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Due to greater specific strength and stiffness than monolithic metal, aluminum matrix composite is in high demand. The present study investigated the interaction of borosilicate glass powder with the AA7075 aluminum alloy matrix. The lower density of borosilicate glass powder compared to AA7075 alloy makes the composite more appropriate for various industrial applications due to the increased material strength. This study uses the stir casting fabrication process to develop microsized borosilicate glass powder-reinforced aluminum matrix composites. The microstructure shows that borosilicate glass powder is near-uniformly distributed throughout the aluminum matrix. It is observed that the 9 wt (%) borosilicate glass powder-reinforced aluminum matrix composite increases the tensile strength by 40.71%, hardness by 21.21%, and impact strength by 34.37% compared to unreinforced aluminum AA7075 alloy. Pin-on-disc wear testing setup was used to determine the wear performance of the base AA7075 alloy and cast composites. The dry sliding wear test revealed that the glass powder-reinforced composites have better wear resistance properties compared to the unreinforced matrix due to the hard and rigid behavior of borosilicate glass reinforcement.

1. Introduction

Composite fabrication has gained popularity in recent decades because of its lower preparation cost and wide range of applications in the aerospace and automotive sectors [1–3]. The mechanical and tribological properties of the materials can be improved significantly by incorporating reinforcement particles in metal matrix composite compared to the base metal. The developed composite enhances the properties like wear resistance, high thermal and electrical conductivity, and high strength and stiffness [4, 5]. The stir casting technique is the most common process for fabricating aluminum matrix composite among different composite synthesis routes because of its low cost, flexibility, and large-scale production [6–8]. Hashim et al. [9] analyzed the problem associated with the implantation of MMCs on the industrial level and observed that the uniform distribution of reinforcement particles in the metallic matrix is essential. The optimization of process parameters is necessary to achieve a better distribution of reinforcement in the molten matrix. Benal and Shivanand [10] investigated the coefficient of thermal expansion of as-casted matrix and heat-treated hybrid AA6061 aluminum alloy matrix composite reinforced by silicon carbide (60μm) and E-glass fiber.
(2-3 mm). It was observed that the coefficient of thermal expansion increased with increasing the aging duration in both as-cast and heat-treated conditions. Due to the difference in coefficient of thermal expansion between as-cast and heat-treated hybrid aluminum matrix composites, the residual thermal stress is developed.

Mallikarjuna et al. [11] evaluate the impact properties of AA4046 hybrid metal matrix composite by reinforcing different compositions of fly ash and S-glass reinforcement. The stir casting technique is used for the uniform distribution of different particulate reinforcements. It was observed that increasing fly ash and S-glass particles had improved the strength of the composite significantly compared to the base alloy. Dehghan Hamedan and Shahmiri [12] modified the stir casting method for SiC nanoparticles-reinforced A356 alloy-based metal matrix composite. The experimental parameters are optimized with the variation of stirring temperature (650°C, 700°C, 750°C, and 800°C), stirring speed (450 rpm, 700 rpm, and 950 rpm), and type of master powder. Yc and Sankar [13] performed the mechanical characterization of glass powder-reinforced Al6061 matrix composites by variation of powder content and particle sizes. It was observed that adding 9 wt. (%) of glass powder into the AA6061 alloy matrix enhanced the strength and hardness compared to all casted composites. Rao and Parmar [14] analyzed the mechanical properties of glass powder-reinforced aluminum matrix composite (AMC) and observed that the hardness value increased from 24 to 78 BHN and ultimate tensile strength increased from 81 to 110 MPa with the addition of glass powder reinforcement. Jims John Wessley et al. [15] fabricated AA6063/borosilicate glass/fly ash composites and observed that the ductility of the materials decreased by 14% to 17% with the addition of borosilicate glass/fly ash reinforcement. Hiremath [16] fabricated and characterized the hybrid AMC reinforced with borosilicate glass and fly ash. It was observed that borosilicate glass and fly ash reinforcement enhanced the tensile strength of the composite significantly. Rathnaraj and Sathish [17] fabricated various weight percentages of waste borosilicate glass powder-reinforced aluminum matrix composite for aerospace application. Microstructure indicated the uniform distribution of glass powder in the aluminum matrix and significantly improved the mechanical properties of composites.

Sardar et al. [18] fabricated Al7075/Al2O3 aluminum matrix composite and analyzed the wear behavior of the composite. The study showed that the composite has superior tribological properties such as lower wear rate and coefficient of friction when compared to unreinforced alloy because of the presence of hard Al2O3 particles in the composite act as primary load-bearing elements. Sardar et al. [19] further investigated the tribological performance of alumina particles-reinforced Al7075 matrix composite by variation of reinforcement contain. It is observed that the specific wear rates of the materials increase as abrasive particle size increases. Akbari and Asadi [20] investigated the carbon nanotubes-reinforced aluminum matrix composite fabricated by friction stir processing. The study revealed that the wear resistance and hardness of the developed composites are significantly higher than those of the base alloy. Akbari et al. [21] evaluated the mechanical properties of SiC, TiC, ZrO2, and B4C-reinforced aluminum matrix composite by using multiple optimization techniques prepared by friction stir processing and revealed that the TOPSIS technique was used to determine the best compromised solution from the provided Pareto-optimal set. Sardar et al. [22] analyzed the wear behavior of Al2O3-reinforced Al-Zn-Mg-Cu matrix composite and observed that cast composite showed a 50% reduction in wear rate and 25% reduction in friction coefficient as compared to the base matrix material. Sardar et al. [23] also studied the wear resistance phenomenon of 10% and 20% alumina-reinforced aluminum matrix composites by varying applied load, grain size, and sliding distance. The studies revealed that introducing ceramic reinforcement lowered the abrasion wear rate, and composite abraded surfaces always had greater roughness values than the base alloy.

Most of the laboratory uses high-precision glass apparatus manufactured by Borosil Glass Works Ltd. (BGWL), a trending name for borosilicate glass. A considerable quantity of borosilicate glass scraps generates from the laboratories. It was observed that using borosilicate can help to utilize the glass waste and support the environment through proper disposal of those glasses. Contemporary literature indicates that most composites are synthesized using ceramic reinforcement such as SiC, WC, Al2O3, and B4C. However, very limited work was observed on borosilicate glass powder-reinforced metal matrix composite. The borosilicate glass-reinforced aluminum matrix can be used for different structural applications because of its higher strength-to-weight ratio. In the present study, AA7075 alloy is reinforced with different compositions of borosilicate glass powder using a stir casting process, and the mechanical and tribological properties are experimentally evaluated.

2. Materials Selection

Extruded AA7075 is used as the matrix material in manufacturing different components for the automobile and aerospace industries. The chemical composition of AA7075 aluminum alloy is presented in Table 1. Borosilicate glass is a special kind of glass with silica and boron trioxide as the primary glass-making component. Borosilicate glass is recognized for having lower coefficients of thermal expansion and is about 1/3 the cost of ordinary soda-lime glass. The resistance to thermal shock of borosilicate glass is higher compared to other common glass. There is a drag in separating waste and recycling glass in developing countries like India. Borosilicate glass powder can be used as a substitute for carbide and oxide reinforcement. In glass powder reinforcement, the presence of SiO2 readily interacts with molten aluminum and forms an intermittent bond.

Borosilicate glass scraps are collected from different scientific laboratories and subsequently cleaned, crushed, powdered, and collected in 38–53 μm particle size. The density of borosilicate glass (2.3 gm/cc) is lesser than AA7075 aluminum alloy (2.7 gm/cc). So, it will help in reducing the overall weight of the final composite. The
chemical composition of collected borosilicate glass powder is presented in Table 2. The AA7075 alloy matrix was reinforced with 0, 3, 6, and 9 wt. (%) with borosilicate glass powder to evaluate the tribological and mechanical properties of the composites. The cast borosilicate powder-reinforced AA7075 matrix composites are indicated as A-0, AG-3, AG-6, and AG-9 for 0, 3, 6, and 9 wt. (%) reinforcement borosilicate glass powder.

### 3. Experimental Procedure

The stir casting technique has recently been the most commonly used liquid state composite fabrication method for high-volume structural components. Factors affecting the stir cast process are stirring time, stirring temperature, stirring speed, reinforcement percentage, and reinforcement size. A schematic diagram of the stir casting setup is shown in Figure 1. Initially, the AA7075 aluminum alloy block melted in a graphite crucible with the help of an induction furnace. Glass powder reinforcement was preheated in a muffle furnace at 450°C to reduce oxides and moisture present. At 750°C melting temperature, the molten slurry was poured into the steel die (100 × 40 × 10 mm³). A permanent die for pouring the molten composite is also preheated at 400°C to reduce cracks and shrinkages. Magnesium 2 wt. (%) was added to the molten matrix to enhance the bonding strength between the AA7075 matrix and borosilicate glass reinforcement particulates. Borosilicate glass powder reinforcement was added to the molten AA7075 and stirred at a stirring speed of 300 rpm for 10 minutes. Then, the molten composite was poured into the steel die to fabricate the cast block.

The cast composite was cut as per the required dimension to analyze the microstructural and mechanical properties. For the microstructural study, the sample was polished with different grades of emery papers, followed by cloth polishing and etching. Tensile specimens were pre-fabricated according to ASTM E08 standard, and the image of the tensile test sample is shown in Figure 2. The tensile test of the sample was performed using HEICO HLC 693-35 testing machine with a cross-head velocity of 0.5 mm/minute. Vickers microhardness tester is used to measure the hardness of the composite with an applied load of 3 kgf and dwell time of 15 seconds as per ASTM E384 standard. The hardness is measured four times for each sample, and the average hardness values are presented. The impact testing sample was prepared as per the ASTM E23 standard and performed using the Charpy impact testing machine. Five specimens for each composition are measured, and the average impact strength values are presented in the present study. A dry sliding wear test was performed using a pin-on-disc wear testing setup. The samples are cleaned properly with acetone before each test. For the wear test, cylindrical samples were prepared with a diameter of 6 mm and length of 40 mm. The pins are rubbed against an EN31 steel plate whose hardness is 62 HRC per ASTM G99 standard at different applied loads.

### 4. Results and Discussions

#### 4.1. Density and Porosity Measurements

Density and porosity content for various weight percentages (0, 3, 6, and 9 wt. (%)) of borosilicate glass powder-reinforced AA7075 matrix composites fabricated by the stir casting method. The theoretical density of casted composite was calculated by using the rule of the mixture as indicated in Equation (1), and the actual density of casted composite was measured using the Archimedes principle. A graphical representation of density variation is shown in Figure 3(a). It is observed that actual density decreased with increased borosilicate glass powder content. The void content of the composite is calculated using the theoretical density as per Equation (2)

\[
\Delta_t = (\Delta_m \times \text{wt. %}) + (\Delta_r \times \text{wt.%}),
\]

where \(\Delta_t\), \(\Delta_m\), and \(\Delta_r\) denotes theoretical density, matrix material density, and reinforcement density of the composite.

\[
\text{Void content(\%)} = \frac{\Delta_t - \text{Actual density}}{\Delta_t} \times 100.
\]

The variation of porosity content of casted composite is depicted in Figure 3(b). It is observed that the void content of AG-3, AG-6, and AG-9 is increased by 20.89%, 24.89%, and 30.47%, respectively, compared to the AA7075 aluminum alloy matrix (A-0). It is observed that higher weight percentages of reinforcement particles and stirring speed of the melt have enhanced the number of air bubbles swirling into the melt [28, 29]. The void content in the composite is increased due by the addition of ceramic reinforcement and by increasing the stirring speed. The agglomeration of reinforcement in the matrix also enhances the void content of the composite [30, 31].

#### 4.2. Mechanical Characterization

The variation of microhardness with an increase in borosilicate glass reinforcement content is shown in Figure 4. It is evident from the figure that the microhardness of the material is increased by 8.33, 13.16, and 17.50% by the addition of 3, 6, and 9 wt. (%) of borosilicate powder, respectively. This may be due to an increase in the resistance to indentation and plastic deformation of the borosilicate glass powder-reinforced composite. As per the Hall–Petch relation, refining granular size may enhance the grain boundary region, enhancing the pickup of dislocation effort, which improves the hardness of the composite [24, 32].

### Table 1: Chemical composition of AA7075 alloy (reproduced from Bhowmik et al. [24]).

<table>
<thead>
<tr>
<th>Elements</th>
<th>Cr</th>
<th>Fe</th>
<th>Si</th>
<th>Mg</th>
<th>Mn</th>
<th>Cu</th>
<th>Zn</th>
<th>Ti</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt. (%)</td>
<td>0.21</td>
<td>0.22</td>
<td>0.04</td>
<td>2.58</td>
<td>0.03</td>
<td>1.65</td>
<td>5.75</td>
<td>0.03</td>
<td>Balance</td>
</tr>
</tbody>
</table>

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The ultimate tensile strength and percentage elongation of the AA7075 alloy and cast AA7075/borosilicate glass powder-reinforced composites is shown in Figure 5. It is observed that UTS increased from 140 to 197 MPa with increasing the weight percentage of borosilicate glass powder reinforcement. The tensile strength of the material is increased due to a hindrance to the dislocation movement because of the smaller interparticle spacing. In plastic flow, coarse grain materials are quicker than fine grain materials that withstand fracture stress and impart ductility [33–35]. Contact between the dislocation and the reinforced particles prevents cracking under tensile stress and improves the interfacial connection between the borosilicate glass powder reinforcement and the AA7075 matrix. Elongation of glass powder-reinforced composites has decreased by 19.35, 38.71, and 67.74% by adding 3, 6, and 9 wt. (%) of glass powder reinforcement, respectively.

Impact strength is measured to analyze the capacity of a metal to resist dynamic loading. The variation of impact strength for the base AA7075 alloy and cast AA7075/borosilicate glass powder-reinforced composites is shown in Figure 6. It is observed that the impact strength of composites is increased with the addition of glass powder reinforcement due to superior interfacial bonding between aluminum matrix and borosilicate glass powder reinforcement.

4.3. Microstructural Evaluation. Figure 7 shows the FESEM micrographs and EDX analysis of as-cast AA7075 alloy and 3, 6, and 9 wt. (%) borosilicate glass-reinforced composites. The EDX of AA7075 alloy shows the presence of the aluminum phase along with the other alloying element phases, as shown in Figures 7(a) and 7(b). Micrographs of 3, 6, and 9 wt. (%) borosilicate glass powder-reinforced AMC shows the dispersion of the reinforcement with mild agglomeration as depicted in the FESEM micrograph shown in Figures 7(c), 7(e), and 7(g). The casting defects, such as metal shrinkages due to thermal contraction and reinforcement agglomeration, are observed in the FESEM micrograph. The micrograph also indicates the presence of glass powder particulates in the intragranular areas.

Density variation between AA7075 matrix and borosilicate glass powder reinforcement plays a vital role in reinforcement distribution due to adequately mixing [36]. Figure 7(c) depicts the fusion of some borosilicate glass powder during composite synthesis. Less aggregation of reinforced particles decreases viscosity, revealing a greater quantity of dross bound to the surface deck [37]. Figure 7(e) shows the formation of pores and reinforcement agglomeration in composite due to higher viscosity. Three-dimensional forces developed during stirring are highly invaded due to stirring speed. The force formed during the synthesis of composite in a shear flow shows in Equation (3). Stiff agglomeration particles cause shear stress inside the fluid, which aids in particle separation and homogenization.

\[ F = 6\pi\mu r^2\alpha, \]  

where \( r \) = radius of glass powder reinforcement in agglomeration, \( \mu \) = viscosity of the melt, and \( \alpha \) = shear rate in a neighboring liquid medium.

Deep blow holes are observed in Figure 7(g) that impact on mechanical properties of the developed composite. Blowholes are basically formed due to inappropriate cooling that can be solved by appropriate stirring speed [38]. Figure 7(g) also exhibits maximum agglomeration of reinforcement with low nucleation during AA7075/borosilicate glass powder composite synthesis due to the higher reinforcement content. It may be reduced by enhancing the temperature of the melt during stirring [39]. EDX analysis is carried out and shown in Figures 7(d), 7(f), and 7(h) to analyze the elements present in AA7075/(3, 6, and 9 wt. (%)) borosilicate glass powder composites.

4.4. Fractography. The fracture surface of the tensile samples was analyzed using a scanning electron microscope to analyze the fracture behavior. Figure 8 shows SEM...
micrographs of the tensile fracture surface of (a) Al7075 alloy matrix and (b) Al7075/9 wt. (%) borosilicate glass powder-reinforced composites. Deep equiaxed dimples were observed in unreinforced Al7075 alloy, indicating the ductile mode of fracture. The fracture surface indicates the formation of microvoids during the tensile plastic deformation on the fracture surface of the samples. The dimple structure on the fracture surface with the cup-like shape shows the ductile mode of fracture of Al 7075 alloy matrix. Microvoids were formed on the fracture surfaces during tensile loading due to local stress by plastic deformation. Shallower dimples are shown in Figure 8(b), indicating the ductile character of the glass powder-reinforced aluminum matrix composite; however, the size of the dimple decreased due to a decrease in the ductility of the materials.

4.5. Wear Behaviour. The dry sliding wear behavior of the material is performed using a pin-on-disc wear testing setup. The wear resistance of the material gives a clear idea about whether the material is suitable for the particular wear application. Figures 9 and 10 show the variation of wear rate and specific wear rate of glass powder-reinforced AMC with the variation of applied load (10, 20, 30, and 40 N) at a fixed sliding velocity of 2 m/s and sliding distance of 2000 m. During the wear test, the hard asperities of the counter plate
plow the materials from the pin surface at the beginning of the sliding and forms scratches, and gradually peaks and valleys were formed on the contact surface of the materials. During the wear test, the wear debris is stocked in the valleys of the contact pin surface. This sticking of softer pin materials on the counter surface of the plate plays an important role in determining the wear behavior of the material [40, 41]. From the graph, it can be observed that the wear rate of the AA7075 matrix is higher as compared to borosilicate glass-reinforced composites. It was observed because the addition of glass particulates reinforcement in the AA7075 alloy matrix enhances the mechanical properties like hardness and strength of the material. In addition, the wear resistance increases due to the oxide formation and strain hardening. The wear rate of the materials also increased with an increase in applied load on the pin sample. The increase in contact temperature due to the sliding frictional heating is the primary reason for the increased wear rate of the material.

The coefficient of friction of AA7075 alloy and cast composite at different applied load conditions is shown in Figure 11. The coefficient of friction was observed to be decreasing with an increase in the reinforcement contain. It was observed due to the lesser number of junctions present at the contact surface with an increase in the borosilicate reinforcement contained. It is also observed that the
Figure 7: FESEM micrographs and EDX analysis of (a, b) AA7075 alloy, (c, d) AA7075/3 wt. (%), (e, f) AA7075/6 wt. (%), and (g, h) AA7075/9 wt. (%) borosilicate glass composites.
coefficient of friction reduces significantly with enhancing applied load. It could be caused by an increase in the friction surface between the pin and the rotating disc [42, 43].

4.6. Worn Morphology. Micrograph of the worn surface of borosilicate glass powder-reinforced aluminum matrix composite with the variation of applied load depicted in Figures 12(a)–12(d). Harder asperities turn into abrasive particulates and stimulate three-body coarse wear observed due to plowing and microcutting mechanisms of the surface material [44]. It was observed that the porosity formed in the materials acts as stress concentrators and affects the massive strain that occurred on the pin surface. The void initiates the crack and gradually grows the crack in different places on the surface [45]. The surface materials were removed due to this, and surface fatigue destruction occurred on the contact surface. Burned patches are also observed on the worn surface of the material, as shown in Figure 12(b). The burned
spot was formed due to the high flash temperature at the contact surface for the higher sliding distance. A secondary layer is evident at higher weight percentages of borosilicate glass powder-reinforced composite, depicted in Figure 12(c). At a higher applied load, some shallower pits are observed on the contact surface caused by dislocating the surface material [36]. It can be observed from the micrographs that the primary surface is protected from sliding along with the formation of the tribo-layers, as shown in Figure 12(d).

5. Conclusions

Following conclusions can be drawn from the present study for the development of Al7075/borosilicate glass-reinforced aluminum matrix composite by stir casting process within the current experimental domain.

(i) Al7075/borosilicate glass powder-reinforced aluminum matrix composite is successfully synthesized using the stir casting process with 3, 6, and 9 wt. (%) borosilicate glass particulate reinforcement.

(ii) The cast Al7075/borosilicate glass composite has a lower overall density due to the lower density of borosilicate glass powder compared to the aluminum 7075 alloy matrix. Al7075/borosilicate glass-reinforced aluminum matrix composite void content increased from 20.89% to 30.47% as reinforcement content increased.

(iii) The hardness, ultimate tensile strength, and impact strength of the materials increased by 17.5%, 28.93%, and 34.37%, respectively, by the addition of 9 wt. (%) borosilicate glass powder reinforcement.

(iv) A microstructural study revealed that the borosilicate glass powder is near-uniformly dispersed in the AA7075 alloy matrix. EDX analysis clearly indicates the presence of borosilicate glass powder in the aluminum matrix composite.

(v) The wear rate significantly decreases with increase in borosilicate powder reinforcement contains. The wear rate increases and the friction coefficient decreases with an increase in applied load during sliding wear of the materials. FESEM micrograph of the worn surface indicates the formation of pits, burned surfaces, secondary layer, and tribo-layer.

Abbreviations

AMC: Aluminum matrix composite
MMC: Metal matrix composite
References


FESEM: Field emission scanning electron microscope
UTS: Ultimate tensile strength
EDX: Energy dispersion X-ray spectroscopy
ASTM: American Society for Testing and Materials
COF: Coefficient of friction.

Data Availability
The datasets generated during and/or analyzed during the current study are available from the corresponding authors and are part of the upcoming study.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

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