# Investigation on Tribological Characteristics of Al 7075 MMNC: Behavior of Micro- and Nano-Sized Composites

Sonagiri Suresh[1,*], Baridu Vinod[1], Sangireddy Sunil Kumar Reddy[1], Uthirapathi Elaiyarasan[2]

[1]Department of Mechanical Engineering, Siddharth Institute of Engineering & Technology, Puttur, India

[2]Department of Automobile Engineering, Easwari Engineering College, Chennai, India

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## Abstract

This study investigates the mechanical properties and the wear behavior of Al 7075/$Al_2O_3$/SiCNP composites. The hybrid composites are manufactured using the stir casting technique. In this work, the Al 7075 alloy is reinforced with five different weight fractions of $Al_2O_3$ and a constant SiCNp, with an average particle size of 50 nm. The aluminum metal matrix composites are examined through surface morphology and X-ray diffraction (XRD) patterns to identify the material behavior. The material characteristics and the wear behavior of the metal composites are examined using a pin-on-disk test. Wear measurements are performed by varying loads, sliding speeds, and sliding distances. The results reveal that the composites reinforced with 4% of $Al_2O_3$ particulates exhibit superior properties. The wear rate and the coefficient of friction (COF) decrease with the increase in the reinforcement content.

**Keywords:** MMNC, mechanical characterization, liquid casting process, surface morphology, XRD analysis

## 1. Introduction

Conventional monolithic materials have restrictions to meet today's demands in the field of advanced technologies. Composites have become essential due to their high strength-to-weight quotient and high stiffness-to-weight ratio. Today's composite materials are at the forefront of materials science, with their cost and quality appropriate for demanding requirements in aerospace, automotive, etc. These materials integrate the best characteristics of dissimilar materials, and enhance the physical and mechanical qualities of the combined materials [1].

Incorporating consistent carbon or boron materials may not yield the high-performance composite material resulting from the adverse chemical reactions between the reinforcements and matrix from early research. At present, with the evolution of many low-cost fibers and modern manufacturing techniques, the metal and ceramic matrix composites are used for commercial applications in automobiles, aircraft, construction, electronic equipment, and others.

Aluminum is widely used as a base alloy for metal matrix composites (MMCs). It is highly desirable for its extensive features, which include low density, good corrosion resistance, and high electrical and thermal conductivity; it is widely used in the automotive, aeronautics, and electronic packaging industries, among other applications [2]. The properties can be tailored by varying the constituents and their volume fractions. The commonly used reinforcements are SiC, $Al_2O_3$, $B_4C$, SiN, fly ash, etc. Aluminum metal matrix composites (AMCs) provide an excellent combination of properties so that the monolithic material cannot be a competitor.

* Corresponding author. E-mail address: sonagirisuresh@gmail.com

Over the decades, AMCs have been experimented with and utilized in structural and non-structural applications across a wide range of engineering disciplines The use of aluminum metal nanocomposites (AMNCs) in various industries is mostly owing to the superior performance as well as the economical and environmental benefits that they provide. AMCs are intended to alternate conventional monolithic alloys, magnesium alloys, titanium alloys, copper alloys, ferrous alloys, and polymer-based composites. The constant nano-silica carbide of up to 3% can enhance the mechanical and physical properties of materials [3]. Lack of material knowledge and usage of aluminum composites is essential in manufacturing sectors due to their unique properties such as high strength-to-weight ratio.

Dhanasekaran et al. [4] investigated aluminum-alloy hybrid composites for heavy vehicle clutch applications. A comparison was made between A356/SiC and A356/$Al_2O_3$ composites fabricated by the liquid metallurgy technique. Because of the inclusion of particles in the matrix, the mechanical characteristics of the cast specimen have been improved. In comparison to the matrix alloy, the mixtures with 20% SiC and 15% $Al_2O_3$ particles have approximately 50% more stability. Radhika et al. [5] investigated the mechanical and tribological properties of LM25 with SiC/$Al_2O_3$ MMCs, which are produced by the stir casting method. A wear analysis was performed to determine the wear rate. The number of grooves in the wear surfaces of the specimen was decreased due to reinforcements, indicating the minimum material removal.

Prakash et al. [6] manufactured A356 and Al 6061 composites reinforced with SiC particulates by the liquid metallurgy technique, and revealed that a two-stage blending process enhanced the wettability of reinforced particulates and ensured excellent particle distribution. Lakshmanan et al. [7] examined the problems associated with attaining homogeneously distributed reinforcements and better wettability with minimum porosity in the casting process. Vinod et al. [8] revealed that the fly ash particulates in the matrix using the squeeze casting method had more advantages than using the manufacturing process of gravity type casting. A homogenous structure with less porosity, excellent interfacial bonding, and uniform distribution between particles was obtained.

The research work aims to fabricate metal matrix nanocomposites (MMNCs) by using a stir-casting technique, and to evaluate the mechanical properties of the Al alloy and various heat-treated Al 7075/$Al_2O_3$/SiC MMNCs. The tribological characteristics, such as the wear rate and the coefficient of friction (COF) of MMNCs, are investigated. The material behavior is identified by conducting the scanning electron microscope (SEM) analysis, energy dispersive X-ray analysis (EDAX), and X-ray diffraction (XRD) analysis.

## 2. Methodology and Experimentation

### *2.1. Materials*

The base alloy used in this study is aluminum cast alloy (Al 7075). Current studies produce materials through a process known as mixed casting. Indian Scientific Business (India) Pvt. Ltd., Tirupathi provides the $Al_2O_3$ and SiC particulates used in the current study. The particle size ranges from 50 nm to 200 nm. Table 1 represents the chemical composition of Al 7075 alloy. The properties of the Al 7075 matrix, $Al_2O_3$, and SiC are represented in Table 2 [9].

Table 1 Chemical composition of Al 7075 alloy (in wt%)

| Elements | Mn | Cu | Si | Fe | Zn | Ni | Mg | Cr | Ti | Al |
|---|---|---|---|---|---|---|---|---|---|---|
| % | 0.075 | 1.62 | 0.06 | 0.19 | 5.63 | 0.05 | 2.54 | 0.23 | 0.048 | Bal |

Table 2 Properties of Al 7075, $Al_2O_3$, and SiC

| Materials | Density (g/cc) | Hardness | Young's modules ($N/mm^2$) | Melting Temp (°C) |
|---|---|---|---|---|
| Al7075 | 2.81 | 60 (BHN) | $71.7 \times 10^3$ | 635 |
| $Al_2O_3$ | 3.94 | 9 (Mohr's circle) | $410 \times 10^3$ | 2072 |
| SiC | 3.21 | 9.3 (Mohr's circle) | $450 \times 10^3$ | 2445 |

### *2.2. Heat treatment process*

The Al 7075 matrix alloy with the nano-$SiCN_p$ and $Al_2O_3$ reinforced composites is subjected to a T6 heat treatment at 475°C with a muffling furnace for two hours [10]. Then, five samples are collected and quenchants are used until room temperature is reached. The artificial aging procedure with the duration of 2 hours is done on all samples. The temperature in the muffle furnace is kept at 120°C for the artificial aging procedure with a soaking time of 7 hours to improve the material hardness.

### *2.3. Preparation of fabricated samples*

A graphite crucible is used to heat the matrix material at its melting point (800°C). Silicon carbide nanoparticles (20 nm) and alumina oxide (20 µm) are used as reinforcements. Fig. 1 represents the experimental setup of stir casting. The silicon carbide and alumina oxide reinforcements in wt% are preheated in a hopper and allowed to fall through the hopper to the molten matrix material. Uniform stirring is done using a stirrer made up of stainless steel coated with alumina so that it can withstand high temperatures. A vortex is created by using a stirrer. The appropriate temperature is allowed to be reached with the Al 7075 ingots placed in the furnace and sustained. After using a degasser, the pure melt is stirred to create a fine vortex using the rotating mechanical stirrer.

When the fine vortex is continuously stirred at 550 rpm for about 10 minutes, the average particles of silicon carbide and alumina oxide are added gradually [11]. A die with a size of 100 × 50 × 50 mm is used in this work. The molten mixture is permitted to flow into the die (a crucible is put below the crucible to keep it in place). The final specimen is now allowed to cool, and then the dies are removed and the composite is taken out. Five specimens, i.e., Al 7075 reinforced with 1, 2, 3, 4, and 5 wt% of ($SiCN_p/Al_2O_3$) composites, are made with the same procedure.

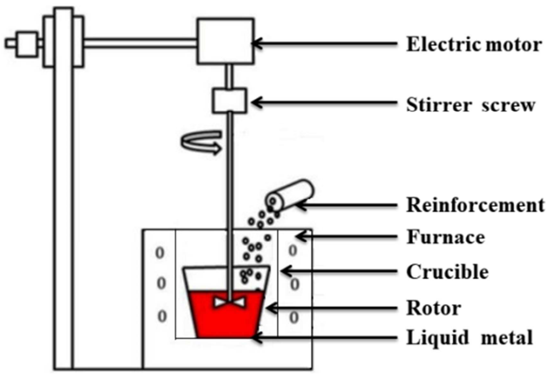


Fig. 1 Experimental setup for the stir casting process

### *2.4. Evolution of mechanical properties*

#### *2.4.1. Density test*

To determine the composite porous percentage, the density is calculated. The density is determined when the values of the theoretical and experimental densities of the composites are measured by the principle of Archimedes using Eq. (1). Three specimens are randomly chosen and carefully measured in both air and distilled water. Weights are calculated by the electronic balance of 0.0001 g.

$$\rho_{mmnc} = \frac{m}{m - m_1 \times \rho_{water}} \tag{1}$$

### 2.4.2. *Tensile test*

The tensile test is carried out to determine the effect of reinforcing particles on hybrid composites. The tensile strength is a very useful property for the design of the components when taking the functional requirements into account. The tensile test measures the resistance of the material to the load.

In this research, the test is conducted by using cylindrical specimens on a computerized 10KN universal testing system in compliance with the ASTM E-8 standard. The load is delivered at both ends, with a crosshead rate of 5 mm/min, to determine how strong the composite samples will be in the long run when put under tension. All of the experiment's samples are tested four times, and the average results are recorded. The prepared composites exceed the base alloy in terms of performance. It improves as the weight fraction of reinforcing particles increases.

### 2.4.3. *Hardness test*

The hardness test evaluates the effect of reinforced particulates on aluminum. The most used instruments for testing durability are Rockwell, Knoop, Brinell, and Vickers hardness tests. In this analysis, the hardness value for the matrix alloy is determined using the Vickers hardness test.

The test is performed on polished composite samples in compliance with the standard ASTM E10-07. A load of 3 kg is put on the specimens for 5 sec dwell time. The average values of four measurements are obtained from various sample areas. The average value is considered the hardness. The Brinell hardness values of the matrix alloy and Al 7075/$SiCN_p$/$Al_2O_3$ composites are identified. The hardness improves as the 4 wt% hard reinforcement particles increase. After the reinforcement particles are incorporated into the reinforcement surface, the higher density offers better resistance to plastic deformation in the material, which makes the composites harder.

### 2.4.4. *Impact test*

The impact strength of the composite materials is evaluated using an ASTM E23-07 standard pendulum form tester. Specimens with a length of 75 mm are taken, and cross-sections of $10 \times 10$ $mm^2$ with a grade of 45° are used for the measurement of the impact strength of Al 7075/$Al_2O_3$/SiC hybrid composites. When evaluating the hardness, the volume of the sample is used. The zone underneath the stress-strain curve is determined.

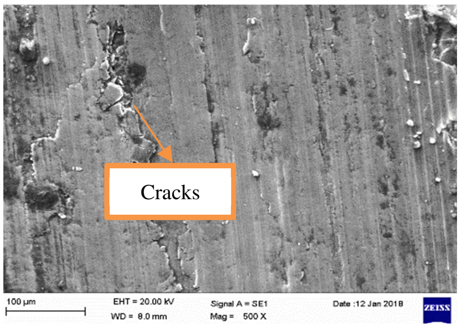
### 2.5. *Dry sliding wear test*

A pin-on-disc test apparatus is used to analyze the wear properties of hybrid aluminum materials. All samples are polished with 600, 800, and 1000 grades of emery paper individually, and specimens are machined with 10 mm of dia and 40 mm of length, respectively. Cast pins are again squeezed over to an EN32 disk with a roughness of about 1.2 μm and resistance of 65 HRC performed at room temperature. The pin is measured for accuracy during both tests.

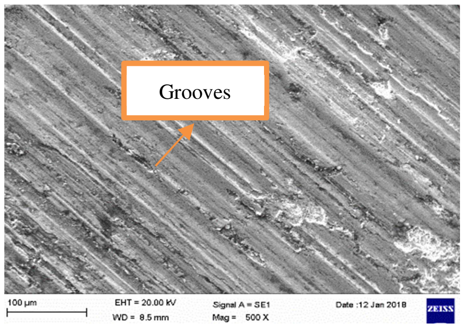
## 3. Results and Discussion

### 3.1. *Microstructural analysis*

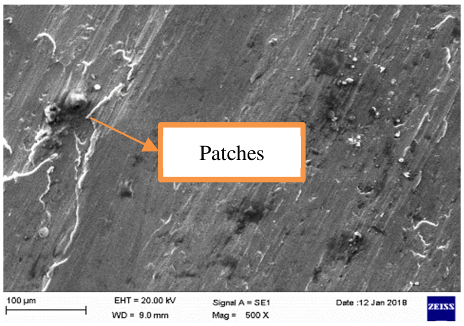
The SEM analysis result of the hybrid composites is shown in Fig. 2, which illustrates the plastic deformation, grooves, and patches. The SEM analysis result shows that the base alloy, $Al_2O_3$, and SiC particulates are well bonded. It can be further observed that the reinforcements are well dispersed in a random and isotropic orientation, and no agglomeration is observed. Magnesium improves the base metal's wear resistance and stability by being added to the mix [12]. Composite materials have a significant impact on the mechanical and wear behavior.



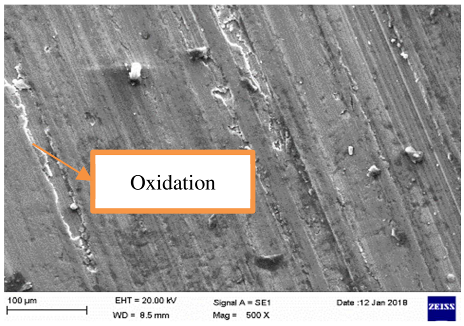

(a) Al 7075 alloy



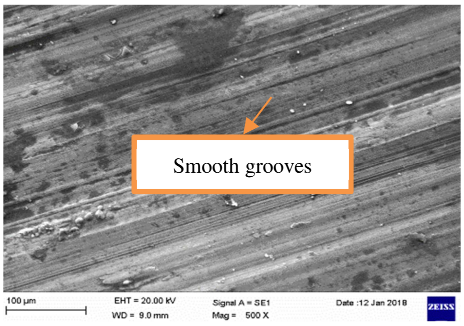

(b) Al/1% $Al_2O_3$/SiC



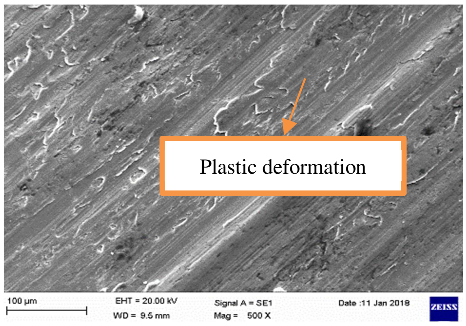

(c) Al/2% $Al_2O_3$/SiC




(d) Al/3% $Al_2O_3$/SiC




(e) Al/4% $Al_2O_3$/SiC

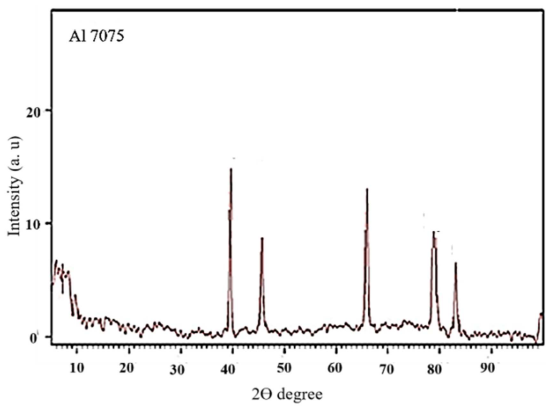



(f) Al/5% $Al_2O_3$/SiC

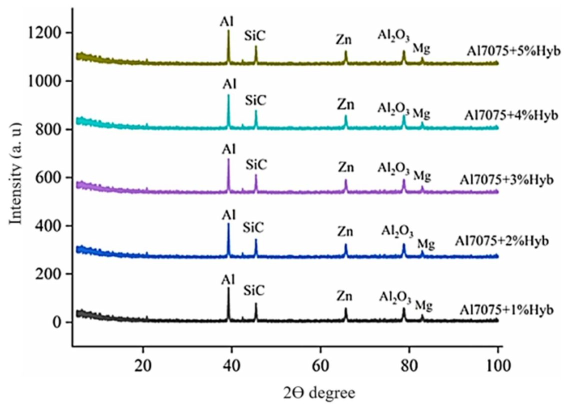
Fig. 2 SEM images of hybrid MMNCs

### 3.2. XRD characterization

Fig. 3 shows the XRD results of Al 7075 reinforced with $Al_2O_3$ (1, 2, 3, 4, and 5 wt%) and SiC (3 wt%). The stir-cast aluminum alloy samples are measured using a SEIFURT diffractometer. The XRD peaks obtained from these samples demonstrate a proportion of $Al_2O_3$ and SiC in the composites. The diffraction pattern shows aluminum in higher content from the intensity of peaks compared to $Al_2O_3$ and SiC. It confirms the objective of adding $Al_2O_3$ and SiC in this research to improve the mechanical and wear behavior of the composites.




(a) Al 7075 alloy




(b) MMNCs

Fig. 3 XRD analysis of aluminum hybrid nanocomposites

### *3.3. Mechanical characterization*

#### *3.3.1. Effect of the reinforcement percentage on the density*

The effect of reinforcing particles on the density is shown in Fig. 4. As compared to the matrix, hybrid composites have a higher density. The density can be improved by adding more reinforcements to the structure. The reinforcement particles are distributed among the larger ones and restrict the pores filled by particles. In comparison to Al 7075, which has a density of 2.81 g/cc, aluminum oxide has a density of 3.94 g/cc. Silicon carbide has a thickness of approximately 3.21 g/cc. The composites reinforced with Al/5% $Al_2O_3$/3% SiC have the highest density (2.89 g/cc), whereas Al/1% $Al_2O_3$/3% SiC has the lowest density (2.80 g/cc). The incorporation of $Al_2O_3$ and SiC in the aluminum alloy is clearly shown to increase the density of composite materials since the resistance densities are enhanced in comparison to aluminum alloys.

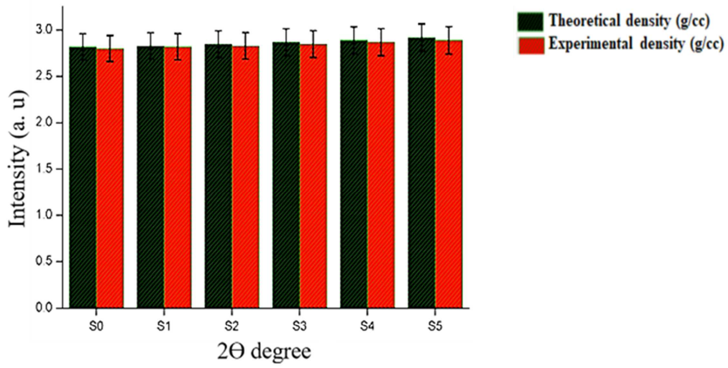



Fig. 4 Density of MMNCs

#### *3.3.2. Effect of the reinforcement percentage on the tensile strength*

The tensile strength of aluminum alloy and various weight fractions are presented in Fig. 5. Fine particles with a variety of weight percentages improve the tensile strength of aluminum composites. The minimum tensile strength (234 MPa) is identified for 1 wt% of $Al_2O_3$ and 3% of SiC reinforced composites. The highest tensile strength (308 MPa) is obtained when adding 4 wt% $Al_2O_3$ and 3% SiC reinforced composites. Thus, an increase in the tensile strength by about 32% is observed in the composites compared to the unreinforced alumnium alloy attributed to a rise in reinforced particulates [13]. Further addition of reinforcement contents (5 wt% $Al_2O_3$ and 3% $SiCN_p$) leads to a reduction in strength due to agglomeration.

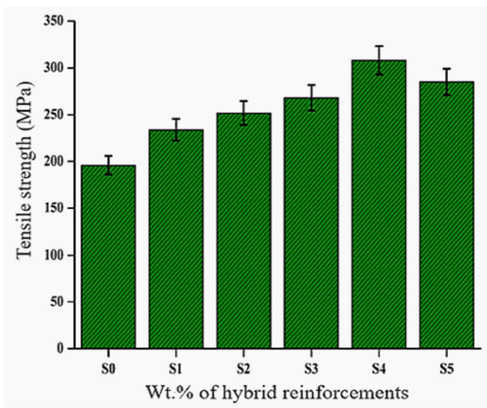



Fig. 5 Ultimate tensile strength of MMNCs

#### *3.3.3. Effect of the reinforcement percentage on the hardness*

A composite sample enhanced with different weight percentages of particles has better hardness, as shown in Fig. 6. The toughness of the manufactured compounds is influenced by different bit supports. The Brinell hardness test shows that the hardness of the composite is greater than the hardness of the cast matrix alloy. As the ceramic phase of composite materials enhances, the toughness value rises linearly, increasing the particle restoration percentage in density. The hardness of the composite is improved by limiting the matrix lattice's dislocation with alumina and silicon carbide particles added to the matrix. Fig. 6 shows the improvement of the Brinell hardness of fabricated MMNCs. A maximum of 56% increase is observed in a 4% $Al_2O_3$ and 3% SiC composite compared to the unreinforced aluminum alloy. Further addition of reinforcement contents (5 wt% $Al_2O_3$ and 3% SiC) leads to a decrease in the composite's hardness. According to the work of Sudhakara et al. [14], adding nano-silicon carbide as the reinforcement to aluminum composites increased their solidity.

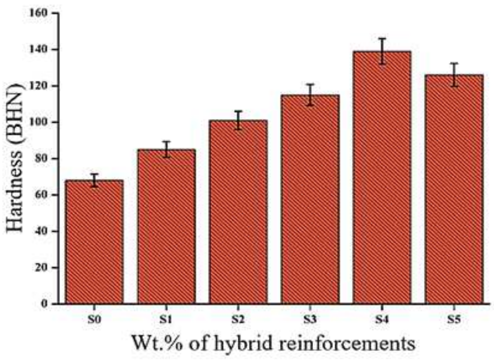



Fig. 6 Brinell hardness of MMNCs

### 3.3.4. *Effect of the reinforcement percentage on the impact strength*

Fig. 7 shows the Izod impact strength of different weight fractions of $Al_2O_3$ and SiC reinforced composites. The findings of the study indicate that the impact resistance reduces as the reinforcement particle increases. The strength of impact for hybrid composites shows lower values than the matrix due to brittle ceramic particulates. A similar trend found by Poovazhagan et al. [15] is that the wear resistance of silicon carbide and boron carbide added to the aluminum is reduced with the increase of these materials.

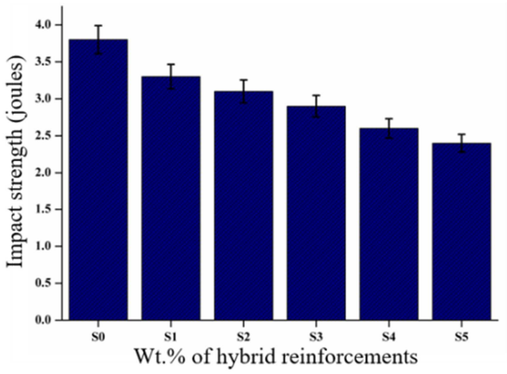



Fig. 7 Impact strength of MMNCs

### 3.3.5. *Effect of the reinforcement percentage on the elongation*

Fig. 8 presents the ductility of the aluminum composites reinforced with different volume fractions of $Al_2O_3$ and SiC. The ductility of the base aluminum alloy (Al 7075) is superior to the hybrid composites. Due to the addition of reinforcements, the ductility of hybrid composite specimens reduces. In the Al 7075, the maximum ductility is observed (7.5%); in the hybrid composites, it varies from 4.3% to 6.8%. The interfaces between the base matrix and the reinforcement particles are significant factors influencing the size of hybrid composites. When the reinforcement particles are incorporated into the aluminum matrix, they produce a crack with high tension [16]. It is mainly attributed to the fact that the material flows take place during the deformation of the particles. With the addition of reinforcements, the resistance to deformation improves, decreasing the composites' ductility.

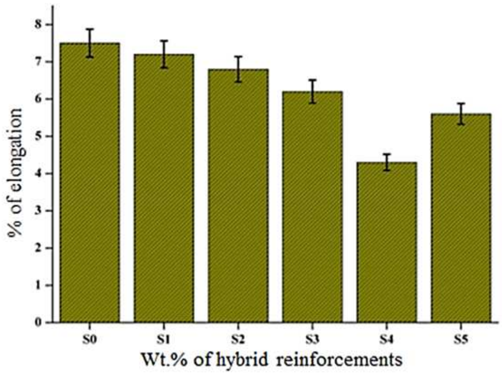


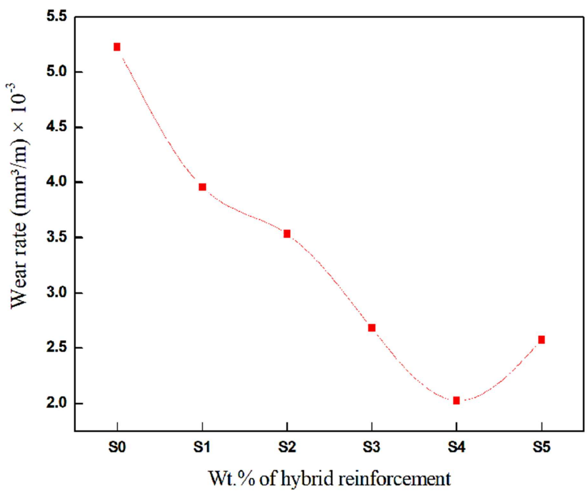

Fig. 8 Elongation percentage of MMNCs

### *3.4. Wear behavior*

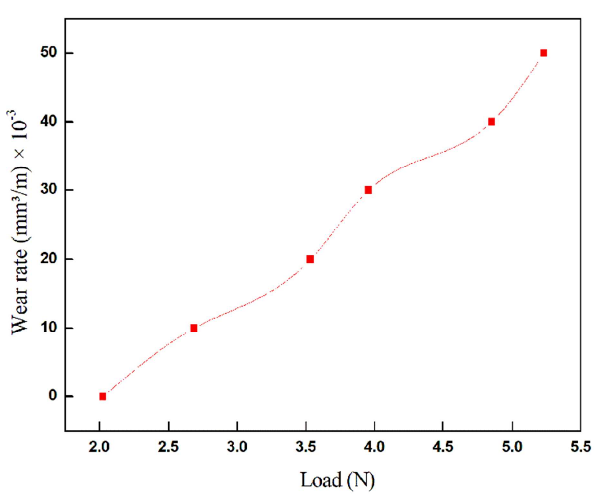
#### *3.4.1. Effect of the reinforcement on the wear rate*

Fig. 9 depicts the influence of reinforcements and loads on the wear rate of Al 7075 hybrid composites. It can be observed that the composites reinforced with $Al_2O_3$ and SiC exhibit considerable wear resistance than the base aluminum alloy. The wear rate of the composites decreases as the percentage of particles increases. This is because the reinforcements act as a load-bearing active ingredient in the composites, and restrict the size of the product that can be reduced. Reinforced compacts lead to improvements in volume, and load-bearing factors lead to a decrease in failure. A few other parameters, such as crystallographic orientation, microstructure, and sample loading direction, play a significant role in the tribological resistance of the reinforcements [17]. Sample loading is an essential factor in this investigation. However, the increases in the strength of the composite specimens (Fig. 9) with the increases in the fine particles can decrease the flowability of the samples.

The increase in particulate composites reduces the deformation of the matrix material, leading to a minimum wear rate. In general, the wear rate decreases with an increase in ceramic particulates. Fig. 9(b) shows that the wear rate improves with the addition of reinforced particles when increasing the load. According to Archard's phenomenon, wear resistance increases as microhardness increases. The Hall-Petch phenomenon, which improves both the microhardness and wear resistance by means of the $Al_2O_3$ presence, results in distinct grain refinement. A similar observation is made by Chakkravarthy et al. [18]. They assumed that an improvement in the reinforcement percentage enables the solidification process to be more durable and improves the composite's wear rate. Also, they found an increase in wear with an increase in the $Al_2O_3$ content.




(a) Wear rate vs wt% of reinforcement

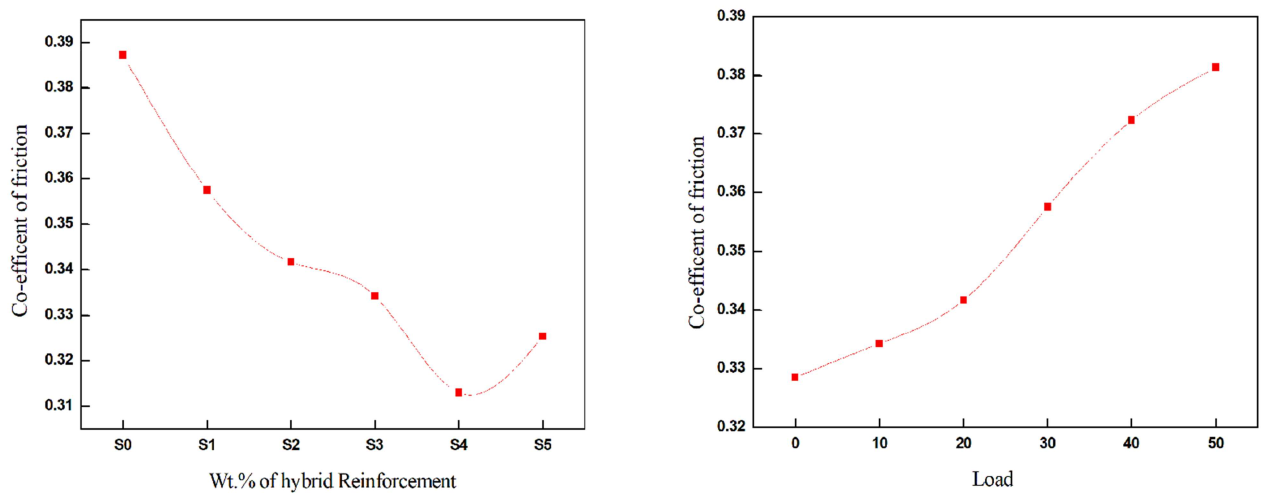



(b) Wear rate vs load

Fig. 9 Effect of the reinforcement on the wear rate

### *3.4.2. Effect of the reinforcement on the COF*

The COF in hybrid composites decreases as the amount of particle reinforcements increases, according to the observations. Fig. 10 shows the difference between the COF of Al 7075 alloy and its composites at a constant sliding speed with different applied loads and reinforcement percentages. As the reinforcement percentage increases, the COF decreases. The surface deformation in the base alloy prevents the counter face from contacting with the revolving disc, reducing the frictional resistance as a result of the addition of $Al_2O_3$ and SiC. Vinod et al. [19] observed that the COF declines due to the inclusion of SiC and $Al_2O_3$ in the Al 6061 alloy. Suresh and Sudhakara [20] also reported a similar decrease in the COF with the addition of a volume fraction of silicon carbide particulates in the Al-1.5% Mg alloy. The main factors influencing the COF are the adhesion on flat regions of the pin and the counterface, the plowing by hard asperities, and the deformation of surface asperities. The reduction in COF is mainly because of the increase in the wear debris pushed out from the wear surface and stuffing in the empty areas between reinforcements, thereby minimizing the penetration depth.




(a) COF vs wt% of reinforcement (b) COF vs load

Fig. 10 Effect of the reinforcement on the COF

## 4. Conclusions

The strengthening mechanism of reinforcement particles had a strong correlation with the tensile strength and hardness. An improvement in particle incorporation reduces the matrix deformation, leading to better tensile strength and durability. The impact strength was reduced due to an increase in particulate enhancement, as compared to the matrix. The maximum increase, which was observed in the tensile strength and hardness of hybrid composites, was 51% and 110% as compared to the base alloy, respectively. The impact strength and density declined to a maximum of 49% and 42%.

After conducting the SEM analysis of the fractured tensile and impact tests, the specimen was characterized by the formation of dimples, voids, ridges, and cracks. A direct relation with wear rate was caused by the alumina oxide and silicon carbide particles. The improved strengthening mechanism limited the distortion of the cast specimen. The relationship between the sliding speed and wear rate was identified (i.e., the increase in the sliding speed results in a high wear rate). The COF had an insignificant correlation with the weight fraction of fine particles, sliding speed, and applied load. In the formation of plowing and delamination, the mechanically mixed layer (MML) could influence the wear behavior of hybrid composites as evidenced by wear micrographs.

## Conflicts of Interest

The authors declare no conflicts of interest.

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