Density and Void Content Characterization of Stir-Cast Al 6061-Marble Dust Reinforced Metal Matrix Composites

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Abstract. Aluminum alloy 6061 is widely used for its lightweight nature, corrosion resistance, and high mechanical properties. 6061 aluminum is often reinforced with various ceramic materials, including synthetic and waste powders, to enhance these properties further and reduce weight. This study uses the stir-casting fabrication technique to incorporate waste marble dust into Al 6061. The experiment was conducted with three levels of reinforcement percentages (1%, 2%, and 3%) and three stirring durations (10, 20, and 30 minutes). The results indicate that at lower reinforcement levels and longer stirring times, the composite's Density decreases while void content increases.

In contrast, higher marble dust concentrations and extended stirring durations lead to a rise in composite Density. However, the final Density of the fabricated metal matrix composite (MMC) was still lower than that of pure Al 6061. The lowest Density reported at 1 wt% marble dust and 30 min stirring time was 2.1657 g/cc. The maximum void content was also achieved under the same parameters, at 6.14%. The maximum Density of 2.61607 g/cc was achieved using 3 wt% marble dust and a stirring duration of 30 minutes.

Keywords: Metal Matrix Composites, Stir-cast MMC, Marble dust reinforced MMC, Density, Void.

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1. Introduction

A composite material is an engineered combination of distinct matrix and reinforcement phases that remain separate and collectively provide enhanced mechanical or functional properties [1]. These composite materials consist of a matrix

a continuous phase, and another reinforcement, a discontinuous phase. The reinforcements are added to the matrix to improve its properties. The matrix can be metal, polymer, or ceramic; based on this, composites are categorized into metal matrix composites, polymer matrix composites, and ceramic matrix composites.[2]. The reinforcements can be of many types, such as powder, fibers, whiskers, etc. These composite materials are in trend nowadays because adding different materials can achieve tailored properties [3]. The optimal way to achieve the desired mechanical and physical properties in composite materials is through the appropriate addition of reinforcement, which can be incorporated either by weight fraction or volume fraction. The primary goal of reinforcement is typically to enhance the composite's overall strength while simultaneously reducing its Density, thereby creating a lightweight yet strong material. However, it is important to note that this outcome is not guaranteed in all cases.[4]. In some instances, the composite's Density may increase rather than decrease, depending on several factors. These include the specific weight or volume fraction of the reinforcement, the intrinsic densities of the reinforcement and matrix materials, and the manner in which these constituents are combined.

To accurately predict and evaluate the effective properties of composite materials, theoretical models such as the Voigt and Reuss approximations are commonly employed. These models help estimate upper and lower bounds for properties such as elastic modulus, thermal conductivity, and other physical characteristics based on the properties and proportions of the individual phases. The Voigt model assumes uniform strain across all phases and thus provides an upper-bound estimate, while the Reuss model assumes uniform stress and therefore offers a lower-bound estimate [5]. Both the Voigt and Reuss models can be used for metal- or polymer-matrix composites. By combining these models, engineers and materials scientists can better understand and tailor composite behavior for specific applications, ensuring the material performs optimally under desired conditions. [6].

The general applications of composite materials are in aerospace, defense, and marine [7], dental materials [8], bio-medical [9] interior, decorative items, etc. Metal matrix composites, generally abbreviated as MMCs, are a subset of composite materials; as discussed here, the matrix is metal only. Nowadays, Al [10], Ti [11], and Cu [12] are popular matrices for MMCs. The most common reinforcements used in MMCs are carbides, borides, nitrides, and oxides. But nowadays, industrial and agricultural waste, such as fly ash [13] and red dust, is also used as reinforcement in MMCs.

The disposal of waste powders, such as rock powder, marble powder, and quarry powder [13], is a significant problem today. Marble dust is one such waste powder.

This marble dust, if mixed with air, can cause health issues. If it is stored on land, it will make the land infertile, and storing large amounts of marble dust/powder also causes handling issues, which is a significant problem in Rajasthan. Researchers are developing different approaches to address this waste of marble dust. One approach is to mix waste powders with a metal, polymer, or cement matrix to improve the physical, mechanical, thermal, tribological, and overall properties of the resulting

composite. These powders are generally categorized as waste-reinforcement materials. These powders can be added as primary reinforcements or secondary reinforcements. Many studies have been conducted on the mechanical properties of MMCs.

In a study, Gangwar et al. [14] found that incorporating marble dust into a silicon bronze alloy decreased the alloy's Density and increased its porosity. In another study, Habib et al. [15] found that mixing marble dust into Al increased the Density and decreased the porosity. Saini and Singh [16] found that the Density decreased upon mixing GMP into Al4.32 alloy. Folorunso and Owoeye [17] found that the Density of the composite was reduced by adding quarry dust to Za-27 alloy. Veeresh et al. [18] found that Density improved when silicon nitride was added to the Al 6063 alloy. Aherwar et al. [19] observed a decrease in Density upon blending porcelain into Al 7075. In a similar study, Alizadeh et al. [20] found that by adding silicon carbide to the Al 5083, the Density of the composite was enhanced.

This article aims to investigate the Physical properties, such as Density and void content, of the marble dust-reinforced Al 6061 MMC. Stir casting was used as a fabrication technique in this research.

2. Materials and Methodology

2.1 Al 6061 Matrix

Al 6061 is chosen as the matrix material for this research work due to its versatility. The basic constituents of the Al are given in Table 1. The Al 6061 was procured from Mallinath Metals Pvt. Ltd., Mumbai. Al 6061 is a corrosion-resistant metal with decent mechanical properties, a high strength-to-weight ratio, and a high specific modulus of elasticity. Because of all these properties, Al 6061 is mainly used in aerospace applications. The Density of Al 6061 is 2.7 g/cc, and its melting point is between 582 and 652 °C.

Table 1. Basic constituents of the Al-6061 alloy

Elements	Wt%	
	Min.	Max.
Cu	0.15	0.4
Mg	0.8	1.2
Si	0.4	0.8
Cr	0.04	0.35
Mn	0.15	
Fe	0.7	
Other	0.4	
Al	Bal	

2.2 Marble Dust

Waste marble dust was collected from a stone sculpture site as shown in Fig.1 (a). After collecting the waste marble dust, it was cleaned and sieved to 106 µm [21] in a foundry lab at MNIT, Jaipur which is shown in Fig.1 (b). The reason for being specific about particle size is that it affects the properties of the fabricated composites [22]. Table 2 presents the primary constituents of marble dust. The Density of marble dust is almost 2.69 g/cc, and its hardness is 3 on the Mohs scale.

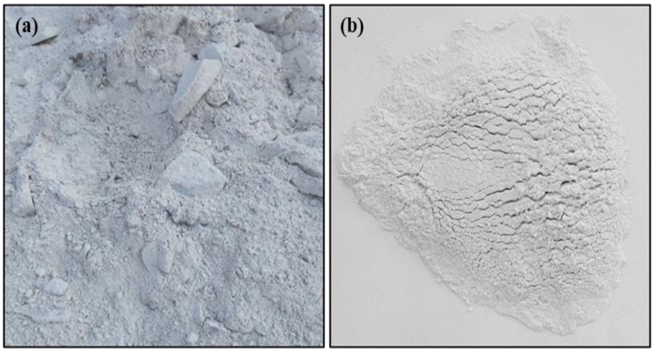

Fig. 1. (a) Marble stone processing site and (b) sieved marble dust to 106 µm.

Table 2. Components of marble dust [23]

Components	CaO	MgO	SiO_2	Al_2O_3	Fe_2O_3
Wt%	42.45	1.52	26.35	0.520	9.40

2.3 Fabrication of the Composite

The stir-casting technique was selected for fabrication due to its ease of use and effectiveness in thoroughly mixing the reinforcement into the matrix using a mechanical stirrer. The stir-casting machine was supplied by Swamequip Pvt. Ltd., an Indian company. The machine comes with a vacuum attachment. Before use, the machine was cleaned for MMC fabrication. A thin graphite coating was applied before heating the furnace. Because graphite is a refractory material, it protects parts such as the stirrer, furnace chamber, and mold from the effects of high temperatures. The machine was preheated to 850°C, and the marble dust was preheated to 250°C to remove its moisture [24]. Marble dust was added at 3 levels (1, 2, and 3 percent by weight), and three stirring durations were 10, 20, and 30 minutes, respectively [25]. Table 3 shows the fabrication conditions for the different wt% of reinforcement and stirring time. Fig. 2 shows a schematic and actual stir-casting machine.

Table 3. Experimental conditions for the fabrication of MMC

Sample no.	**Percentage of reinforcement**	**Stirring duration**
1		10 minutes
2	1%	20 minutes
3		30 minutes
4		10 minutes
5	2%	20 minutes
6		30 minutes
7		10 minutes
8	3%	20 minutes
9		30 minutes

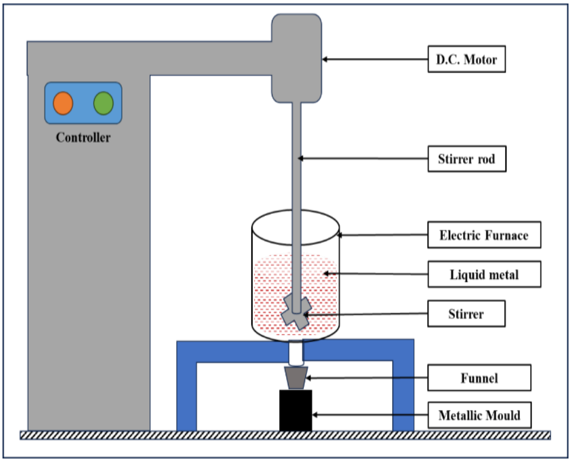

Fig. 2. Schematic and actual Stir-casting machine

3. Experimentation

3.1 Density

The material's Density is an essential factor in determining its properties and mechanical and tribological behavior. The theoretical Density of the material can be calculated by the Rule of Mixtures, which says [1]:

$$\rho_t = \frac{1}{\frac{w_m}{\rho_m}+\frac{w_p}{\rho_p}} \tag{1}$$

Where,

- ρ_t = Theoretical Density
- w_m= The weight fraction of the matrix
- ρ_m= The Density of the matrix
- w_p= The weight fraction of the particulates
- ρ_p= The Density of the particulates

The actual Density of the fabricated samples was measured by the densitometer available in the tribology lab at MNIT Jaipur, shown in Fig. 3. The measured value of the specimen gives the actual Density of the composite by putting it into Archimedes' formula, which is:

$$\rho_c = \frac{\rho_w}{1-\frac{W_f}{W_i}} \tag{2}$$

Where,

- ρ_c = Actual Density of the composite
- ρ_w = Density of the water
- W_f = Final weight of the water
- W_i = Initial weight of the water

Fig. 3. Densitometer tester

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3.2. Void Content

Voids can be formed in the material as a result of agglomeration during the fabrication of the MMC. The discrepancy between the observed actual Density and the theoretical Density that was computed is known as a void. The following formula can be used to determine the percentage of voids[2]:

$$V_c = \frac{(\rho_t - \rho_c)}{\rho_t} \times 100 \tag{3}$$

4. Result And Discussion

4.1 Density

The actual Density was lower than the theoretical Density because the assumptions used in the theoretical calculation do not always hold in practice. Fig. 4 illustrates the difference between the actual and theoretical densities of the produced composite material. The effects of different parameters, such as reinforcement and stirring time, are shown in Fig. 5.

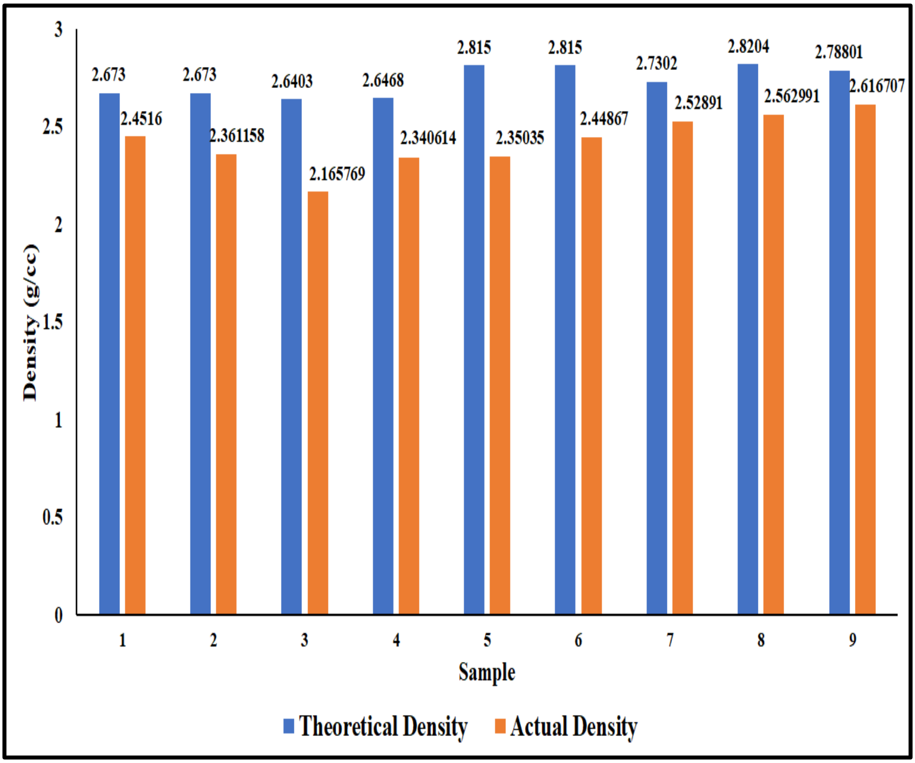

Fig. 4. The comparison between the theoretical and actual Density

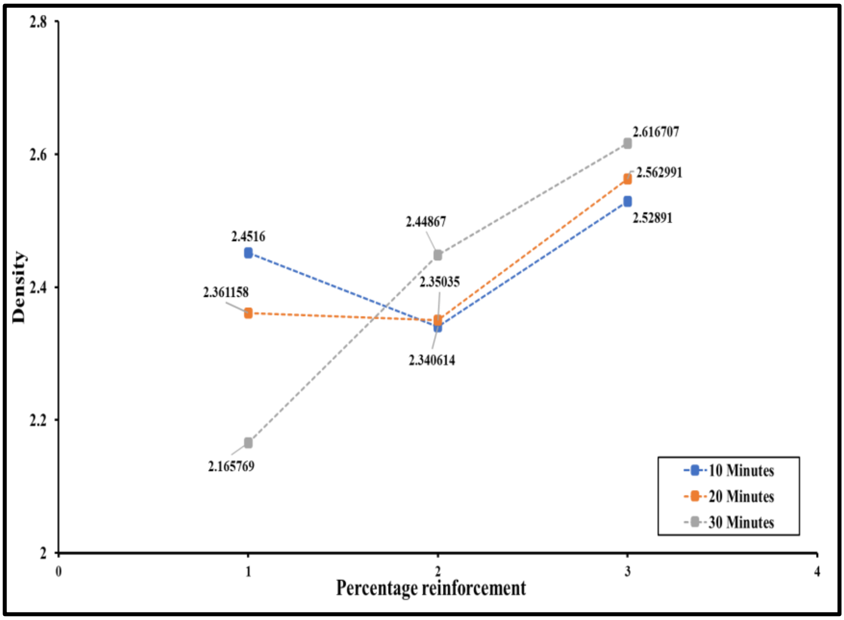

Fig. 5. Density variations at different levels of reinforcement

Fig. 5 illustrates the impact of varying reinforcement percentages on the Density of the fabricated composite at different stirring times. The graph shows that for stirring times of 10 and 20 minutes, the Density initially decreases and then increases as the reinforcement percentage increases. In contrast, for longer stirring times, the Density consistently increases with the percentage of reinforcement. However, the rate of growth in Density is less pronounced when the reinforcement percentage changes from 2 to 3 wt%.

It is evident that, regardless of the stirring time, the Density increases with a higher percentage of reinforcement, likely due to the improved bonding between the matrix and reinforcement material. The effect of stirring time suggests that the reinforcement particles are uniformly mixed. Nevertheless, the increase in Density diminishes with longer stirring times, and the lowest Density of the material is observed at the maximum stirring time of 30 minutes and 1 wt% reinforcement. This reduction in Density at extended stirring times is likely due to the entrapment of air bubbles within the composite material [3].

Although the maximum Density for the 9 was achieved at 2.6167 g/cc, which is close to the matrix density of 2.7 g/cc, this indicates that the mixing and chemical bonding between the reinforcement and the matrix are adequate and strong.

4.2 Void Content Test

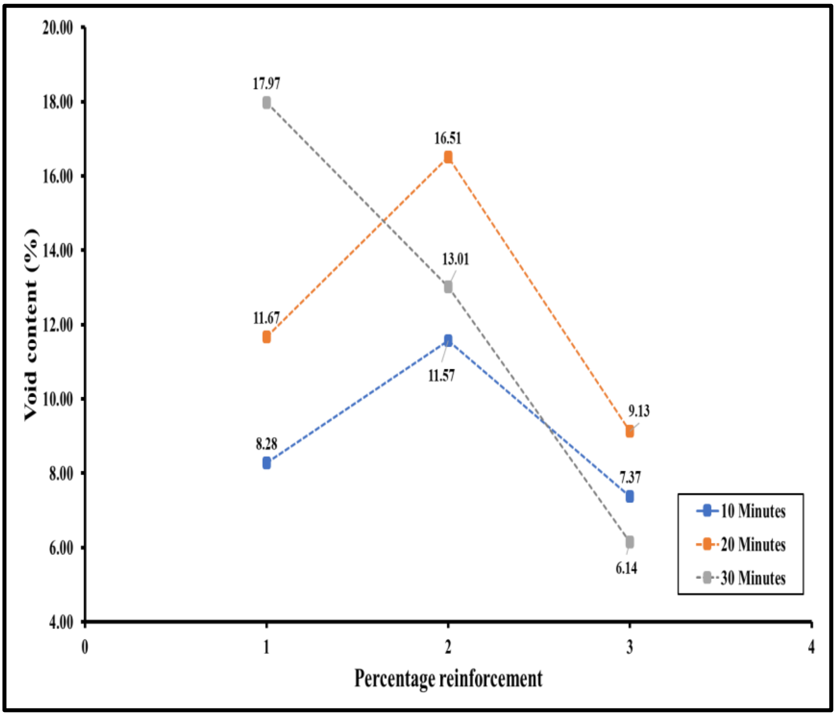

Fig. 6. Void content (%) with increased reinforcement levels and stirring time.

Fig. 6 illustrates the variation in void content (expressed as a percentage) with reinforcement rate, categorized by stirring time. We observe that the void content shows a negative correlation with Density, as expected. For the 10-minute and 20-minute stirring times, the void content initially increases and then decreases as the reinforcement percentage increases. For the 30-minute stirring time, the void content continuously decreases, indicating that mixing is more adequate at longer stirring durations. However, the highest observed void content was 17.97% in sample No. 3, which had 1 wt% reinforcement and a stirring time of 30 minutes. This suggests that air bubble entrapment may occur at longer stirring durations.

5. Conclusions

The Al 6061 was reinforced with marble dust and successfully fabricated using a stir-casting machine. Its physical properties, i.e., density and void content, were tested, and the following conclusions were drawn:

- As the stirring time at a lower percentage of marble dust increases, the Density of Al6061/MD MMC decreases, reaching a minimum of 2.1657 g/cc at 1 wt% marble dust and 30 minutes of stirring time, as observed in sample S3.

- The overall Density of Al6061/MD increases with higher levels of marble dust, peaking at 2.6167 g/cc for 3 wt% marble dust and 30 minutes stirring time, as observed in sample S9. However, the overall Density remains lower than that of pure Al6061, meeting the requirement for a lightweight composite.

- The percentage of void content exhibits an inverse relationship to Density, as expected. The lowest void content, 6.14%, was observed in sample S9, which also had the highest Density.

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