concludes the study with future scope of A6061/B4C MMCs.
2. Experimentation

2.1. Matrix material and reinforcement particles

The aluminium alloy 6061 (A6061) has been used in the present investigation as base alloy with T6 grade. It is in the form of rod with the size of 20mm. The boron carbide reinforcement particles with 3%wt, 6%wt, 9%wt and different particle size having mesh size 230(60µm), 325(40µm) and 450(30µm) were used. Aluminium 6061 alloy and boron carbide were purchased from Coimbatore Metal suppliers, Coimbatore, Tamil Nadu, India. The table 1 shows the composition of A6061 alloy [14]. The physical properties of A6061 and B4C are shown in table 2 [15] and table 3 respectively [16].

| Component | Magnesium | Silicon | Iron | Copper | Zinc | Titanium | Manganese | Chromium | Others | Aluminium |
|-----------|-----------|---------|------|--------|------|----------|-----------|----------|--------|-----------|
| Weight % (wt%) | 0.8 - 1.2 | 0.4 - 0.8 | 0.15 Max. | 0.7 | 0.40 Max. | 0.15 | 0.15 | 0.35 | 0.05 | Balance |

Table 1. Composition of A6061 alloy [14]

| Property | Unit | Value |
|----------|------|-------|
| Density  | g/cm³ | 2.7   |
| Melting point | ⁰C | 580 |
| Modulus of elasticity | GPa | 70 - 80 |

Table 2. Physical properties of A6061 [8]

| Property | Unit | Value |
|----------|------|-------|
| Melting point | ⁰C | 2445 |
| Modulus of elasticity | GPa | 450 |

Table 3. Physical properties of B4C [17]
2.2. Fabrication

Stir casting technique had used for the manufacture of composite, the reinforcement materials added as per the design of experiments. The boron carbide particles with 3%wt, 6%wt, 9%wt and different particle size having mesh size 230(60µm), 325(40µm) and 450(30µm) have been used as reinforcement particles. The present study comprises of 2 control factors with 3 levels. The different possible designs are L9, L18, L27, L36, L54 under single level and mixed 3 level. The base DOF for this experiment is calculated as,

$$\text{DOF} = (\text{number of control factors}) \times (\text{number of level} - 1)$$

$$\text{DOF}_T$$ for the Taguchi’s design based on DOE = (number of orthogonal array in Taguchi design- 1)

This value of $$\text{DOF}_T$$ must be greater than or equal to base DOF. Also for the reduced number experiments the Taguchi’s L9 orthogonal array is selected. Nine experiments were executed separately for the stir casting setup. In the current work all the analysis were carried out using Minitab statistical software. The various parameters for this experiment were shown in table 4. The persistent parameters used in this fabrication process have been presented in table 5.

| Table 4. Parameters for experiment | Table 5. Stir casting parameters |
|-----------------------------------|---------------------------------|
| Parameters                        | Levels                          | SI No | Parameter | Unit | Value |
| wt% of B4C                        | 1                               | 1     | Preheat   | °C   | 300   |
| Particle Size(µm)                 | 2                               | 2     | Temperature of Reinforcement Particles | °C | 750   |
|                                  | 3                               | 3     | Reinforcement Particles adding temperature | °C | 650   |
|                                  |                                  |       | Stiring RPM | rpm | 300   |
|                                  |                                  |       | Stiring time | Minutes | 5 |

The procedure of stir casting has been presented in figure 1. The reinforcement particles were preheated to 300°C. After that it is mixed to liquid metal in the furnace and temperature being raised to 850°C. Then the molten metal is poured in to preheated (250°C) cast iron mould and permitted to set at 26°C. The fabricated casting size is 100×100×10mm of square prism. The figure 2 shows stir casting arrangement[18]. The details of fabricated cast samples were displayed in table 6.
Fig. 1. Stir casting procedure

Fig. 2. Stir casting arrangement

Table 6. Fabricated samples

| Exp. No. | Base Matrix Alloy | Reinforcement Particle | wt% of Reinforcement Particle | Size of Particle (µm) | Metal Matrix Composite fabricated |
|----------|-------------------|------------------------|------------------------------|----------------------|----------------------------------|
| 1        | A6061             | B4C                    | 3                            | 30                   | A6061+3% B4C                    |
| 2        | A6061             | B4C                    | 6                            | 40                   | A6061+6% B4C                    |
| 3        | A6061             | B4C                    | 9                            | 60                   | A6061+9% B4C                    |
| 4        | A6061             | B4C                    | 3                            | 30                   | A6061+3% B4C                    |
| 5        | A6061             | B4C                    | 6                            | 40                   | A6061+6% B4C                    |
| 6        | A6061             | B4C                    | 9                            | 60                   | A6061+9% B4C                    |
| 7        | A6061             | B4C                    | 3                            | 30                   | A6061+3% B4C                    |
| 8        | A6061             | B4C                    | 6                            | 40                   | A6061+6% B4C                    |
| 9        | A6061             | B4C                    | 9                            | 60                   | A6061+9% B4C                    |
2.3. Archimedes test

The Archimedes test gives the density and the porosity levels of the fabricated samples. The main factors controlling the properties are percentage porosity as well as its size. The air entering during pouring and stirring may cause porosity. For achieving good mechanical properties, the porosity should be very negligible value. The equation 1 gives the fabricated composites density [19].

\[
\rho = \left( \frac{W}{W_1 - W_2} \right) \times \rho_w
\]

where \( \rho \) = density of fabricated part
\( \rho_w \) = density of pure water
\( W \) = weight of composite in air
\( W_1 \) = weight of composite in water

The density theoretical (\( \rho_{th} \)) was observed by the rule of mixture

\[
\rho_{th} = \rho_m V_m + \rho_r V_r
\]

where \( \rho_m \) theoretical density of fabricated sample, \( V_m \) sample volume fraction, \( \rho_r \) B4C theoretical density and \( V_r \) is the B4C volume fraction[20].

2.4. Rockwell hardness test

The hardness has been obtained from Rockwell hardness experiment. The B scale hardness values are observed under the load of 100kg, with three different locations in the surface of the sample. The wire EDM machine has been used to prepare the specimens of size 15mm*15mm*5mm for the test. A 1/16” (2.11mm) diameter steel ball has been used under a load of 100Kgf. Three set of readings at different locations have been taken on the composite surface to reduce errors.

2.5. Microstructure studies

Microphotographs disclose uniform dispersal of B4C particles throughout fabricated composites. The porosity has found to be less and better bonding has been observed between B4C particles and A6061 alloy.

2.6. XRD Analysis

The test composites prepared with the dimensions 15mm*15mm*2mm have been analysed with x-ray diffraction technique.
3. Result & discussion

3.1. Density

Experimental outcomes are investigated by following the standard way and the results are shown in table 7. The actual density is observed from the Archimedes test and theoretical density from rule of mixture. The figure 3 shows disparity in the actual and theoretical density along with wt% of the B4C in the composite fabricated. It is observed that the relative density reduced a little with the wt% of B4C particles from 3 to 9. The relative density is obtained from the equation 3.

$$\rho_{rel}(\%) = \left(\frac{\rho}{\rho_{th}}\right) \times 100$$  \hspace{1cm} (3)

The percentage porosity is obtained from the equation (4).

$$Porosity(\%) = \left(1 - \frac{\rho}{\rho_{th}}\right) \times 100$$  \hspace{1cm} (4)

The variations of relative density and percentage porosity with wt% boron carbide were shown in figure 4 and figure 5 respectively.

Table 7. Experimental results
| Exp. No | wt% of particles | Particle size (µm) | Actual density (g/cc) | SN Ratio | Actua density predicted | % Error of actual density | Rockwell Hardness (HRB) |
|---------|------------------|--------------------|------------------------|----------|-------------------------|--------------------------|-------------------------|
| 1       | 3                | 30                 | 2.6461                 | -8.4742  | 2.6521                  | 2.6503                   | 0.2511                  | 0.2252                  | 0.1587                  | 69                      |
| 2       | 3                | 40                 | 2.6324                 | -8.4089  | 2.6386                  | 2.6456                   | 0.0194                  | 0.234                   | 0.5014                  | 73                      |
| 3       | 3                | 60                 | 2.6182                 | -8.3355  | 2.6116                  | 2.6353                   | 0.2733                  | 0.246                   | 0.6608                  | 81                      |
| 4       | 6                | 30                 | 2.6497                 | -8.4588  | 2.6446                  | 2.6366                   | 0.06                    | 0.1917                  | 0.4944                  | 75                      |
| 5       | 6                | 40                 | 2.6271                 | -8.3934  | 2.6311                  | 2.632                   | 0.0448                  | 0.153                   | 0.1865                  | 79                      |
| 6       | 6                | 60                 | 2.6058                 | -8.3201  | 2.6041                  | 2.6217                   | 0.0158                  | 0.0645                  | 0.6102                  | 86                      |
| 7       | 9                | 30                 | 2.6429                 | -8.4247  | 2.6372                  | 2.6095                   | 0.1913                  | 0.2164                  | 1.2638                  | 70                      |
| 8       | 9                | 40                 | 2.6197                 | -8.3593  | 2.6237                  | 2.605                   | 0.0645                  | 0.1519                  | 0.5611                  | 72                      |
| 9       | 9                | 60                 | 2.5892                 | -8.286   | 2.5967                  | 2.5948                   | 0.2605                  | 0.2889                  | 0.2163                  | 77                      |

Fig. 3. Actual density Vs wt% of B4C

Fig. 4. Relative density Vs wt% of B4C
Two-way ANOVA

The optimum level arrangements of input parameters like wt% of particles and particle size of each process parameters have been determined using ANOVA technique. The two way ANOVA have been used to discover the parameters, which are considerably affect the density. The analysis has been conducted with MINITAB software. The performance characteristics used are lower than better criteria. The S/N ratios of different parameters are given in table 8. The P value expresses the importance of the most dependent parameter and is less than 0.05 which indicates that experiments performed are within standard acceptable limits of 5%.

Regression analysis

Regression analysis of density versus wt% of particles, Particle size has been conducted. The regression equation is

\[
\text{Density} = 2.70 \times \left[(0.00248) \times (\text{wt% of particles})\right] - \left[(0.00135) \times (\text{Particle size})\right]
\]

The residual plots for density is shown in figure 6.
Fig. 6. Residual plots for density  

Fig. 7. Predicted density of composite

**Prediction of density**

The densities of the fabricated composites have been predicted using taguchi method, regression method and Poisson prediction method. The Table 8 shows the experimental results of density and predicted densities. The figure 7 shows the optimal value of density predicted using Poisson method. Figure 8 and figure 9 show the various predicted density versus the wt% B4C and particle size of B4C respectively.

![A6061+wt% B4C (Particle size 30µm) Composite](image1)

![A6061+3%wt B4C Composite](image2)

**3.2. Hardness**

The rockwell harness values of the composites versus particle size and wt% of B4C in the A6061/B4C MMCs fabricated have been shown in figure 10. From this graph, the HRB values rise with the particle size and wt%B4C in the fabricated composite.
3.3. Microstructure

The uniform distributions of particles have been observed with optical microscope. The microstructure of A6061 alloy and A6061/9% wt B4C MMCs with reinforcement particle size 60µm have been shown in Figure (11-12). Also the greater hardness is related with minor porosity of the A6061/B4C MMCs.

Fig. 11. Micro structure of A6061 alloy          Fig. 12. Microstructure of A6061/9%wt B4C MMC

3.4. XRD analysis

Figure 13 shows the XRD patterns for optimal density A6061/9%wt B4C composites prepared through stir casting method. The XRD analysis gives, a clear picture of the unwanted material existing in the fabricated material. In figure 13, the diffraction angle θ is between 0° and 80°, here four peeks are obtained for A6061 corresponding to 39.085°, 45.309°, 65.608°, 78.790° angles. The peaks for B4C have been observed for twelve peeks, such as 17.270°, 20.598°, 22.971°, 32.38°, 35.264°, 36.293°, 38.013°, 40.788°, 42.382°, 43.184°, 57.191° and 75.043°. From the XRD analysis, it is clear that the B4C particles are uniformly dispersed in base alloy. On comparing the above XRD results with A6061 alloy results as shown in figure 14, the peaks observed for A6061 as 38.905°, 44.83°, 65.608° and 78.790°. It is observed that a small shift in peaks occurred for the fabricated composite at 39.085° and 45.309°.
4. Conclusion

The major findings of the current research are:-

- A6061/B4C composites can be easily made by stir casting technique.
- According to Archimedes principle, the fabricated composite shows higher density than base alloy.
- The actual density of fabricated composites reduces with rise in particle size, wt% B4C and A6061/9%wtB4C with 60µm particle size composite shows the lowest density of 2.5892g/cc.
- The 60µm size 9%wt B4C composite possesses low relative density with respect to base alloy.
- The percentage porosity turns out to be bigger due to wt% of B4C and 6%wt B4C with 30µm size composite shows 1.41% porosity.
- The predicted density of 60µm, 9%wt B4C reinforced A6061/B4C composite with Poisson method gives minimum density of 2.5948g/cc and is nearer to the actual density.
- Rockwell Hardness of composite increases as the particle size increases. The A6061/B4C MMC with 6% wt B4C with 60µm shows a highest hardness of 86HRB. Also 3%wt B4C with 30µm size shows lowest of 69HRB among the nine fabricated composites.
- Microstructure and XRD analysis of the fabricated material indicate that B4C particles are properly dispersed.

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Conflict of interest

None.

Ethical approval
The authors state that the research was conducted according to ethical standards.

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