Arch. Metall. Mater. **71** (2026), 2, 653-666

DOI: https://doi.org/10.24425/amm.2026.158858

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A STUDY OF AL 7075 ALLOY'S STRENGTHENING AND WEAR RESISTANCE WITH SiC AND GRAPHITE HYBRID REINFORCEMENT

The hybrid reinforcement of SiC and graphite was used to study the mechanical and tribological properties of Al 7075 alloy. Five weight percent Gr and ten weight percent SiC were added to Al 7075, which has a very high strength to-weight ratio. The testing included hardness, wear resistance, tensile strength, and coefficient of friction. **The hybrid composite performed better than the unreinforced alloy in all respects.** Hardness increased from 130-135 BHN to 170-180 BHN, and tensile strength increased from 510-540 MPa to 600-630 MPa. The wear rate decreased from 8.5×10^{-4} to 3.5×10^{-4} $mm^3/N\cdot m$, and coefficient of friction reduced to 0.30-0.32. SEM studies revealed good distribution of reinforcement with less porosity. **The main advantage of this hybrid composite is SiC bearing the load, whereas graphite provides good lubrication.**

Keywords: Alloy; Silicon carbide; Graphite; Hybrid; Tribological characteristics

1. Introduction

Aluminum alloy 7075 (Al 7075) from the 7000 series is often used in the aerospace and automotive industries for high-stress structures because it is very strong, tough, and resistant to fatigue [1]. Copper and magnesium are often found in small amounts in zinc alloys. Zinc is the most important metal used to make alloys. The metal is very strong for its weight, which is why it is used in so many different types of buildings, such as cars, ships, planes, and missiles [2].

Pure Al 7075 has great mechanical properties, but it doesn't resist wear well and has a lot of sliding friction. These defects become catastrophic when durability and reliability are paramount. The use of composite engineering as a method of enhancement has thus grown in popularity. Metal matrix composites, which incorporate ceramic or solid lubricant particles into a metal matrix, may provide an answer to these problems [3]. Notable reinforcements that complement each other include silicon carbide (SiC) and graphite (Gr): Graphite enhances lubricity and wear resistance, whereas SiC increases hardness and strength.

When used in conjunction with metal matrices, the ceramic phase SiC considerably improves the materials' resistance to wear, stability at high temperatures, and pulling strength. When used alone, graphite's soft lubricant phase improves self-lubricating characteristics and decreases friction, but it weakens composite strength [4].

Hybrid MMCs may be made by incorporating ceramics, fibers, or solid lubricating materials into metal matrices the majority of which are aluminum-based [5]. Composites made using this method are enhanced mechanically and tribologically, and they are very stiff and have a low density. For lightweight and long-lasting structural applications, aluminum-based MMCs are highly sought after due to their resistance to corrosion and high specific strength [6].

Aluminum, magnesium, and copper come together in Al 7075, a zinc alloy with exceptional strength. It has become the standard in high-performance automobiles and aircraft due to its exceptional mechanical characteristics [7]. Unreinforced Al 7075 has poor wear and friction properties. There are still limits for extreme tribological conditions, although studies have shown that treatment procedures like retrogression and reaging can improve wear resistance under certain conditions [8].

A lot of study has gone into the possibility of using SiC to strengthen aluminum MMCs. Durability and resistance to wear are both greatly enhanced. The hybrid composite of Al_2O_3 and SiC also showed improved tensile and wear characteristics [9].

Graphite's properties as a solid lubricant, such as lower friction and wear resistance, help aluminium composites. Com-

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posites filled with graphite create a tribo-lubricating layer that cuts down on wear and contact between metals. An excess of graphite can hurt the strength and fracture toughness of composites, though [10].

There is a need for further investigation into the potential for integrating SiC and Al_2O_3, or TiC and Ti, into hybrid metal matrix composites (MMCs). For example, stir-cast Al 7075 MMCs reinforced with SiC and Al_2O_3 were made and improved using response surface methodology (RSM). These materials were much more resistant to wear. made the Al 7075 composites stronger by adding SiC and TiC reinforcements, which made them harder and less likely to wear out [11]. Other ceramic combinations, such as Si_3N_4/TaC/Ti, have demonstrated remarkable enhancements in mechanical and tribological properties.

Achieving homo dispersion and strong interfacial bonding is crucial for miniature multilayer composites. Composite performance can be drastically reduced by problems like reinforcement agglomeration and porosity. There have been reports regarding specific hybrid composites regarding graphite poor interfaces or SiC agglomeration [12]. The SEM results show that the aforementioned problem is directly eliminated by the homo dispersion of SiC + Gr with extremely small porosity, indicating successful processing and enhanced interfacial interactions in this study.

In short, the literature shows that SiC always makes things stronger and more resistant to wear, but it can also make machining and even agglomeration harder. Although graphite improves self-lubrication and decreases friction, its mechanical strength decreases with prolonged use. These advantages could be accommodated by hybrid composites, but to eliminate undesirable effects like porosity or insufficient interface bonding, extremely controlled processing and composition are necessary [13].

Recent research work has also revealed the superiority of hybrid Al MMCs with a controlled combination of reinforcement materials and their dispersion, especially when it comes to dry friction conditions. In most such researches, however, either ceramic-ceramic hybrid materials are studied or optimizing models are applied, which provide few laboratory contributions toward the approach when ceramics are combined with solid lubricants [14,15].

Under the above references, a novel aspect of the current study is the evaluation of a particular hybrid composition (10 wt.% SiC + 5 wt.% Gr) in Al 7075 under a set of combined parameters such as strength, tribological properties, and friction coefficient by micro-structural investigations using SEM, since the above previous researches are preferably conducted by the optimization strategies or a combination of the above ceramics. There is a direct relationship between the load-carrying capacity of SiC and the graphite lubrication by a simple processing technique.

2. Experimental

2.1. Materials and methods

Zinc, copper, and magnesium are the main constituents of the incredibly durable aluminium alloy Al 7075. It is a popular option in the automotive, defence, and aerospace industries due to its exceptional strength-to-weight ratio. Despite being mechanically stronger, it has poor tribological behaviour and wear resistance under heavy loads. To improve surface durability while maintaining weight reduction, reinforcing with ceramic and solid lubricant particles is crucial [16].

A hard ceramic with a very high elastic modulus, wear resistance, and thermal stability is silicon carbide [16]. SiC reinforcement has the potential to greatly increase the composite's hardness, tensile strength, and load-bearing capacity. Better dimensional stability under service conditions is also influenced by its high stiffness and thermal conductivity. However, hybrid reinforcement concepts are needed because SiC alone can cause increased brittleness and decreased ductility [17].

Basal planes are easily sheared in graphite because of the layered structure of this naturally occurring crystalline carbon form. Because of this, it is an excellent solid lubricant for composites because of its low coefficient of friction. The tribological performance, self-lubrication, and wear rate of Al 7075 are all enhanced by the addition of graphite. Low strength owing to softness might result from an excess of graphite.

Fig. 1 illustrates the raw materials: Al 7075 ingot, SiC particles, and Gr powder. Fluxes are added at melting to avoid oxidation of the molten aluminum and to filter out impurities through dissolving them. Degassing agents such as hexachloroethane or inert gases such as argon are used to eliminate trapped hydrogen and other dissolved gases, which otherwise form porosity and decrease the cast composite's strength. Their employment ensures improved microstructural integrity, uniform dispersion of reinforcements, and improved mechanical properties [18].

Fig. 1. Raw Materials

2.2. Casting by Stir

The hybrid composite of Al 7075, SiC, and Gr is produced using machinery that employs the stir-casting technique. First, use an electric resistance furnace to bring the Al 7075 ingots to a temperature of approximately 740 to 760°C. Prior to adding the reinforcing particles, the base alloy can be uniformly heated and melted in the furnace.

In the present investigation, mechanical stirring has been carried out at 450-500 rpm speeds for 8-10 minutes. The melting point of Al 7075 has been maintained at 740-760°C. Silicon carbide, as well as graphite, has been preheated at 450°C. Steel cast molds have been preheated at 250-300°C.

A mechanical stirrer rotates the melted material into a vortex. The stirrer is very important because it makes sure that the reinforcing particles are mixed and spread out evenly. Before entering the vortex, graphite powder and preheated SiC are added. Particle agglomeration and pores are less likely to form when materials are preheated, which improves wettability and removes adsorbed moisture. The reinforcement materials are mixed evenly throughout the matrix by keeping the stirrer in a state of constant agitation for a few minutes.

After mixing, the composite slurry is poured into hot steel molds. Preheating helps reduce cracking and improve solidification homogeneity by preventing thermal shocks. As the composite cools and solidifies in the mold, it undergoes structural refinement, capturing the SiC and graphite particles that are part of the aluminum matrix. Consequently, a hybrid MMC was produced, which showed improved tribological properties as well as mechanical properties [19].

Fig. 2 illustrates the stir casting of Al 7075 with SiC/Gr reinforcements. Fig. 3 illustrates the obtained Al 7075–SiC/Gr composite samples.

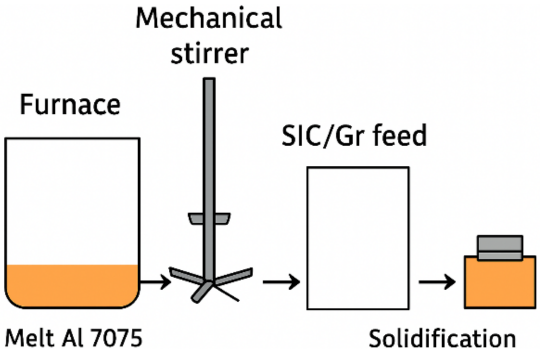


Fig. 2. Stir Casting Process

Fig. 3. SiC and Gr particles reinforced fabricated Al 7075 composite specimens

2.3. Brinell Hardness Test

Another common technique for assessing the dent resistance of metallic and composite materials is Brinell hardness testing (see Fig. 4). This method applies a specific load for a predetermined period of time by pressing an indenter made of tungsten carbide or hardened steel against the surface of the test piece. Substituting the imprint surface area and the applied load yields the Brinell Hardness Number, an expression for hardness. The Brinell test is also preferred for aluminum matrix composites due to its ability to provide a mean hardness value across a large surface area, which mitigates the effects of reinforcement clusters in specific areas [20].

Fig. 4. Hardness Test Machine

Hardness tests were conducted in this study according to ASTM E10 standards. In all Brinell hardness tests, a 10 mm diameter tungsten carbide indenter was used, as specified by ASTM E10. Before testing, the test specimens were polished to get rid of any rough spots on the surface. A 10 mm indenter and a 15-second dwell time were used to apply a 500 kgf load. For accuracy and reproducibility, more than one reading was taken from different parts of each specimen, and the mean value was recorded. This makes sure that the data shows the real hardness of the hybrid composites without changing how hard they are in different places. It has been observed in TABLE 1.

TABLE 1

Hybrid Al7075 + 10%SiC + 5%Gr (Hardness)

Specimen ID	**Hardness (BHN)**
S1	170
S2	175
S3	172
S4	168
S5	174
Mean = 171.8 BHN	

The following line graph (Fig. 5) shows the values of Brinell hardness of the five test pieces. There is a consistent trend with values ranging between 168 to 175 BHN, showing good consistency in reinforcement distribution in the matrix. The horizontal dashed red line shows the mean hardness value (171.8 BHN), showing improvement over that of the base Al7075 alloy. The small variations between specimens can be attributed as an outcome of minute variations in particle dispersion and microstructural effects at the local level but overall, the data confirms the enhanced hardness achieved by the hybrid reinforcement.

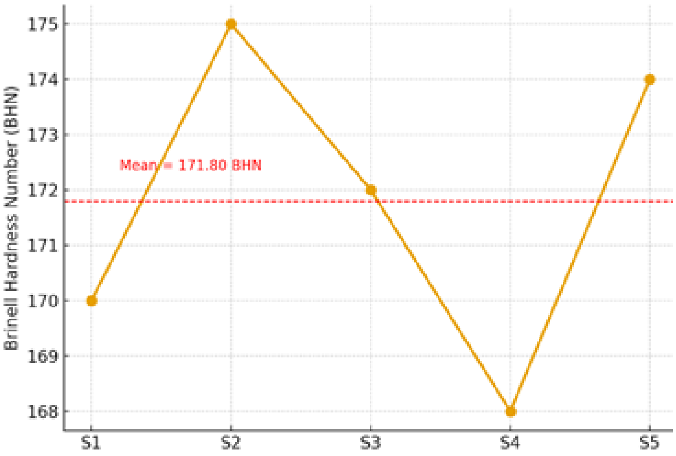


Fig. 5. Line Graph for Brinell hardness

2.4. Tensile Test

Tensile testing is one of the most basic methods for figuring out the mechanical characteristics of metallic and composite materials. These significant figures determine a number of critical structural applications, including yield strength, percentage elongation, and ultimate tensile strength (UTS) [21]. The specimen is tested by putting it under uniaxial tensile loading until it breaks. The behaviour of stress and strain is then measured. Fig. 6 shows how much reinforcement particles affect load transfer, crack initiation, and ductility in aluminium matrix composites. This shows how useful the tensile test is for these materials.

Fig. 6. Tensile Test

Fig. 7: A diagram of the sample for the tensile test, following ASTM E8 standards. The gauge length of the sample is 25 mm.

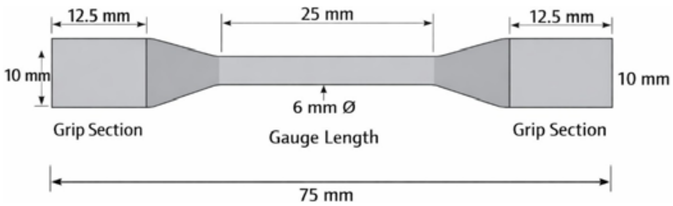


Fig. 7. ASTM E8 Tensile Specimen

The current study used the ASTM E8 guidelines for tensile testing, which include controlling the strain rate, the shape of the specimen, and the loading. We used a 25 mm gauge length to turn the samples into a dog-bone shape. We used a universal testing machine (UTM) to keep the loading rate at 1-2 mm/min, which was almost static. After the test pieces were put under more and more stress until they broke, the tensile strength values were recorded. We made sure that the results were repeatable by taking multiple samples and finding the average values. The results are in TABLE 2.

TABLE 2

Hybrid Al7075 + 10%SiC + 5%Gr (Tensile)

Specimen ID	Tensile Strength (MPa)
S1	610
S2	625
S3	618
S4	602
S5	628
Mean = 616.6 MPa	

Fig. 8, which is a line plot with markers, shows the tensile strengths of the five hybrid composite samples. The average tensile strength is 617 MPa, and the highest is 628 MPa. The standard Al7075 alloy usually has a range of 510-540 MPa, so this is a significant increase. The results show that a low scatter value means that the reinforcement is evenly spread out across the matrix. Local microstructural inhomogeneities, like graphite clustering or uneven SiC dispersion, can cause very small differences.

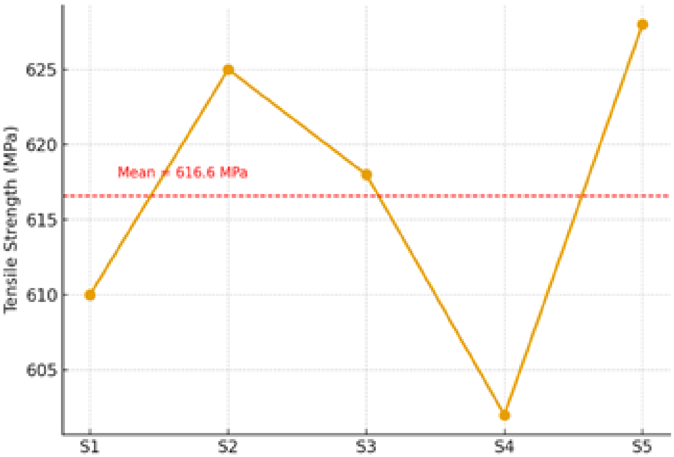


Fig. 8. Tensile Strength Line Plot

Significant improvement a synergistic strengthening effect is observed. Graphite reduces stress concentration at particle-matrix interfaces, while SiC particles act as effective load carriers by lubricating particle-matrix interfaces and SiC particles act as load carriers. This additional effect makes the hybrid composite tougher and better able to withstand damage.

2.5. Wear of Pin-On-Disc

The pin-on-disc test is frequently used to assess the tribological characteristics and wear resistance of metal and composite materials [22]. In the pin-on-disc test, a hardened steel or EN31 disc is rotated under a constant normal load while a specimen is clamped down by a fixed pin. It records the coefficient of friction and the rate of sliding wear. This method (Fig. 9) is ideal for aluminium matrix composites because it simulates sliding contacts, a feature common in the automotive and aerospace industries.

Wear rate, W, was calculated using a standard formula,

$$W = \Delta V / (F \times S)$$

where ΔV is volume loss in mm^3, F is the normal load in N, and S is the displacement of friction surface in m.

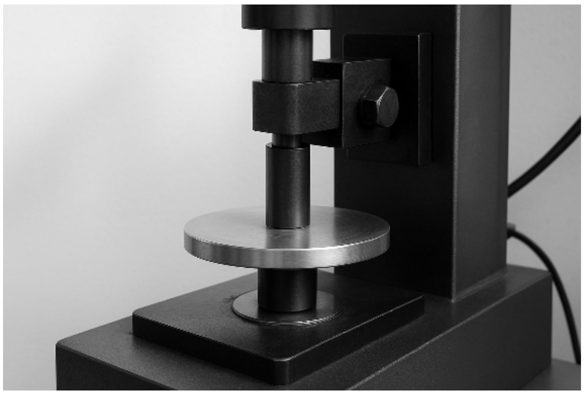


Fig. 9. Wear Test

The ASTM G99 guidelines were followed when conducting the tests [23]. Pins with a diameter of 8 mm and a length of 30 mm were produced based on the findings of the hybrid composite tests. The counter face's roughness value was approximately 0.2 μm, and it was a hardened steel disc. A 1000 m course, a 30 N load, and a 1.5 m/s sliding speed were all part of the experimental setup. The wear rate was calculated by measuring the weight change during wear using a precision balance. Without continuously monitoring the friction coefficient, which was accomplished with a load cell assembly, the testing could not continue. TABLE 3 presents the results.

TABLE 3

Hybrid Al7075 + 10%SiC + 5%Gr (Wear)

Specimen ID	**Wear Rate**	**Friction Coefficient**
S1	3.6	0.31
S2	3.5	0.30
S3	3.7	0.32
S4	3.4	0.31
S5	3.5	0.30
Mean Wear Rate = 3.54×10^{-4} $\text{mm}^3/\text{N}\cdot\text{m}$		
Mean COF = 0.31		

Under standard ASTM G99 conditions, the wear rate of a hybrid composite material comprising Al7075, 10% SiC, and 5% Gr was evaluated using the pin-on-disc machine. The five specimens that were tested had wear rates that varied little from 3.4×10^{-4} $\text{mm}^3/\text{N}\cdot\text{m}$ to 3.7×10^{-4} $\text{mm}^3/\text{N}\cdot\text{m}$. The mean value for unreinforced Al7075 alloy was 3.54×10^{-4} $\text{mm}^3/\text{N}\cdot\text{m}$, which was much higher than this. Both the load-bearing capacity of hard SiC particles and the solid lubricating qualities of graphite contribute to the wear-reduction effect. Fig. 10 clearly demonstrates that all of the specimens perform similarly with a good reinforcement distribution and homogeneity.

The pin-on-disc wear test machine was used in experiments to examine the frictional behavior of Hybrid Al7075 composites in accordance with ASTM G99. The machined parts were

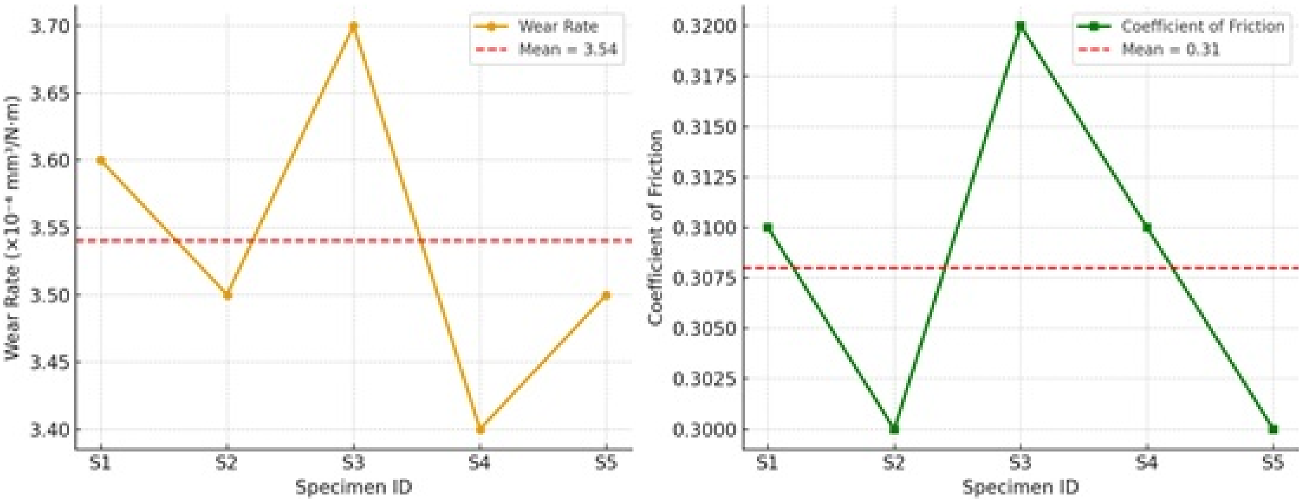


Fig. 10. Hybrid Material Friction Coefficient and Rate of Wear: The composition is Al7075 with 10% SiC and 5% Gr

a hardened EN31 steel disc counter face (HRC 60) and a cylindrical composite cast pin sample with a diameter of 10 mm by 25 mm. Specifics of the experiment: There is a 1000 m sliding distance and a speed of 1 m/s. There is a 30 Newton force applied. In a typical laboratory setting, dry sliding conditions are present.

An electronic load cell was used to continuously monitor the frictional force in order to calculate the test's Coefficient of Friction (COF):

$$\mu = F_f / N$$

where N was the applied normal load and F_f was the measured frictional force. TABLE 4 presents the outcomes.

TABLE 4

Hybrid Composite – 10% SiC + 5% Gr (COF)

Specimen ID	COF
S-1	0.31
S-2	0.30
S-3	0.32
S-4	0.31
S-5	0.30
Mean	**0.31**

Friction coefficient recorded for similar specimens was 0.30-0.32 with average value of 0.31. In relation to the base alloy, having COF value typically over 0.40, the hybrid composite has better tribological characteristics. The reduction in COF is actually caused by the graphite particles creating a lubricating film on contact interface that acts to decrease adhesion and energy losses [24]. The uniformity of COF in all samples as shown by the bar chart (Fig. 11) graph verifies the synergistic effect of SiC and Gr in enhancing wear resistance and surface durability.

The presence of graphite particles, which serve as a solid lubricant, is primarily responsible for the low COF. When you slide the coated discover a thin layer of graphite, it makes a protective lubricating film that keeps metal from touching metal as much [25]. But SiC particles do the opposite; they lower plastic deformation at the interface while still supporting the load. The combination of Gr and SiC will make the composite system more energy efficient, cause less wear on the adhesive, and create less friction.

3. Results and Discussions

3.1. Base Al7075 Alloy

Unreinforced pure Al7075 alloy's microstructure consists of a homogeneous aluminium matrix devoid of reinforcement or secondary particles. It has an even and smooth surface when observed under SEM, establishing the fact that there is no presence of any reinforcements. This unreinforced microstructure serves as the benchmark for comparison against reinforced composites. Lack of particles means lack of stress transfer points, limiting mechanical performance of the alloy to its inherent characteristics.

The XRD pattern for the unreinforced Al7075 alloy shows prominent diffraction peaks at 2θ = 38°, 44°, 65°, and 78°, reflecting the (111), (200), (220), and (311) planes of the FCC aluminum phase. The absence of secondary peaks suggests that the material is a single-phase alloy without any external reinforcements. These peaks will be used as a reference baseline against which composite samples will be compared, shown in Fig. 12.

3.2. Al7075 + 10% SiC Composite

The SEM micrograph of silicon carbide-reinforced Al7075 containing 10% silicon carbide contains well bright SiC particles well dispersed in the aluminum matrix. While the majority of the particles are well dispersed, there is partial agglomeration or clustering in some regions. SiC greatly enhances hardness and wear resistance, but agglomerated particles can act as stress raisers and initiate cracking under loading. This shows how important it is to have even dispersion during processing.

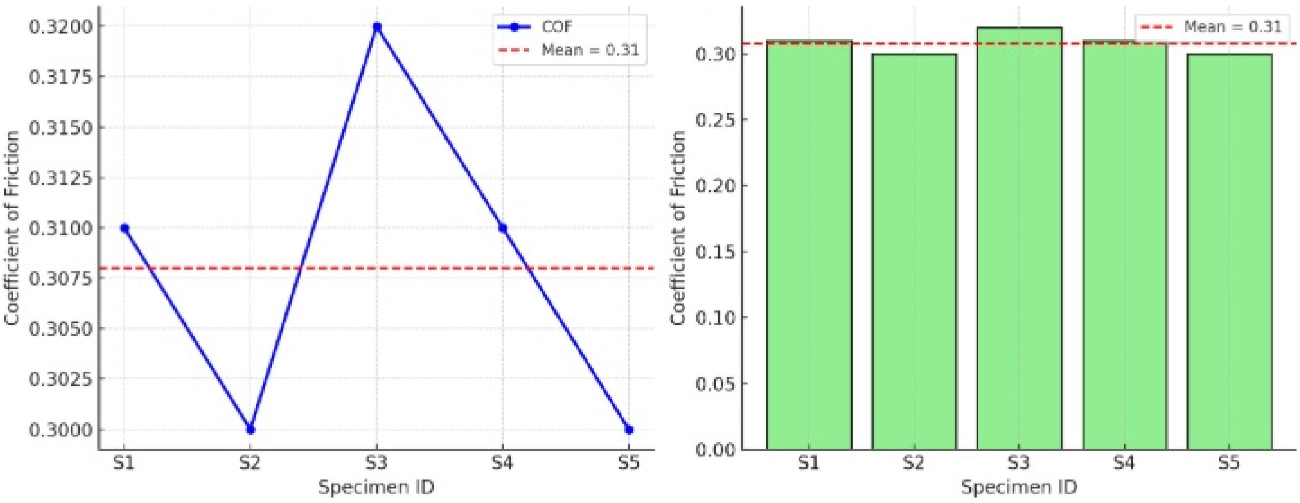


Fig. 11. Coefficient of Friction of Hybrid Al7075 + 10%SiC + 5%Gr

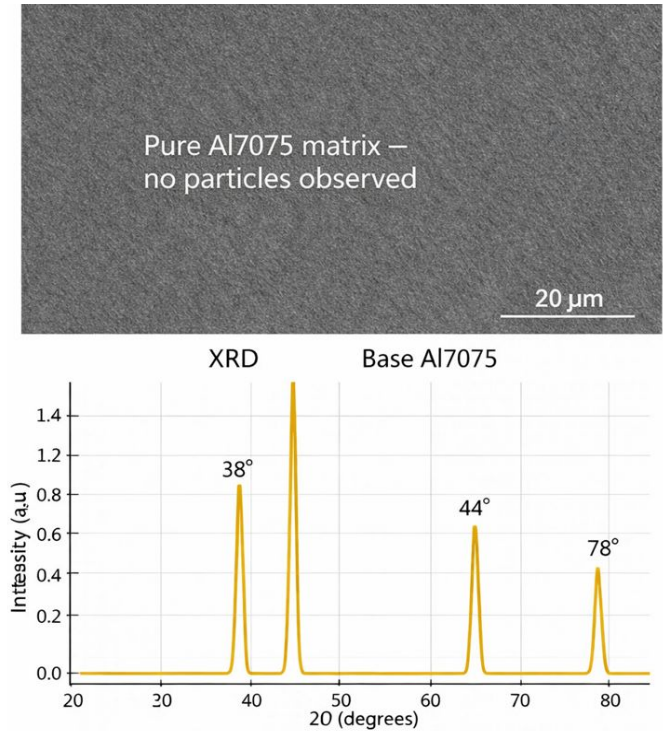


Fig. 12. XRD – Base Al7075

The XRD pattern for the 10% SiC reinforced composite has the same Al peaks as the matrix alloy, but it also has extra diffraction peaks at 2θ = 35.6°, 60°, and 72°, which are due to silicon carbide particles. The presence of both Al and SiC peaks confirms that the SiC reinforcements have been successfully added to the matrix. There is a slight broadening of the Al peaks, which could be caused by the hard ceramic particles distorting the lattice, as shown in Fig. 13.

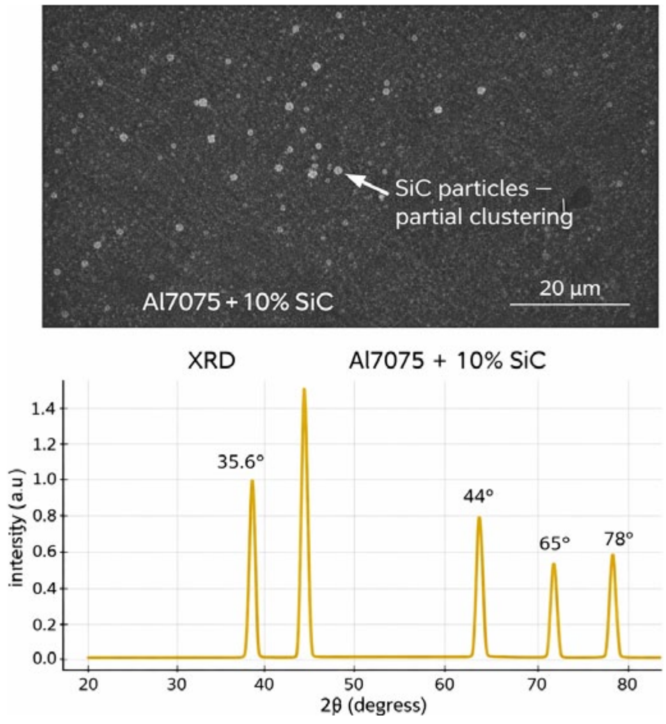


Fig. 13. XRD – Al7075 + 10%SiC

3.3. Al7075 + 5% Graphite Composite

There are dark flakes of different shapes and sizes in the Al7075 matrix, which is made up of 5% graphite. The picture shows that the flakes aren't all the same and that some parts of the graphite are porous. Bonding is harder when graphite and aluminium aren't very wettable, which is why the distribution is uneven like this. Graphite makes the composite's tribological and self-lubricating properties better, but its overall strength and integrity may be hurt by its porosity and weak bonding.

The XRD pattern of the composite with graphite filler shows the characteristic aluminium peaks and a distinct graphite diffraction peak at 2θ = 26.5°, which is the (002) plane of crystalline graphite. This shows that the matrix has stable crystalline graphite in it. The graphite reinforcement makes up 5% of the total weight, which makes sense because the graphite peak is much weaker than the aluminium peaks. Fig. 14 shows that the pattern might also show a small widening of the peaks. This could be due to stresses at the interface between the Al matrix and the graphite flakes.

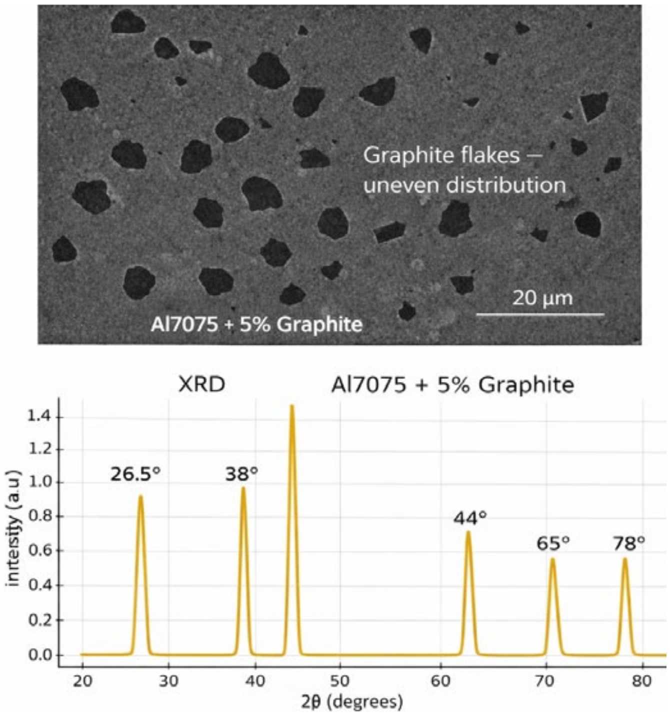


Fig. 14. XRD – Al7075 + 5% Graphite

3.4. Hybrid Composite (Al7075 + 10% SiC + 5% Gr) – Low Magnification

When viewed at low magnification, the aluminium matrix looks like a hybrid composite because it has both bright SiC particles and dark graphite flakes. Overall, the distribution is uniform, and the number of defects is lower compared to composites with only one reinforcement. The combination of SiC's increased hardness and wear resistance with graphite's solid lubrication and low friction makes for a very useful material.

The hybrid composite's improved strength and wear resistance are results of this balance.

The XRD pattern of the hybrid composite shows all three phases: the carbon (Cr) phase at 26.5°, the aluminum (FCC) phase at 38°, 44°, 65°, and 78°, and the silicon carbide (SiC) phase at 35.6°, 60°, and 72°.

Verification of proper reinforcement incorporation into the aluminum matrix is provided by the co-occurrence of Al, SiC, and graphite diffraction peaks. Since SiC has a higher content (10% vs. 5%), the intensity ratio reveals that its peaks are more prominent than graphite's. Fig. 15 shows that the composite is stable due to the absence of phase transformation and chemical reactions caused by the far-apart peaks.

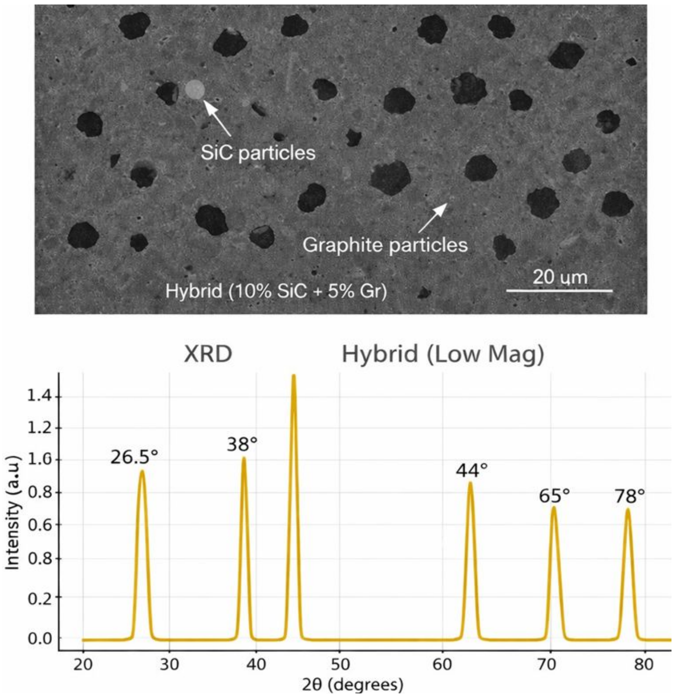


Fig. 15. XRD – Al7075 + 10% SiC + 5% Gr (Low Magnification)

3.5. Hybrid Composite (Al7075 + 10% SiC + 5% Gr) – High Magnification

As XRD is independent of magnification, the high-magnification pattern will be purely identical to that of the low-magnification scenario. The peaks of Al, SiC, and graphite occur at the same 2θ values. But on careful observation, there will be subtle peak broadening or shifting, which could be due to residual stresses and fine grain structure achieved during composite processing. The mixture of SiC (which imparts hardness and wear resistance) and graphite (which offers lubrication) is well defined in the multiphase XRD pattern, shown in Fig. 16.

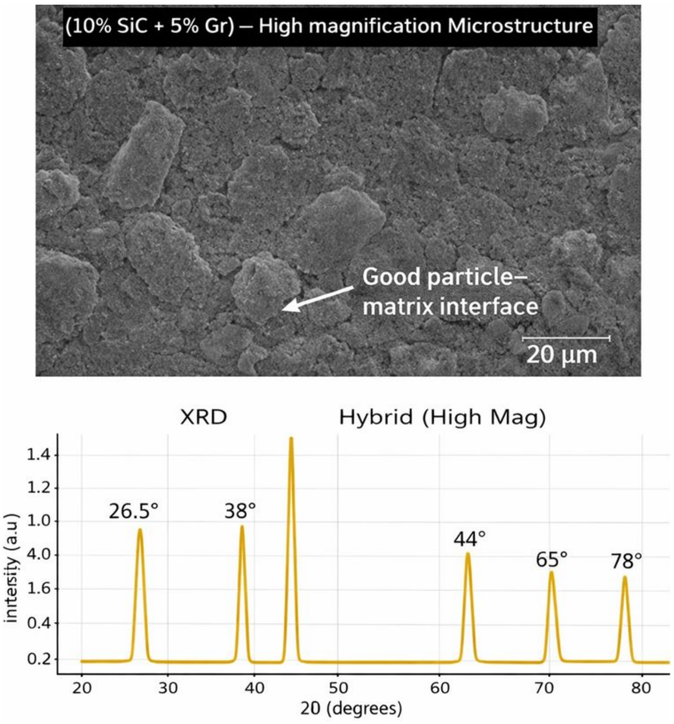


Fig. 16. XRD – Al7075 + 10% SiC + 5% Gr (High Magnification)

3.6. Interface Quality and Phase Analysis

The comparison of the microstructures makes it clear how the type of reinforcement and the quality of the interface affect the overall performance of the Al7075-based composites. Without secondary phases, the unreinforced alloy can only transfer loads through the aluminium matrix, which limits its mechanical and tribological performance. SEM shows that most of the SiC particles in the Al7075 + 10% SiC composite is well embedded in the aluminium matrix. However, there are some areas where the particles are clumped together. In fact, these kinds of agglomerates can act as stress-concentration points and start microcracks when they are put under mechanical stress, which makes them less ductile.

On the other hand, the graphite-reinforced composite has weak particle-matrix interfaces because graphite doesn't mix well with molten aluminium. This causes some areas to become porous and unevenly dispersed, which can weaken the overall structure while making it easier for it to self-lubricate. The better interface quality of the hybrid composite (Al7075 + 10% SiC + 5% Gr) is due to graphite, which reduces the stresses at the interface and makes it easier for the two materials to slide past each other. SiC particles, on the other hand, act as the main load-bearing reinforcement. This kind of reaction makes the dispersion more even, the porosity lower, and the bonding between the particles and the matrix stronger in both low- and high-magnification SEM images.

The results of the XRD test also confirm what was seen in the microstructure. The unreinforced Al7075 alloy has sharp FCC aluminium peaks, which means it has a single-phase matrix. The SiC-reinforced composite has more SiC peaks and slightly wider aluminium peaks, which show that the hard ceramic particles are causing the lattice to distort. The graphite-reinforced composite has a relatively low-intensity graphite (002) peak that matches its lower weight fraction and layered crystal structure. Minor peak broadening could be caused by residual stresses and weak bonding between the two surfaces.

The fact that the XRD analysis of the hybrid composite shows peaks for aluminium, SiC, and graphite, but no new intermetallic phases, shows that the system is thermally and chemically stable. The SiC peaks are stronger than the graphite peaks because they have more reinforcement, which supports the idea that SiC is the main strengthening substance. These results are very similar to the most recent studies on Al7075-based hybrid metal matrix composites that were published between recent years. They show that ceramic-solid lubricant hybrid systems have better dispersion, interface quality, and tribological properties than composites that are only reinforced with one type of material. The hybrid composite shown here has better microstructural homogeneity and phase stability than what is currently known, and it doesn't need to use complicated optimization methods. This shows how effective and useful the proposed strategy of reinforcement is in industry.

3.7. Hardness Comparison

See TABLE 5 for the Brinell hardness (BHN) values of Al7075 and composites. The average hardness of the unreinforced base alloy was 132 BHN, but after adding 10% SiC, it increased to 155 BHN, a growth of approximately 17%. The dislocations can't move around much because SiC particles are so hard and stiff. Since graphite, being a solid lubricant, does not add much to hardness but does improve tribological properties, adding 5% graphite resulted in a moderate rise in hardness (143 BHN). The maximum hardness of the hybrid composite (Al7075 + SiC + Gr) was 171.8 BHN, which is 30% harder than the base alloy. The load-carrying capacity was enhanced by the synergistic effect of uniformly distributed dispersoid graphite and hard SiC particles, as shown in Fig. 17.

TABLE 5

Comparison (Hardness in BHN)

Condition	S1	S2	S3	S4	S5	Mean
Base Al7075	130	132	131	134	133	132
10% SiC	155	158	152	156	154	155
5% Gr	142	145	143	144	141	143
Hybrid	170	175	172	168	174	171.8

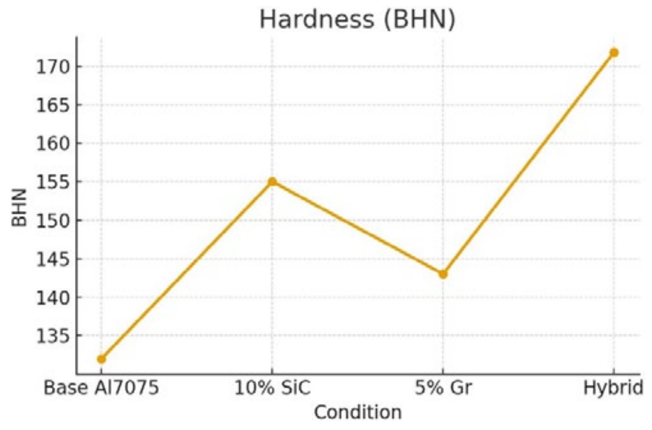


Fig. 17. Comparison plot for Hardness

3.8. Tensile Strength Comparison

TABLE 6 shows that the parent Al7075 alloy had an average ultimate tensile strength (UTS) of 521.4 MPa. The strength of a 10% SiC composite increased by about 8% to 563 MPa due to the efficient transfer of stress from the matrix to the ceramic reinforcement. The 5% Gr composite only experienced a moderate increase (530.8 MPa) due to graphite, which is primarily used as a lubricant and has very little reinforcing effect. The hybrid composite was 17% stronger than the base material, Al7075, reaching a maximum tensile strength of 610 MPa. This is due to the fact that the synergistic strengthening effect of SiC particles and the lubrication-enhanced crack-bridging effect of graphite cooperate to postpone failure, as illustrated in Fig. 18.

TABLE 6

Comparison (Tensile Strength in MPa)

Condition	S1	S2	S3	S4	S5	Mean
Base Al7075	512	525	518	530	522	521.4
10% SiC	560	565	570	558	562	563
5% Gr	530	535	528	532	529	530.8
Hybrid	605	620	612	598	615	610

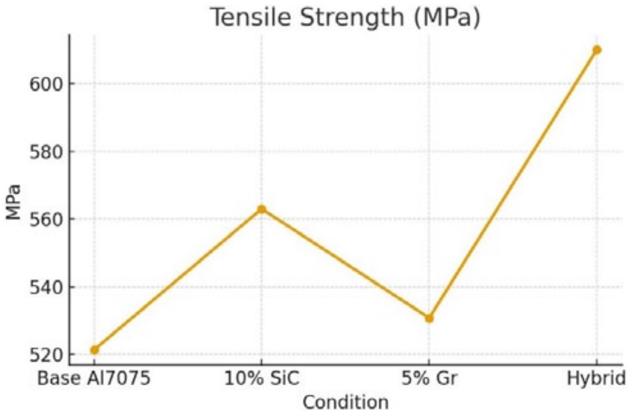


Fig. 18. Comparison plot for Tensile Strength

3.9. Wear Rate Comparison

TABLE 7 and Fig. 19 show the outcomes of the wear tests. The base alloy had the highest wear rate (8.5×10^{-4} mm^3/N·m) because it was the softest. Adding SiC reduced the wear rate to 5.0×10^{-4} mm^3/N·m due to the hard SiC particles' resistance to abrasion. Because graphite's lubricating effect created a transfer layer on the counter surface, the wear was reduced to 6.0×10^{-4} mm^3/N·m with its addition. The hybrid composite had a wear rate of 3.5×10^{-4} mm^3/N·m, which was 59% lower than the base alloy. This demonstrates that the wear resistance is significantly higher when Gr’s lubricity is combined with SiC’s hardness-improving characteristics.

TABLE 7

Comparison (Wear Rate in mm^3/N·m$\times10^{-4}$)

Condition	S1	S2	S3	S4	S5	Mean
Base Al7075	8.6	8.4	8.7	8.5	8.3	8.5
10% SiC	5	4.8	5.2	4.9	5.1	5
5% Gr	6	5.8	6.1	5.9	6	6
Hybrid	3.4	3.6	3.5	3.3	3.7	3.5

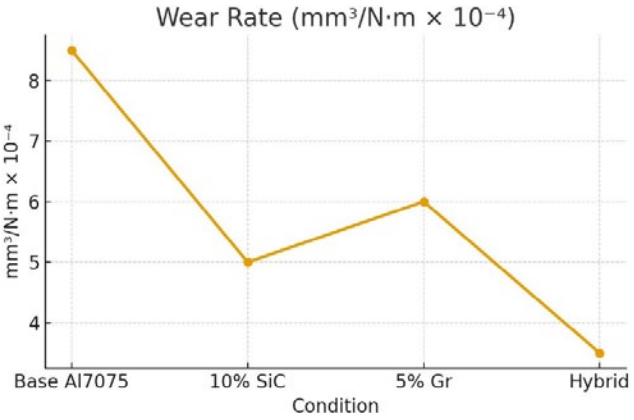


Fig. 19. Wear Rate Comparison Plot

3.10. Friction Comparison Coefficient

The COF numbers are in TABLE 8. The base Al7075 had the highest mean coefficient of friction (0.414), which means it had the most severe sliding wear. Graphite reinforcement made a film that acted as a lubricant, which lowered the COF to 0.334. SiC reinforcement lowered it to 0.374. The hybrid composite had the lowest COF (0.308) because of the combined effects of graphite lubrication and SiC strengthening. Fig. 20 shows that the hybrid composite works better in terms of tribology because the COF value goes down at the same time as the wear rate value.

TABLE 8

Comparison (COF)

Condition	S-1	S-2	S-3	S-4	S-5	Mean
Base Al7075	0.42	0.4	0.41	0.43	0.41	0.414
10% SiC	0.38	0.36	0.37	0.39	0.37	0.374
5% Gr	0.34	0.33	0.32	0.35	0.33	0.334
Hybrid	0.31	0.3	0.32	0.3	0.31	0.308

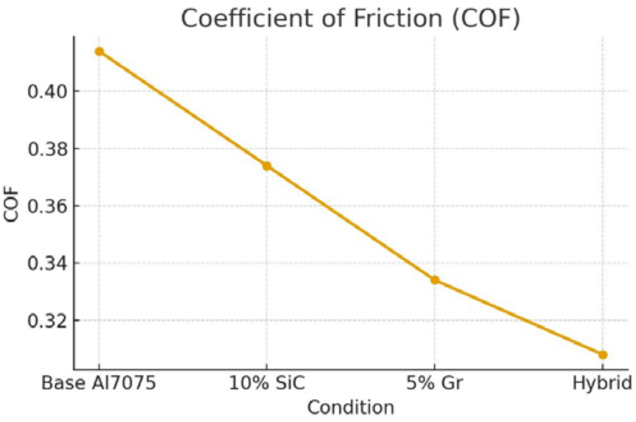


Fig. 20. Comparison plot for COF

3.11. A Review of the Mechanical and Tribological Properties of Al-7075 Material

Fig. 21 shows the combined graphs of hardness, tensile strength, wear rate, and coefficient of friction (COF) for the four conditions that were looked at: Base Al7075, 10% SiC, 5% Gr, and Hybrid (Al7075 + 10% SiC + 5% Gr). The results show that the ceramic and solid-lubricant reinforcement work together to greatly improve the alloy’s mechanical and tribological behaviour.

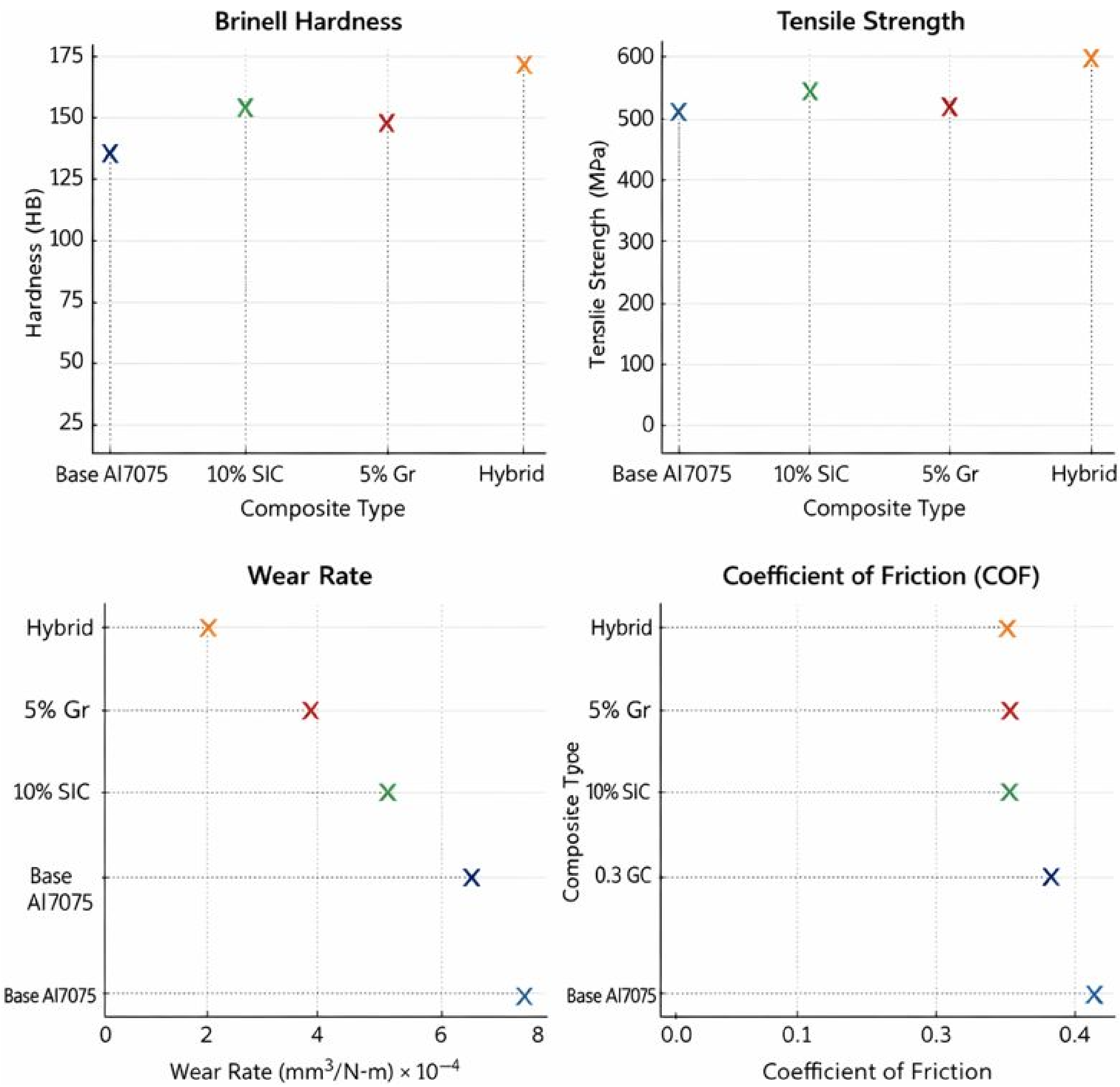
The unreinforced matrix Al7075 had an average Brinell hardness of 132 BHN. Adding SiC particles made the material harder, raising the hardness to 155 BHN. When combined with hard ceramic reinforcements, these particles greatly reduce dislocation mobility. Graphite is not as hard as SiC, so adding it alone only raised the hardness by a small amount (143 BHN). Hardness testing showed that the best microstructure and indentation resistance in the hybrid composite came from mixing SiC (particle reinforcement) and Gr (lubricating filler). The highest value was 171.8 BHN.

A similar trend was noted for tensile strength. The base alloy had a tensile strength of 521.4 MPa on average. However, the composite with 10% SiC had a tensile strength of 563.0 MPa because the particles made it stronger and helped it transfer loads better. After adding graphite, there was a small improvement of 530.8 MPa. This could be because graphite has a flake-like structure that doesn’t really help with load transfer. The hybrid composite had a maximum tensile strength of 610 MPa, which is a big jump of 17% over the base alloy. Graphite makes it easier for cracks to bend and stress to spread out when they are loaded, while SiC particles make the matrix stronger.

The data on wear rates showed that hybridization was the most important factor. The 10% SiC and 5% Gr composites had lower wear rates than the base Al7075 (8.5×10^{-4} mm^3/N·m and 6.0×10^{-4} mm^3/N·m, respectively). This is because SiC is hard and graphite is slippery, which reduces the amount of metal-to-metal contact during sliding. The hybrid composite had the lowest wear rate (3.5×10^{-4} mm^3/N·m), which shows that the two reinforcements work together to stop wear mechanisms.

These findings were confirmed by the COF results. The average COF of the base alloy went down to 0.374 when SiC was added and to 0.334 when graphite was added. The hybrid system got the lowest COF (0.308) by using graphite to lower frictional resistance and SiC to keep the surface intact under load.

In conclusion, the results emphasize the importance of hybrid reinforcing techniques for Al7075 composites. Adding SiC or graphite alone can improve some properties, but the hybrid


Brinell Hardness

Tensile Strength

Wear Rate

Coefficient of Friction (COF)

Fig. 21. Summary of Al-7075 Composites' Mechanical and Tribological Characteristics

composite always outperformed the others. This compromise on mechanical strength, hardness, wear resistance, and minimum friction makes it possible to use hybrid Al7075-SiC-Gr composites in high-performance structural and tribological applications, such as aerospace and automotive parts.

3.12. Worn Surfaces

3.12.1. Pure Al7075 Matrix – No Reinforcement Particles

Prior to Wear: Pure Al7075 alloy micrograph reveals a smooth and featureless surface without any reinforcement particles visible, just the aluminum matrix.

Post-Wear: Pure Al7075 matrix after the wear test reveals severe damage to the surface in the shape of deep grooves and sliding direction plastic deformation. Insufficiency of reinforcement particles renders the alloy more prone to adhesive wear, resulting in excessive material transfer, ploughing, and even local delamination. The surface after wear is rough with micro fractured cracks and pits due to microfractures of the matrix. This microstructure has the poorest wear resistance in all samples, shown in Fig. 21(a).

3.12.2. Al7075 + 10% SiC

Scanning electron micrographs show that the SiC particles are scattered throughout the Al7075 matrix prior to wear, with some even grouping together. Compared to an unalloyed alloy, a reinforcing alloy is more durable and wear-resistant.

Broken or fractured SiC particles are embedded within the matrix on the surface that has been worn after the wear test. Vapors and micro-pits are created when certain SiC particles displace. Grooves do form due to abrasive sliding, but they are less deep in reinforced alloy than in unreinforced alloy, indicating better resistance to wear. Fig. 22(b) shows that although SiC prevents plastic deformation, sliding causes stress concentration, which in turn induces microcracks around particle-matrix interfaces.

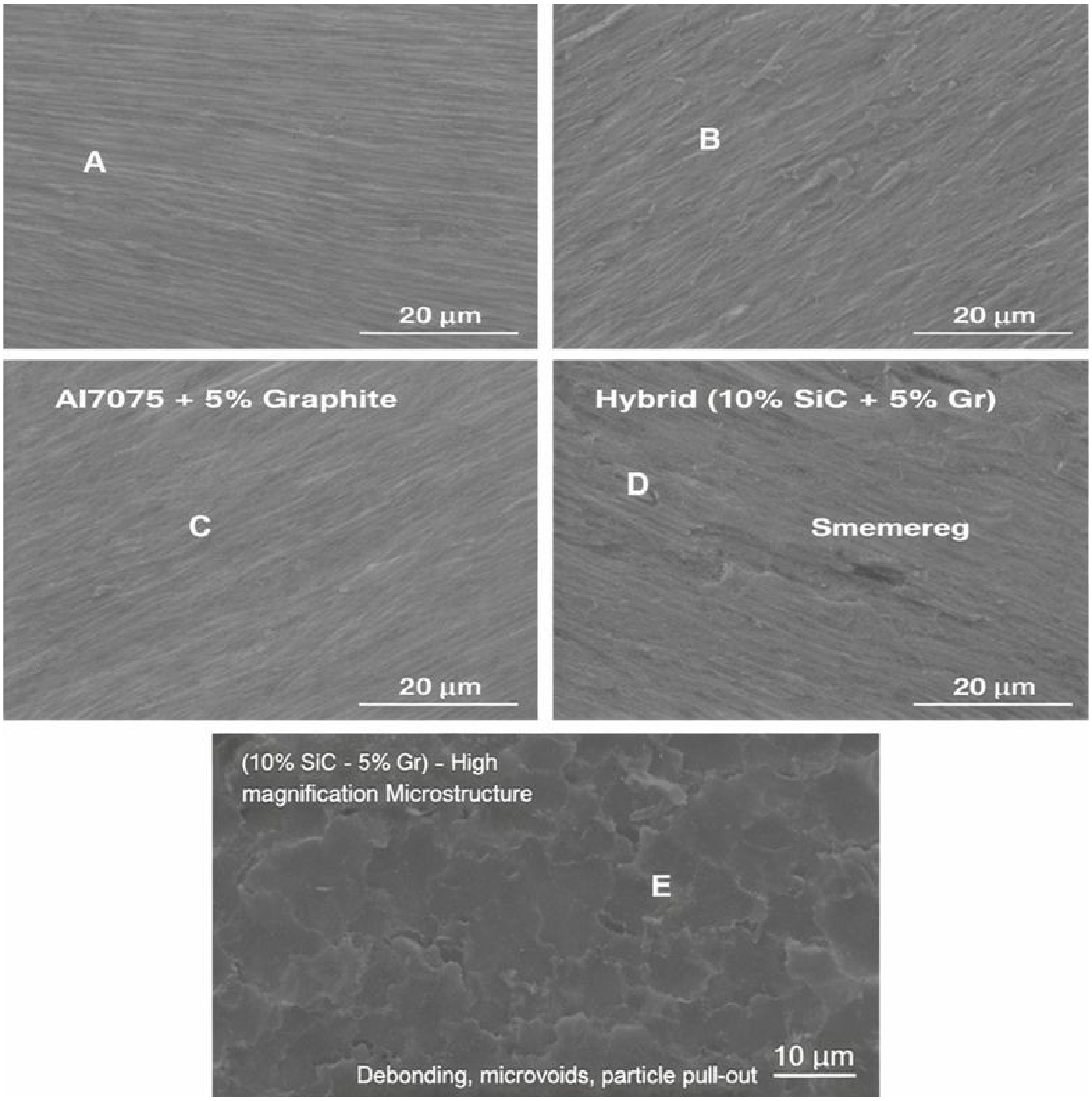


Fig. 22. Worn Surfaces

3.12.3. Al7075 + 5% Graphite

Prior to Wear: The microstructure reveals that the matrix contains graphite flakes that are dispersed in an irregular pattern. As a solid lubricant, graphite reduces sliding friction.

Following the wear test, a thin lubricating film will form and graphite smearing will be visible on the wear track's surface. It produces grooves that are not as noticeable as those of pure alloy. It will remove some flaky graphite particles and leave small surface pits, but the lubricating action is lessening significant ploughing. Because of graphite's self-lubricating qualities, a wear mechanism that combines lubricated adhesive wear with mild abrasive wear results in less surface damage Fig. 22(c).

3.12.4. Hybrid (Al7075 + 10% SiC + 5% Graphite)

Before Wear: SiC and graphite particles are easily visible in the hybrid composite microstructure preserved in the matrix. SiC provides hardness and wear resistance, and graphite provides solid lubrication.

After Wear: Maximum combination of properties is achieved in the hybrid composite after wear test. Relatively shallow grooves on the worn surface are due to both SiC's deformation resistance and graphite's friction lowering. Very few SiC particles debond or crack, and smeared graphite partially fills up voids and forms a protective tribolayer. Such a reinforcement synergistic effect enhances wear resistance to far above single-phase composites. The wear microstructure is smoother than for individual Al+SiC and less cracked and pitted than for individual Al+Graphite, shown in Fig. 22(d).

3.12.5. Hybrid (10% SiC + 5% Gr) – High Magnification (Good Particle-Matrix Interface)

Before Wear: Particles of graphite and SiC are clearly visible in the hybrid composite microstructure that is retained in the matrix. Graphite offers strong lubrication, while SiC offers hardness and wear resistance.

After Wear: The post-wear test SEM photomicrographs taken at high magnification indicate that although some particles are well-bonded, others may experience partial debonding under the sliding stresses. Small voids and microcracks occur where particles are pulled out. The graphite particles smear onto the surface, leaving thin lubricating films in the grooves, while broken SiC particles are responsible for abrasive wear but also shield the surface from over-deformation. The cumulative worn microstructure also exhibits excellent performance in comparison with single-reinforced composites, which supports that hybrid reinforcement maintains a healthy particle-matrix interface even in wear, shown in Fig. 22(e).

3.13. Overall discussion

Experimental observations indicate uniform enhancement in mechanical and tribological performance with reinforcement. SiC contributed hardness and wear resistance primarily, and graphite added substantial enhancement in lubricity and minimum COF. Hybrid composite, when used in combination, delivered the best overall performance with enhanced hardness and tensile strength, along with enhanced wear resistance and minimum COF.

Surface wear analysis, obtained after pin-on-disc tests, gave more insight into wear mechanisms. The majority Al7075 alloy showed extensive abrasive grooves and material delamination, implying deteriorated sliding wear resistance. SiC composite illustrated less surface damage with softer grooves due to hard SiC particles resisting micro-cutting. The worn tracks were smoother and the transfer film was established for the graphite-reinforced composite as would be the situation for its solid lubricant behavior. The hybrid composite had the most even worn surface, with the least amount of ploughing and smoother tracks. This was because the graphite lubrication and SiC strengthening worked together. This once more shows how much better the hybrid reinforcement method works in tribology.

Al7075-SiC-Gr hybrid composites are the best choice for aerospace and automotive applications because they are both strong and resistant to wear.

4. Conclusion

This study demonstrates that the mechanical and tribological properties of the Al7075 alloy were significantly improved through the addition of hybrid reinforcing particles composed of graphite (Gr) and silicon carbide (SiC) during the stir-casting process. The experimental procedure involved material preparation, stable stir-casting, and a standardized method for evaluating hardness, tensile strength, wear behavior, and the coefficient of friction (COF). Microstructural analysis showed that the hybrid composite had less porosity and was able to incorporate particles better than the test specimens that were reinforced with only one material.

Compared to the parent alloy and certain reinforcements, the hybrid composite material's capabilities were significantly superior. The increases in tensile strength (from 521.4 MPa to 610 MPa) and hardness (from 132 BHN (parent) to 171.8 BHN) demonstrated that SiC was involved in the load-carrying and hardening processes at the interface between the matrix and the reinforcement. According to tribological tests, the coefficient of friction decreased less (from 0.414 to 0.308) and the wear rate decreased significantly (from 8.5×10^{-4} to 3.5×10^{-4} $mm^3/N\cdot m$). This is because Gr's solid-lubricating qualities were enhanced by SiC's wear resistance.

These conclusions were supported by the post-wear surface examination results: the hybrid composite showed less surface degradation and smoother tracks, the base alloy showed significant wear damage, the SiC reinforcement reduced abrasive wear, and graphite increased the production of lubricating films. The results show that the hybrid system exhibits the best combination of strength, wear resistance, hardness, and lubricity.

Ultimately, the hybrid reinforcement technique improved the tribological and mechanical characteristics at the same time. This shows that Al7075-SiC-Gr composites can be used in automotive and aerospace applications where materials must be incredibly strong, lightweight, and resistant to wear. The best ways to scale processing methods, the best ways to heat treat materials, and the ideal ratios of reinforcement can all be investigated in future studies.

In order to increase strength, ductility, and wear resistance, future research may optimize the reinforcement weight fraction ratio. It would be very helpful to conduct a thorough analysis of how post-processing heat treatments, such as solution treatment and aging, affect the development of microstructure and tribological characteristics. The application potential of Al7075/SiC/Gr hybrid composites in aerospace applications will be greatly expanded by additional research on fatigue behavior, high-temperature wear resistance, and scaling up the stir-casting process.

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