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Development and Performance analysis of Novel Cast AA7076-Graphene Amine-Carbon Fiber Hybrid Nanocomposites for Structural Applications

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Abstract: Lightweight aluminum metal matrix nanocomposites play an important role in aerospace, military, automotive, electricity, and structural applications due to their improved mechanical, physical, and tribological properties. The hybrid nanocomposites were made using a motorized stir casting technique to achieve the desired mechanical properties. The composites were made using a mixture of graphene amine and carbon fibers in various weight proportions. The hybrid nanocomposites were created by varying the weight percentage (wt.%) of reinforcements in the AA7076 base matrix, such as 0.5wt % carbon fiber (micro filler) and 0.5wt % graphene (nanofiller). X-Ray Diffraction (XRD) and scanning electron microscopy (SEM) were used to investigate the homogeneous distribution of the fabricated hybrid composite. The mechanical properties of the hybrid composites were assessed using hardness and tensile measures. The composite with 1wt. percent reinforcements had a 50 percent increase in hardness and a 42 percent increase in tensile strength as compared to the base AA7076 matrix content. The wear tests were conducted using a pin-on-disc tribo tester, and the results showed that the hybrid composite (1wt.%) outperformed the AA7076 matrix material in terms of wear resistance.

Keywords: lightweight; nanocomposites; hybrid; mechanical properties; tribological behavior.

1. Introduction

Aluminum is the most favorable metal for manufacturing metal matrix composites (MMCs) due to its outstanding fabrication technique and engineering properties [1]. Metal matrix nanocomposites (MMNCs) are synthesized through various routes like stir casting, friction stir processing, ball milling (powdered form), etc. Aluminum-based metal matrix nanocomposites (AMMNCs) have gained prominence due to their excellent mechanical properties such as tensile strength, ductility, hardness, toughness, and wear resistance properties [2]. The lightweight aluminum matrix composites are used in marine, aircraft, and structural applications due to their excellent properties. Although the properties of the MMCs have been more effective by the incorporation of micro and nanomaterials such as fillers into the base matrix. The addition of reinforcement fillers would give an added advantage to the fabricated products. The various types of micro and nano reinforcements include silicon carbide (SiC), alumina (Al_2O_3), fly ash, carbon fibers, graphite, graphene amine, MWCNTs, and carbon fibers have been used as fillers in the base aluminum matrix to form a composite. The composites produced by combining more than one reinforcement (micro and nanofillers) are referred to as hybrid composites [3]. Hybrid composites primarily consist of one matrix and more than one reinforcement. In terms of mechanical, physical, electrical, and tribological properties, hybrid composites play a critical role in achieving the requirements in the fields of aerospace, vehicle, and structural applications. The hybrid composites were found to have higher tensile strength, impact strength, hardness, and wear resistance properties as compared to the conventional aluminum matrix composites (AMCs) [4-5]. According to the literature, adding reinforcements to a composite improves its mechanical and tribological properties. The properties of hybrid composites are improved, making them suitable for automotive, aerospace, and structural applications [6-7].

Kannan *et al.* have studied the mechanical and microstructural characterization of AA7075 nanohybrid nanocomposites. They had used alumina as the nanofillers and silicon carbide as the micro fillers. The results revealed a significant improvement in the hybrid composite's mechanical properties compared to the parent aluminum alloy AA7075 [8]. Prasad Reddy *et al.* [9] have fabricated hybrid metal matrix nanocomposites using Al6061 alloy and silicon carbide as micro filler and graphite as the nanofiller in a different composition. The investigation discovered a uniform distribution of silicon carbide and graphite nanoparticles. The addition of reinforcements increased the wear resistance of the hybrid composite, lowering the coefficient of friction [10]. Rajmohan *et al.* [11] have synthesized and characterized aluminum hybrid composite with micro silicon carbide particles and nano copper oxide (CuO) by a sintering process. The mechanical properties of the developed hybrid metal matrix composite improved by adding nano CuO particles in the matrix. Saurabh Bidari *et al.* [12] have fabricated aluminum metal matrix nanocomposites using multi-walled carbon nanotubes (MWCNTs). According to the test results, the addition of reinforcements increased the nanocomposites' hardness and tensile strength [12]. Jiangshan *et al.* [13] used a milling method to create an aluminum graphene composite. According to the test results, the hardness of the composites increased by 115 percent compared to the parent aluminum alloy. In this step, graphene nanosheets were used as reinforcements. The addition of hard graphene nanosheets to the composite strengthened the composite's hardness [14, 15-24].

The present investigation emphasizes enhancing the mechanical and tribological properties of the hybrid composite by the addition of graphene amine and carbon fiber reinforcements (micro and nano form) into the AA7076 alloy. In this present investigation, the motorized stir casting technique is used to fabricate the hybrid composite. According to the test results, the addition of graphene amine and carbon fiber reinforcements to the AA7076 alloy matrix strengthened the composite's mechanical and tribological properties.

2. Materials and Methods

The matrix material in this analysis was the AA7076 alloy, and the micro-fillers were carbon fiber. Graphene was chosen as the nanofiller because of its excellent thermal, electrical, and mechanical properties. Graphene has a very high melting point of around 3600 °C as well as high thermal conductivity, which makes it a suitable nanofiller to be used in metal matrix composites. The chemical composition of AA 7076 alloy is mentioned in Table 1. Graphene amine was procured from United Nanotech Innovation Pvt. Ltd, Bangalore, India. Hybrid reinforced nanocomposites were created using a base matrix containing 0.5 weight percent nanographene amine particles and 0.5 weight percent micro carbon fiber particles. The hybrid composites were made using an automated bottom pouring style stir casting technique. The stir casting machine was procured from Svaksha thermal equipment's Chennai, Tamil Nadu. The alloy was cut into pieces and weighed. Around 1.3 kg AA7076 alloy was heated and melted in the induction furnace, as shown in figure 1. Preheating of the graphene as well as carbon fibers was carried out in the preheater chamber. The preheat temperature was maintained at around 300 °C. After the preheating was carried out, the reinforcements were introduced into the furnace. Initially, the nanofillers were introduced, and then the micro fillers were introduced. Stirring was done with the help of a stainless-steel stirrer which was attached to the motor. The movements of the motor were controlled by an interface. The stirring speed was maintained at 400 rpm throughout the fabrication process. Uniform dispersion of the nano and micro fillers was ensured by vortex formation in the crucible during stirring. During the fabrication process, magnesium was added to increase the wettability of the melt. Later the bottom part of the furnace was opened, and pouring was carried out into the preheated metallic mold so that sudden solidification does not take place [25]. The developed composites were taken from the mold for sample preparation. Table 2 gives the physical gist of the micro and nanofillers used in the fabrication of hybrid composites.

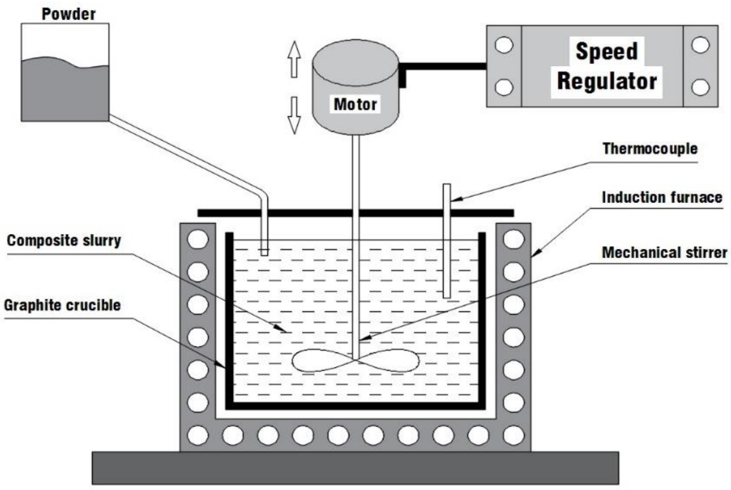


Figure 1. Schematic diagram of stir casting setup.

Table 1. AA7076 alloy chemical composition.

Composition	Zn	Mg	Fe	Cu	Mn	Si	Ti	Al
AA 7076	7.0	1.2	0.4	0.5	0.5	0.3	0.1	Balance

Table 2. Physical gist of reinforcements.

Reinforcement	Magnetic point	Purity	Density	Grain size
Carbon fiber	3652 °C	> 98%	1.8 g/cc	8 to 10 μm
Graphene	3600 °C	> 99%	0.24 g/cc	2-4 nm

3. Results and Discussions

The work is divided into two parts in the findings and discussion section. The microstructural properties of the AA7076/carbon fiber and graphene amine reinforced composites fabricated using the bottom pouring style stir casting technique are explained in the first section. The mechanical properties of hybrid composites are explained in the second section.

3.1. The microstructure analysis of AA7076/carbon fiber and graphene amine hybrid composite.

Figure 2 and 3 shows the microstructure and EDS spectra of the hybrid composites. It can be observed from the figure that the distribution of nanofiller graphene as well as micro-fillers carbon fiber can be seen in the microstructure. Although the fibers are visible, there is an agglomeration of the particles due to the addition of both reinforcements [26]. Dispersion of the reinforcements in a metal matrix is a great challenge as there is a variation of density between the reinforcements and the matrix. Figure 3(b) also shows the energy dispersive spectroscopy in which various elemental mapping of the constituents can be done. The presence of carbon signifies the presence of carbon fiber and graphene reinforcements [27-28].

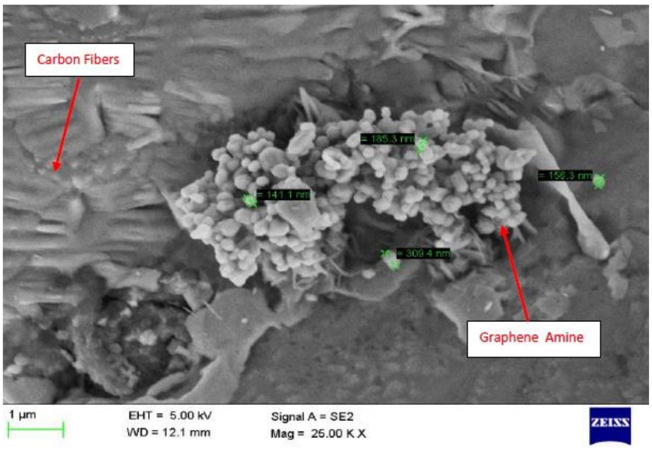
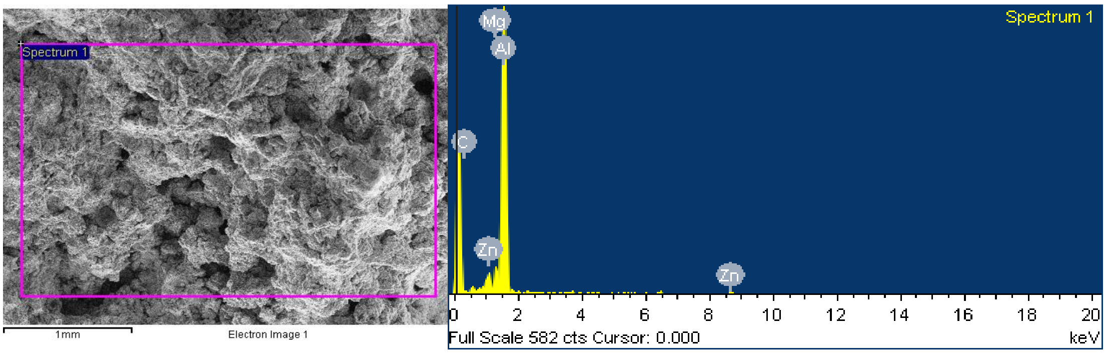


Figure 2. FESEM Micrograph of AA7076 and carbon fiber/graphene amine hybrid composite.



(**a**) (**b**)

Figure 3. (**a**) SEM; (**b**) EDAX Analysis od hybrid composite.

3.2. Mechanical properties of a hybrid composite made of AA7076, carbon fiber, and graphene amine.

The samples were prepared for different mechanical tests such as hardness, wear, and tensile test according to the ASTM standards. Figure 4 shows the results of the Vickers hardness test conducted on the specimens. It can be observed that the hardness number kept on increasing with the increase in dosage of the nano as well as micro fillers up to 1 wt.%. After that, there is a decrease in the hardness value of the hybrid composite, which can be observed from Figure 4 [29]. The reason behind this might be that ductility might have reduced for the hybrid composite after a certain amount of reinforcement being used in the matrix.

Precipitation hardening of the hybrid composite might be one of the reasons as well. The depth of indentation was also increased by an increase in the dosage of the reinforcements.

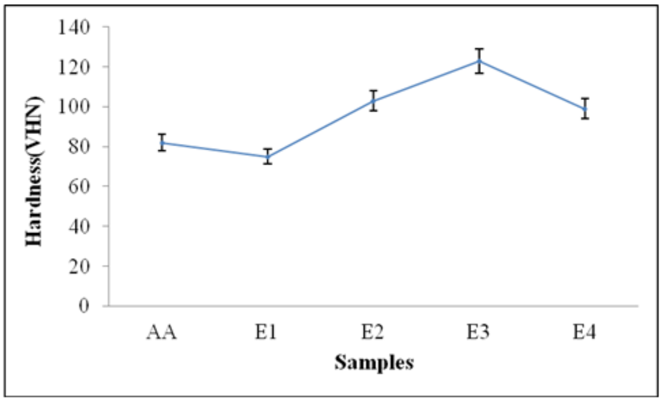
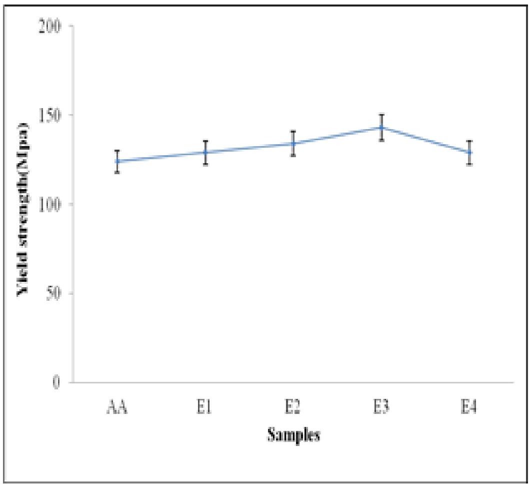
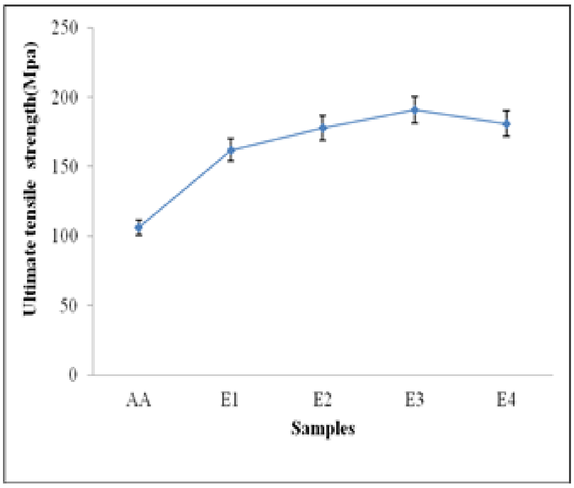


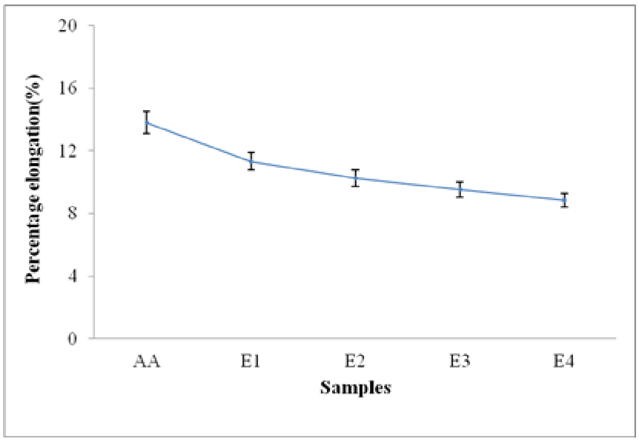
Figure 4. Hardness of the hybrid composite.

Figure 5(a,b and c) compares the yield strength, ultimate tensile strength, and percentage elongation of the AA7076/graphene amine /carbon fiber hybrid composite to the base AA7076 matrix alloy. It can be observed from the graph that up to 1 wt% of the reinforcements used in the hybrid composite, the yield strength and ultimate tensile strength are increased. However, after 1%, the composite's strength begins to deteriorate. Although tensile strength has increased, there is a reduction in the percentage elongation of the hybrid composite; this can be observed in Figure 5(b). As the reinforcements in the base matrix alloy agglomerated, the tensile strength of the hybrid composites decreased.





(a) (b)



(c)

Figure 5. (**a**) Yield strength; (**b**) Ultimate tensile strength; (**c**) Percentage elongation of the hybrid composites.

3.3. Fracture surface analysis.

Figure 6 depicts the SEM tensile fracture surface morphology of the AA7076 matrix with grapheme and carbon fiber reinforcements.

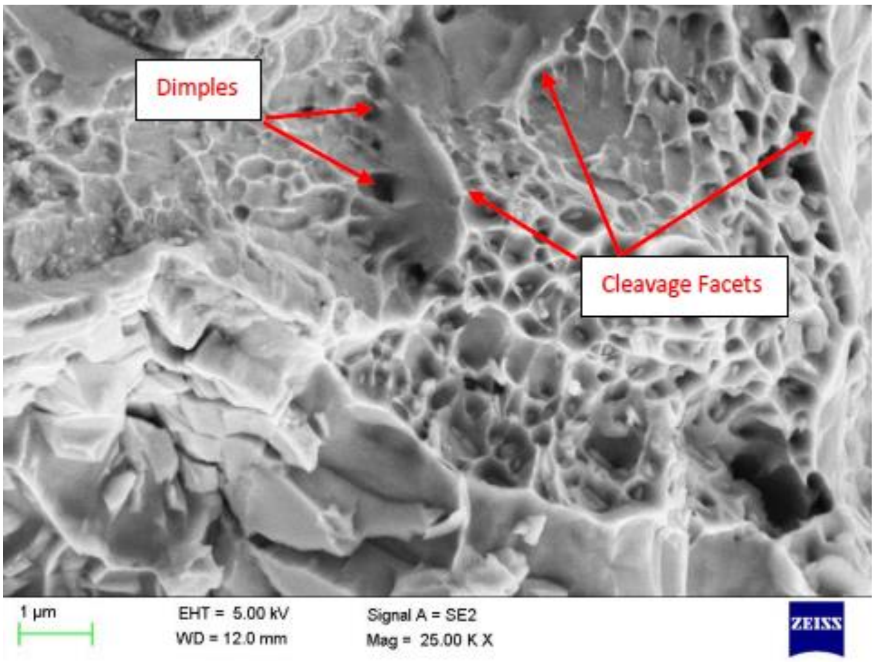


Figure 6. SEM micrograph of the fracture surfaces of tensile specimens for hybrid composite with graphene and carbon fiber reinforcements.

The tensile fracture morphology observations from Figure 6 depict the formation of interdendritic cracking. However, the hybrid composite with 1 wt.% graphene and carbon fiber reinforcements shown in Figure 6 depicts that the fracture surface appears dimples. The formation of dimples may be due to nucleation of voids and shear deformation.

3.4. Wear test.

A pin-on-disc test apparatus was used to determine the dry sliding wear characteristics of composite specimens. The specimen preparation for the wear test was carried out according to ASTM G99 standards using a DUCOM pin on the disc wear test apparatus. The specimens were thoroughly cleaned before conducting the examination. One end of the specimen was marked for the process in which, before and after the test, specimens were weighed with a digital weighing machine. The wear test parameters considered according to the literature in the study were as follows:

Weight percentage of – graphene (nano filler) + carbon fiber (micro filler) (0.5, 0.75,1 and 1.5 Wt.%).

Applied load (10, 20 and 30 N).

Sliding velocity (1.51 m/s, 2.92 m/s and 4.34 m/s).

3.5. Influence of varying load on wear rate.

In this case, the parameters considered for varying load were sliding distance: 750 meters, track diameter: 90mm.

Table 3. Wear details for varying load conditions

	Varying Load		
	Wear rate in mm^3/m		
Wt.% of Graphene + Carbon fiber	10 N	20 N	30 N
0(AA)	2.91E-03	3.82E-03	3.82E-03
0.5(C1)	2.761E-03	3.34E-03	4.19E-03
0.75(C2)	2.42E-03	2.84E-03	3.87E-03
1(C3)	2.049E-03	2.79E-03	3.47E-03
1.5(C4)	1.79E-03	2.50E-03	2.80E-03

Table 3 shows the variation in wear rate of the composite prepared with various weight percentages of Nano particulates added under different loading conditions of 10, 20, and 30N. In this condition, the two other parameters, like sliding distance and sliding velocity, are kept constant at 750m and 2.92 m/s, respectively. For all the wear rate analyses, the disc diameter was unchanged to 90cm. From Table 3, it is clearly observed that as the percentage of the reinforcement increases, the wear rate decreases correspondingly [30-36]. Even at higher loads, the wear rate exhibits a complete decrement without any variation. As the load increases, the pin's pressure on the disc is also increased, which results in a higher wear rate [37]. The presence of hard ceramic particulates collected at the matrix's boundary region allows the composite to withstand the strain. The worn-out surfaces of the composite samples subjected to SEM observation are shown in Figure 8 (a and b), which show no formation of an oxide layer in the wear direction. When stress is applied to the specimen, adhesive wear appears on the sample surface.

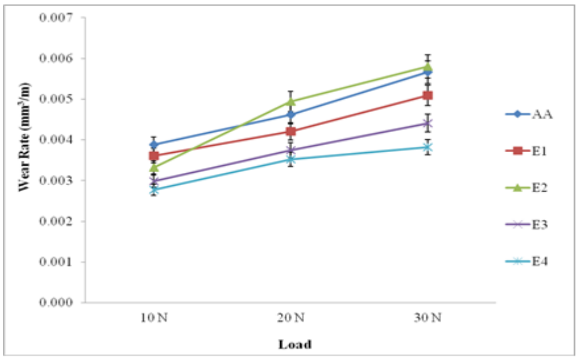
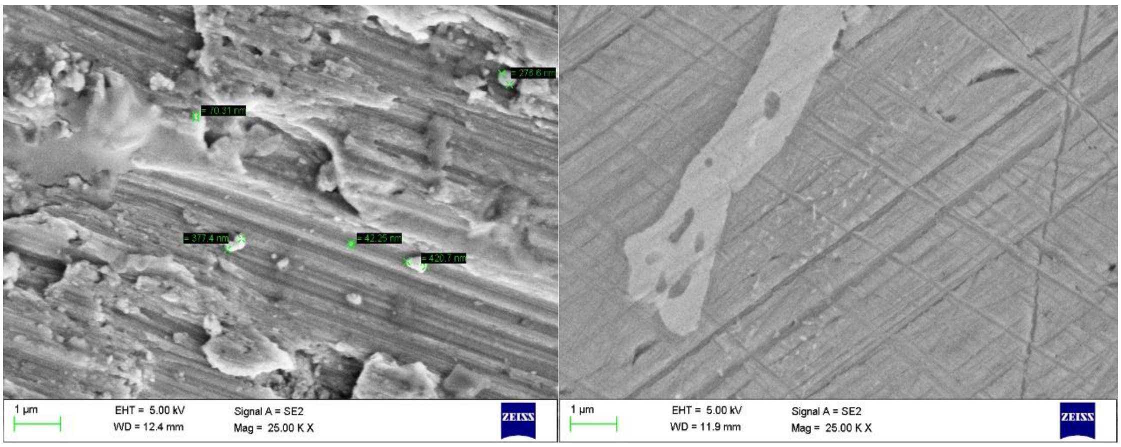


Figure 7. Variation of wear rate for different weight percentages of the composite at different loading conditions.



(**a**) (**b**)

Figure 8. Micrographs of the worn-out surface of the AA7076 matrix with (**a**) graphene and **(b)** carbon fiber reinforcements.

Figure 8 (a) and (b) displays the microstructure of the hybrid composite's worn-out surface as determined by a dry sliding pin on a disc tribo tester. It can be noticed that the AA7076 matrix hybrid composites show larger grooves and deform plastically. This shows the formation of adhesive wear and generates the maximum amount of frictional heat during dry sliding wear.

4. Conclusions

A motorized stir casting technique was used to fabricate AA7076/carbon fiber and graphene composites successfully. The uniform dispersion of nano and micro fillers of particles in the base aluminum matrix was shown by SEM micrographs. The hybrid composite with 1wt.% reinforcements had a 50 percent increase in hardness and a 42 percent increase in tensile strength compared to the AA7076 matrix content. According to the wear test results, the hybrid composite (1wt.%) had better wear resistance than the AA7076 matrix material.

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Conflicts of Interest

There are no potential conflicts of interest for the writers to disclose. There are no financial interests to mention, and all co-authors have seen and agreed with the manuscript's contents.

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