Effect of Different Volume Fractions on Tribological and Mechanical Behavior of Al/SiC$_n$/Gr$_\mu$ Hybrid Composites

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Hybrid composites, specifically Al/SiC/Gr, are a promising area of research in material science. This work deals with the Al/SiC$_n$/Gr$_\mu$ hybrid composite, which includes the additional nano silicon carbide particles (SiC$_n$) at 2, 4, 6, 8, and 10% volume fraction (VF) and 1 and 5 % VF of micro-graphite particles. The process involves blending metal powders, cold pressing, and sintering at 620°C for 2 hours to create a specific green part. The results show that the increased volume fractions of SiC and Gr result in higher porosity, lower density and reduced wear rate compared to pure Al matrix. The microhardness values of 168, 191 HV were evinced by reinforcing with Al+6%SiC+1%Gr and Al+6%SiC+5%Gr, respectively. The highest compressive strength values of 153.38 MPa and 95.77 MPa were found in Al+6%SiC+1%Gr and Al+6%SiC+5%Gr, respectively.

Keywords: Metal matrix; Hybrid composites; Powder metallurgy; Tribological properties
Received: 17 September 2023; **Revised:** 12 October 2023; **Accepted:** 19 October 2023

1. Introduction

AMC is a material made of an aluminum matrix and strengthened with different ceramic nanoparticles like Al$_2$O$_3$, ZrO$_2$, TiB$_2$, B$_4$C, and SiC [1-5]. It has been utilized to improve the properties of the Al matrix to gain a significant improvement in the mechanical properties of the composite, especially hardness and strength [6]. Due to their small size and large surface area-to-volume ratio, nanoparticles have unique properties that differ from those of their bulk counterparts. For example, nanoparticles can exhibit enhanced reactivity, improved mechanical properties, and altered optical and electronic properties. These properties of applications in electronics, energy, medicine, and environmental cleanup are just a few of the industries where nanoparticles are appealing [7,8]. The following description of nanoparticle-reinforced composite properties is succinct:

1- The fracture mode in nanocomposites has changed from inter-granular fracture in monolithic metal to trans-granular fracture.
2- Moderate to considerable strength improvement.
3- Increasing fracture toughness.
4- Improving wear resistance, creep resistance, and thermal shock resistance.
5- Improved structural stability at high temperatures.

The nanoparticles or clusters were normally reincorporated into the matrix or embedded in a groove inside the matrix metal, so the main obstacle in research is the agglomeration of nanoparticles. A lack of fundamental knowledge and technical expertise on how to achieve uniform nanoparticle dispersion in MMNCs has hindered the rapid development of the MMNC field. The mechanisms and concepts involved in achieving a good distribution and optimal mixing during wet and dry mixing processes. Wet mixing is done by immersing the powder in a liquid; the particles become saturated and evenly distributed throughout mixing and stirring. Agglomerates are broken down, promoting the particles to disperse evenly and achieve a good distribution. Through dry mixing, the particles collide and intermingle. Through the application of mechanical energy, such as rotation speed, particles experience consistent motion, facilitating a good distribution [9].

The choice of technique will depend on the desired properties of the nanoparticles as well as factors such as cost, scalability, and safety. There are several methods that can be used to fabricate MMNCs: stir casting, additive manufacturing, and powder metallurgy [10]. The powder metallurgy technique was successfully established to reveal the essential conditions for nanoparticle dispersion in composites. The properties of powder metallurgy products are highly dependent on some parameters, which can determine the performance of MMCs, such as composition and the microstructure of MMCs, size, volume fraction, and distribution of particles in metal matrices, as well as the properties of the interface between the metal matrices and the reinforcements. During the manufacturing processes of MMCs, the PM method presents excellent control over the microstructure, including size, morphology, volume fraction of matrix, and reinforcement. MMCs have gotten significant attention worldwide because of their superior mechanical and tribological properties [11], which allow them to support heavy loads without distortion, deformation, or fracture during performance and maintain good tribological behavior. Hard ceramics are materials that are characterized by their high hardness and strength, as well as their resistance to wear and abrasion. These materials are typically made from non-metallic compounds such as oxides, carbides, nitrides, or borides. Some common examples of hard ceramics include alumina, silicon carbide, boron carbide, and titanium diboride. These materials are used in a wide range of applications, such as cutting tools, wear-resistant coatings, ballistic armor, and electronic components [12]. When employing silicon carbide in a particular application, an external lubricant like graphite can be employed to enhance the tribological properties of a hybrid composite by reducing friction and improving slip. Materials scientists can get the better of two materials that are superior to the simple combination of properties of the components, and that refers to hybrid materials. Various researchers used Gr as reinforcement to make AMCs lighter and improve their wear rates for automotive, general engineering, and nuclear applications [13]. Zawrah et al. used the nanocomposites sic to enhance the composite's mechanical properties, i.e., microhardness, without a significant loss in the electrical and thermal properties, compression strength, elastic modulus, or wear resistance [14]. Ravichandran et al. used reinforced (TiO_2) and (Gr) that were blended with the Al matrix (2.5 wt.% of TiO_2 and 2 wt.% of graphite) and (2.5 wt.% of TiO_2 and 4 wt.% of graphite). The addition of both TiO_2 and Gr particles increased the strength and hardness of the composite, while the addition of more graphite to the matrix decreased the density values [15]. Graphite and ZrO_2 powder were used as reinforcement materials with a Ni matrix prepared by the powder metallurgy technique. The influence of increasing graphite content was a decrease in bulk densities and an increase in apparent porosities of the hybrid composite, which enhanced the microhardness and compressive strength [16].

Powder metallurgy is used in this study to test what happens when micro-Gr particles are added to an Al/SiC_n metal matrix composite. Additionally, study the influence of variations in the volume fraction of the Gr effect on the wear and mechanical properties of the hybrid composite.

2. Methods and materials

The hybrid MMCs contain Al/SiC/Gr powder materials used in this research. Pure Al powder with a particle size of 1.96 µm is from CDH CO, India. Graphite 45 µm and silicon carbide 50 nm from Hefei EV NANO Technology Co., Ltd., China. The powder metallurgy technique was fabricated to prepare two groups, as shown in table (1).

Table (1) Composition of hybrid composite materials

Group	SiC_n vf%	Gr_μ vf%
A	2, 4, 6, 8 and 10	1
B	2, 4, 6, 8 and 10	5

Wet mixing of powder was done by using a magnetic stirrer with distilled water for 120 minutes and sonication with ultrasonic for 40 minutes, then drying in an oven at 90°C for completed dryness to obtain a homogeneous powder mixture. The uniaxial cold compaction process prepared two cylindrical specimens: 10×5 for wear and hardness tests and 10×20 for compression tests. The uniaxial presser of powder was at 180 MPa for 3 min. Lastly, specimens were carried out in an electric muffle furnace at 620°C for 120 minutes for sintering, and samples were then allowed to cool in the furnace.

3. Testing and Characterization

In the department of applied sciences at the University of Technology, the microstructure of a hybrid composite was examined using an optical microscope, model MT9430 from MEIJI TECHNO CO., LTD. Japan. It is provided with a digital camera that uses an X100 magnifying lens and is connected to a computer system. After the grinding and polishing operation, the test samples were cleaned with distilled water to get rid of any surface contaminants. The samples were looked at under X100 magnification and a Tescan VEGA II field-emission scanning electron microscope (FE-SEM). According to ASTM D792, apparent porosity and bulk density were used to determine the density and porosity of the hybrid composites (A and B). A variety of mechanical tests were utilized, including the Micro-Vickers Hardness Tester (type HVS-1000, China), which has an indenter made of a diamond pyramidal section with a square base and opposing faces at a 136° angle. The test was conducted in accordance with ASTM (C1327-99), with a 100-gram weight applied for 30 s. The results were calculated by averaging five measurements. The calculation of the compressive strength was according to ASTM D695 by using an Introns WDW-200E machine, at a crosshead speed of 1 mm/min at room temperature by applying a vertical load to the specimen's surface. Specimens were weighed before and after the wear test using a sensitive balance Denver instrument type (Max-210 gm), in accordance with ASTM G99's Pin on Disc technique. The sliding distance and wear rate were divided by the weight loss (w). The load was 10 N for 1 minute and the speed was 750 rpm.

4. Results and Discussion

An optical microscope allows studying the Al-SiC-Gr hybrid microstructure by using specific magnifications and illumination techniques. From Fig. (1), the optical microscope shows (a) Al/4%SiC/1%Gr, (b) Al/8%SiC/1%Gr, (c) Al/4%SiC/5%Gr, and (d) Al/8%SiC/5%Gr. It can be observed that the reinforcing particles of different volume fractions are visible and fairly distributed in the Al/SiC/Gr hybrid composite, with the presence of some agglomeration of silicon carbide particles. This is consistent with findings from previous research by

Jin and Batra [17], as well as the interfacial area of aluminum decreases with increased volume fractions of SiC and Gr particles.

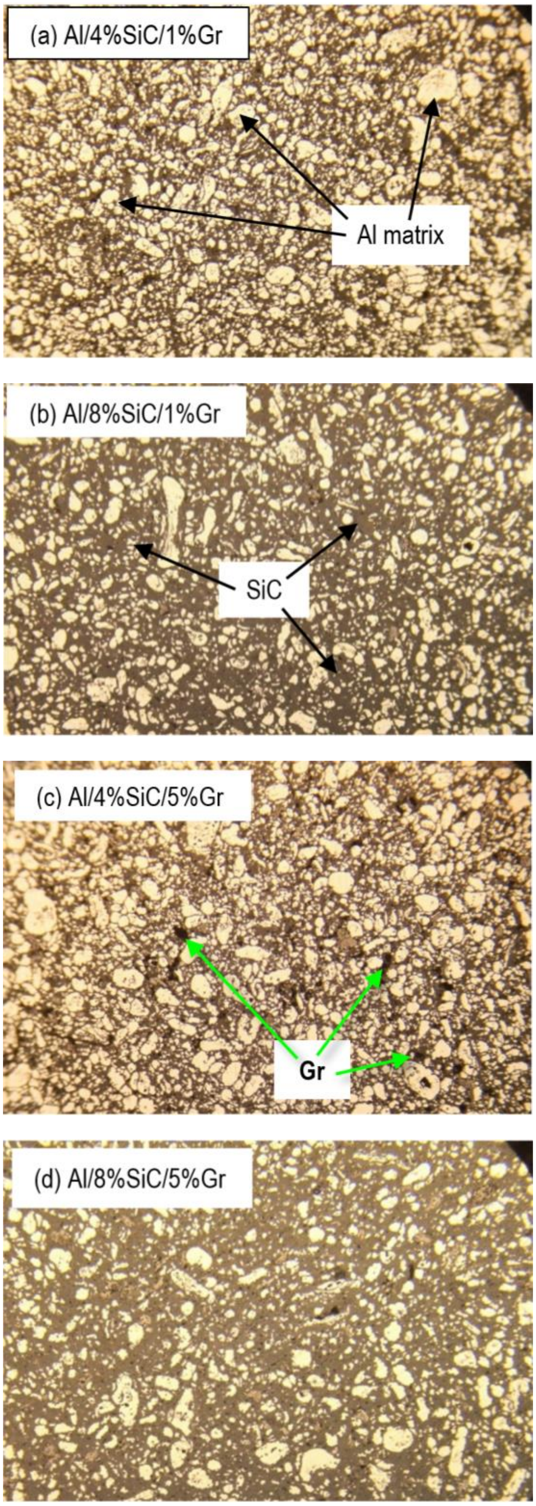


Fig. (1) Optical microscope images of Al/SiC/Gr hybrid composite at (a) Al/4%SiC/1%Gr, (b) Al/8%SiC/1%Gr, (c) Al/4%SiC/5%Gr, (d) Al/8%SiC/5%Gr (X100 magnification)

Density is an indication that reflects the degree of densification of the processed powder samples. Density was inversely proportional to the porosity value. The variation in measured density and the porosity of the hybrid composites are shown in figures (2) and (3), respectively. It could be observed that the two groups (Al/SiC/1%Gr and Al/SiC/5%Gr) have a high percentage of apparent porosity and a low bulk density because the incorporation of hard particles (SiC and Gr) in the composite, which poses several challenges during compaction and sintering, resulting in a composite with high porosity and low bulk density. During compaction, when force is applied to reduce the empty spaces between the composite particles, the SiC and Gr tend to resist plastic deformation. Ahmed et al. [18] concluded that too. At high volume fractions (8 and 10) % SiC (in both 1% and 5% Gr), the increase in porosity and decrease in density can be attributed to the effect of nanoparticle agglomeration of SiC and pore between the reinforced particle surface.

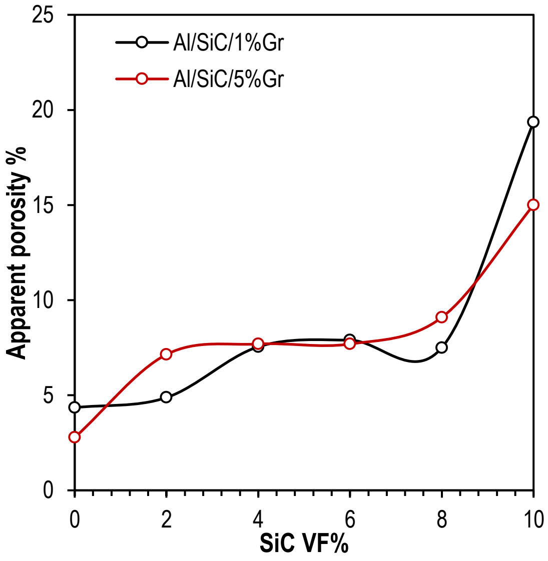


Fig. (2) Apparent porosity of Al/SiC$_n$/Gr$_\mu$

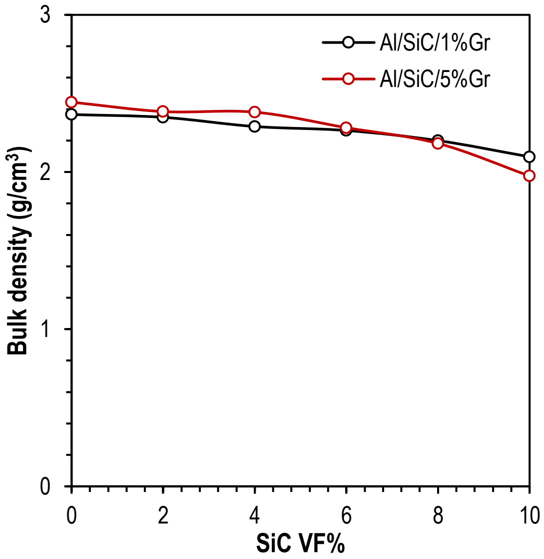


Fig. (3) Bulk density of Al/SiC$_n$/Gr$_\mu$

The relation between the different volume fractions of SiC with 1% and 5% Gr and microhardness can be shown in Fig. (4). The results of the microhardness test showed that the values of microhardness increased with an increase in SiC volume fraction and reached the optimum value at Al/6% SiC/1%Gr, which was equal to 168 MPa. This increase was because the SiC particles acted as strengthening agents within the composite and had a high hardness, making it more resistant to deformation and more difficult to scratch or indent, similar to the result of Ismail et al. [19]. When a material is deformed, stress is distributed throughout the material, and the presence of hard SiC particles can impede the movement of dislocations (small defects in the crystal structure) that contribute to plastic deformation. By adding a higher volume fraction of graphite 5%, the hardness can increase up to 191 MPa at (Al/6%SiC) due to the well mechanisms compact between matrix and reinforcement particles. One of them is very hard and rigid (SiC), and the other (Gr) can act as a lubricant, which can facilitate the dispersion and distribution of the SiC particles in the matrix material. This can lead to a more homogeneous microstructure and a more even distribution of the reinforcing SiC particles in the graphite, which can act as barriers to dislocation movement and increase the hardness of the material.

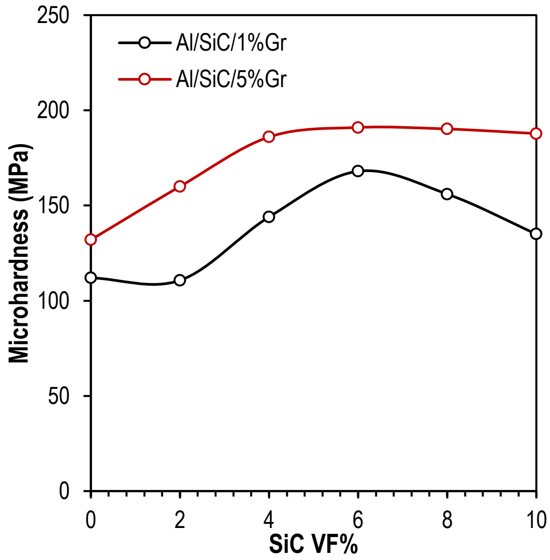


Fig. (4) (HV) Al/SiC$_n$/Gr$_\mu$

The reduction behavior of microhardness for both (Al/SiC/1%Gr) and (Al/SiC/5%%Gr) to 135 and 187.8 MPa at 10 vf% of SiC content, respectively. Variation in porosity at high SiC content was caused by the clumping and aggregation behavior of SiC particles in specific regions during the sintering process. This lead to the Al matrix and reinforcement's weak bonding agent caused the composites' microhardness to decrease even more. Similar results have been found in the literature of Manivannan et al. [20].

The effect of the Gr content on the compressive strength of the Al/SiC/Gr hybrid composite is shown in Fig. (5). The compressive strength increased up to 153.38 MPa at (Al/6%SiC/1%Gr) and then decreased to 46.44 MPa at (Al/10SiC/1%Gr). When SiC is added to the aluminum matrix, it serves as a strengthening agent. It is capable of efficiently transferring loads from the softer matrix material (aluminum) to the composite structure, and as a result, the composite exhibits a higher compressive strength, which is similar to the result of Ravikumar et al. [21]. When the volume fraction of the SiC increased from 8 to 10%, the compressive strength started to decrease. The composite may become more brittle and tend to fracture under lower compressive loads. This is due to several factors, including the gaps, voids, or porosity (Fig. 2) between the reinforcement particles that can cause stress concentrations, which reduce the load transfer efficiency, and an increased likelihood of crack nucleation and propagation.

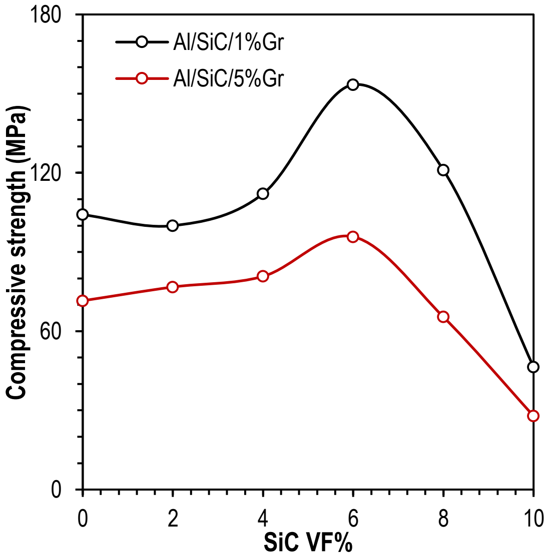
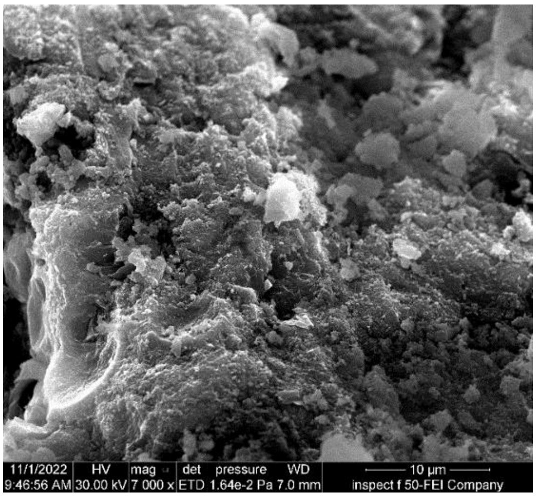


Fig. (5) Compressive strength of AL/SiC$_n$/Gr$_\mu$

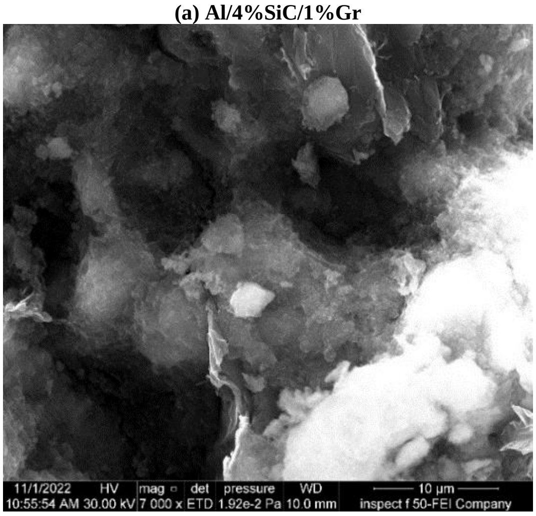
Similar results were observed by adding Gr at Al/SiC/5%Gr; the compressive strength increased to 95.77 MPa at 6 vf%SiC, the presence of SiC particles resists deforming stresses. This enhanced the compressive strength of the composite material, and the addition of hard ceramic particulates has caused the MMCs to behave as brittle rather than ductile materials in high content, as is evident from the above results, so the compressive strength decreased to 27.88 MPa at 10vf%SiC.

The content of 5%vf Gr negatively affected the behavior of hybrid composites compared to 1% Gr by reducing the compressive strength. Graphite has a layered structure held together by weak Van der Waals forces, resulting in relatively low interfacial bonding with the surrounding Al matrix. This weak bonding can create stress concentration points and reduce the strength of the hybrid composite. The graphite particles can act as stress concentrators and hinder efficient load transfer between the matrix and reinforcement phases; which results in decreasing compressive strength. Similar results have been found in the literature [22,23].

In Fig. (6), FE-SEM images evaluate the fracture surface of the compression test for two groups. The addition of graphite with different volume fractions can have varying effects on the microstructure of a hybrid composite. At lower volume fractions of Gr particles at Al/4%SiC/1% Gr, graphite particles may be more uniformly distributed, resulting in a more homogeneous microstructure and good bonding between the graphite particles and the surrounding matrix materials (e.g., aluminum). However, at higher volume fractions of Gr particles at Al/4%SiC/5% Gr, there may be a greater tendency for graphite particles to agglomerate, leading to a less uniform distribution, weaker interfaces, and more concentration stress areas due to porosity and defects that can affect the microstructure of the hybrid composite.



(a) Al/4%SiC/1%Gr



(b)Al/4%SiC/5%Gr

Fig. (6) FE-SEM of $Al/SiC_n/Gr_\mu$ hybrid composite

The wear behavior of the hybrid composite represented in Fig. (7) shows that the rate of wear decreased until it reached the minimum limit of 0.242 g/cm at Al/4%SiC/1%Gr and then increased to 0.436 g/cm at Al/10%SiC/1%Gr. The wear behavior of hybrid composites is enhanced due to the positive effect of nanoparticle incorporation on wear rate and hardness. This can be attributed to the good mechanical compactness, sintering, and improved dispersion of the nanoparticles in the Al matrix. SiC particles serve as load-supporting components and lessen the plastic deformation at the subsurface; this result agrees with Taheri-Nassaj [24]. At high volume fractions of SiC (8 and 10) %, SiC experienced rapid increases in porosity and low hardness, which increased the ware rate in hybrid composites (Al/SiC/1%Gr). The same behavior can be observed when added Gr 5vf% in the hybrid composite (Al/SiC/5%Gr). The value of the wear rate decreased to 1.14 g/cm at 4%SiC and then increased to 3.3 g/cm at 10% SiC. The ware rate increased due to the increased pores and agglomeration in the hybrid composite (Al/SiC/5%Gr). However, when it compared the two behaviors, it found that the wear rate at (Al/SiC/5%Gr) was higher than the wear rate at (Al/SiC/1%Gr). This is because graphite particles are typically poorly wet with Al and SiC, resulting in limited interaction or bonding between reinforced particles. Similar results were found in [25].

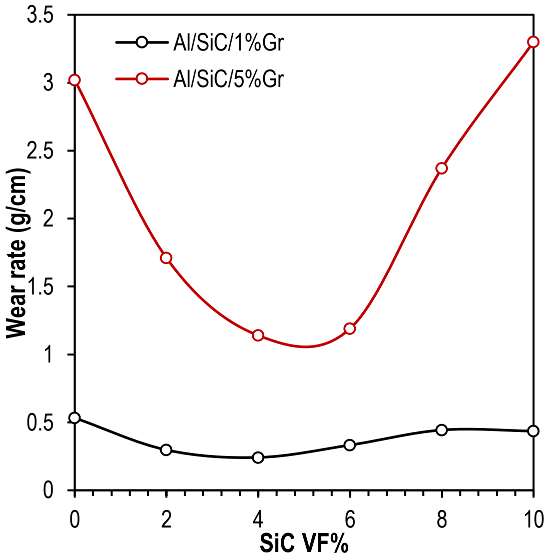


Fig. (7) Wear rate of $Al/SiC_n/Gr_\mu$

5. Conclusion

The specific result of the different volume fractions (SiCn, Grμ) on the aluminum metal matrix is the high porosity and low bulk density of the hybrid composite. The reinforcement of the Al matrix with SiCn and Grμ as hybrid materials enhanced the hardness of the hybrid composite (Al/6%SiC/1%Gr) and (Al/6%SiC/5%%Gr) compared to the Al matrix by 168 and 191 HV, respectively. The compressive strength of the composite (Al-6%SiC) increased significantly by 153.38 and 95.77 MPa for 1% and 5% Gr, respectively. Adding SiCn with 1% Gr reduced the wear rate compared to the Al matrix, while adding Grμ 5% Gr increased the wear rate.

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