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Nano-Sized Al_2O_3−Gr Reinforced Al7075 Hybrid Composite: Impact of Cooling Agents on Mechanical, Wear, and Fracture Behavior

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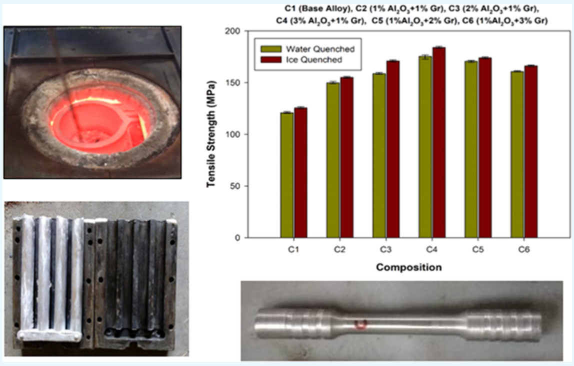
ABSTRACT: Aluminum metal cast composites (AMCCs) are frequently used in high-tech sectors such as automobiles, aerospace, biomedical, electronics, and others to fabricate precise and especially responsible parts. The mechanical and wear behavior of the metal matrix composites (MMCs) is anticipated to be influenced by the cooling agent's action and the cooling temperature. This research paper presents the findings of a series of tests to investigate the mechanical, wear, and fracture behavior of hybrid MMCs made of Al7075 reinforced by varying wt % of nano-sized Al_2O_3 and Gr and quenched with water and ice cubes. The heat-treated Al7075 alloy hybrid composites were evaluated for their hardness, tensile, and wear behavior, showcasing a significant process innovation. The heat treatment process greatly improved the hybrid composites' mechanical and wear performance. The samples quenched in ice attained the highest hardness of 119 VHN. There is a 45.37% improvement in the hardness of base alloy with the addition of 3% of Al_2O_3 and 1% of graphite particles. Further, the highest tensile and compression strengths were found in the ice-quenched 3% Al_2O_3 and 1% graphite hybrid composites with improvements of 34.2 and 48.83%, respectively, compared to the water-quenched base alloy. Under the samples quenched in ice, the mechanical and wear behavior improved. The tensile fractured surface showed voids, particle pullouts, and dimples. The worn-out surface of wear test samples of the created hybrid composite had micro pits, delamination layers, and microcracks.



1. INTRODUCTION

Aluminum alloys are employed as auxiliary structural metals second only to steel. Aluminum wrought materials are those aluminum products subjected to plastic deformation by secondary operations like hot and cold working processes.[1,2] Cast iron and steel parts can be replaced with metal matrix composites (MMCs), especially when aluminum is utilized as the basis material (Al).[3] As aluminum alloy offers low density, high specific strength, and a greater strength-to-weight ratio than ordinary Al alloy, it has recently drawn much attention for use in aerospace applications.[4] Al composites are the most cutting-edge lightweight materials.[5,6]

Stir casting is the primary technology used to create aluminum composites. The stir-casting process is a particular liquid-state casting procedure (vortex technique).[7] The production of Al MMCs employing silicon carbide/alumina oxide as reinforcing particles can often benefit from this. The reinforcing particles distribute extremely effectively into the liquid metal aluminum in this procedure and can be cast into any desired shape.[8] To prevent the molten metal's chemical reaction with oxygen, making it gas-free before adding the reinforcing particles is crucial. Proper mixing is crucial to ensuring the reinforcing particles are evenly dispersed throughout the metal.[9] Therefore, a rotor is revolved inside the molten metal to generate a vortex, ensuring proper operation, and the gas-free reinforcement is added to the liquid. The traditional casting procedure can be used to form the fabrication. Many problems, including gas entrapment and slag creation in the melt, could arise during this process.[10] As a result of these two problems, the melt could develop flaws, including high porosity and micro imperfections. There may also be unintended interactions between reinforcements and the matrix.[11] To prevent these problems, process variables like melt holding temperature, melting stirring time, molten metal temperature, choice of a suitable matrix, and reinforcement must be carefully regulated.[12] In general, the wettability of reinforcements is one issue with the stir-casting procedure used

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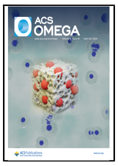

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to fabricate composites. The limited wettability causes reinforcements to be distributed unevenly.[13] An uneven distribution of reinforcements can cause a material's strength to decrease. The heat treatment procedure is one method for increasing material strength.[14]

In addition to increasing grain refinement, heat treatment processes can strengthen the bonds between the reinforcement and matrix. An Al composite that is often used in automobile components is Al7075-Al_2O_3-Gr. For automotive parts, Al composites are frequently heat-treated under T6 conditions.[15] Heat treatment is a set of heating and cooling procedures used to alter the mechanical and physical characteristics of the resulting composite.[16] The heat treatment involves heating to a specific temperature and cooling in various cooling media. Al MMCs are typically heated under T6 conditions, followed by several stages: solutionizing, quenching, and artificial aging, which are the final steps.[17,18]

Earlier studies demonstrate that heat treatment significantly affects the Al alloy's characteristics.[19] Results demonstrate that the heat treatment significantly influences the intermetallic bonding between the reinforcement and matrix material. Compared to their as-cast state, Al composites significantly improve their mechanical characteristics after heat treatment.[2021] At temperatures between 250 and 350 °C with strain rates between 0.001 and 0.1 s^{-1}, a tensile test of an Al alloy reinforced by silicon carbide and alumina particulates produced by powder metallurgy were carried out. The samples' yield and ultimate tensile strength declined as the temperature and strain rate rose. As the true strain rose, the work hardening of particulate-reinforced Al composite materials suddenly surged to a maximum and rapidly declined. Higher work hardening rates might be achieved at larger strain rates and lower temperatures.

Cevik et al.[22] investigated how peak-aged heat treatment affected the corrosion behavior of the Al_3Ti-containing AA 6063 alloy. With an increase in the Ti concentration, the alloys that underwent the homogenizing heat treatment became harder. But while alloys without titanium (Ti) obtained high hardness over a shorter time, alloys with titanium (Ti) attained lower hardness over a longer time. The findings of the corrosion tests showed that, in homogenized and aged circumstances, the corrosion rate decreased in alloys containing less than 1% Ti and also increased in alloys containing more than 1% Ti content. Another finding was that heat treatment during aging increased corrosion resistance. Typically, this precipitation improves a produced material's tensile and hardness properties. The material properties of the composite were impacted by heat treatment using various quenching media. The cooling rate should be high enough for the developed composite to have superior strength. Slamet et al.[23] investigated the impact of heat treatment on the mechanical characteristics and microstructure of Cu 20 wt % Sn. The study concludes that postcasting heat treatment changes the material's microstructure by enlarging small coarse grains and causing segregation at grain borders. Decreased porosity is followed by increased mechanical qualities such as hardness, bending strength, tensile strength, and modulus of elasticity as the density increases. Cooling rates greatly influence composites' material characteristics and microstructure.[24,25] The precipitant is typically changed by the pace of cooling, which modifies the alloy's material properties. The development of severe precipitation causes a loss in the mechanical characteristics of the formed composite materials, though reinforcements are added further. For the Al "7" series, cooling must be done slowly, and the generated material subsequently needs to be quenched at delicate temperatures to prevent heterogeneous precipitation.[11,26] The better mechanical behavior occurs when the temperature is below 200 °C since the cooling rate is typically retarded at that temperature.[27−29]

Leyland et al.[30] demonstrated the significance of maximizing the hardness-to-elastic modulus ratio for creating coatings for applications requiring wear resistance. It has been shown that in this sense coatings made of nanocomposite materials offer unique benefits. In particular, metal−metal nanocomposites show promise due to their corrosion characteristics, mechanical and tribological behavior, and ability to compete economically with conventional coatings regarding feasible thicknesses and deposition rates. Also, the work is extended to the creation of ceramic−ceramic, ceramic−amorphous, and ceramic−metal nanocomposite coatings and discusses how important they are for real-world use. They also discussed how important elastic strain is for failure and how fracture toughness affects tribological behavior.[31]

Ravikumar et al.[32] examined Al7075, reinforced with nanoscale SiC−Gr using a stir-casting method, and both its mechanical properties and microstructure were assessed. It was discovered that the reinforcements are distributed uniformly across the foundation material. When SiC particles are added to the base material, the mechanical properties of the generated MMCs are enhanced. Furthermore, it was revealed that adding solid lubricants, such as graphite (Gr) particles and hard ceramic particulates, reduced the hybrid composites' strength. The impact of boron on Al_2O_3 on mechanical and wear characteristics of Al composites. The micro−nanocomposites containing 1, 2, 3, and 4% Al_2O_3 particulates in Al were created. It was discovered that higher concentrations of Al_2O_3 in both micro- and nanoparticle forms led to better hardness, increased tensile strength, and good wear resistance.[33] To understand the wear and corrosion behavior of Al−Mg/Al_2O_3 (0−8% weight) metal matrix nanocomposites, a two-step stir-casting method was used to create them. Al−Mg/Al_2O_3 (0−8 wt %) was subjected to the pin-on-disk dry sliding wear test utilizing the design of the experiments method while varying the contact stresses and sliding distance in accordance with the ASTM G99 Standard. According to the experimental findings, the specific wear rate decreases as the sliding distance increases. Taguchi's technique and study of variance (ANOVA) were used in the statistical study to identify the most important element influencing a given wear rate at the ideal weight percentage of reinforcement.[34] The number of experimental trials was designed using the face-centered central composite design (CCD) of the response surface method (RSM), and a response surface approach was implemented to predict the ideal combination of processing variables in the wear process. The SiC reinforcement significantly enhanced the wear resistance of the Al7075-SiC-cenosphere composites. Overall, the investigations demonstrate the outstanding tribological capabilities of the Al7075-6 wt % SiC-5 wt % cenosphere.[35]

The novel integration of aluminum 7075 with Al_2O_3 (alumina) and graphene (GR) particles in an MMC represents a groundbreaking advancement in materials engineering. This innovative amalgamation not only harnesses the inherent strength and lightweight properties of aluminum 7075 but also introduces a synergistic combination of Al_2O_3's robustness and graphene's extraordinary mechanical and thermal characteristics. The resulting MMC showcases a unique fusion of strength, stiffness, wear resistance, and enhanced thermal conductivity, opening unprecedented possibilities for aerospace, automotive, and electronics applications. This pioneering development promises to redefine material performance standards, paving the way for a new era in high-performance composite materials with exceptional multifunctional attributes.

Fewer studies have been performed on the effectiveness of various quenching agents. Also, the combination of nano alumina and graphite particles in the Al7075 alloy matrix is minimal. The current study aims to develop the varying wt % of Al_2O_3 and graphite particles reinforced Al7075 alloy hybrid composites and evaluate the effect of various quenching agents on the tensile, hardness, and wear behavior of hybrid composites. The main objective of the current study is to support the idea that it is crucial to discover the effect rates of cooling under various quenching mediums to improve the mechanical characteristics and wear resistance of Al7075 Al_2O_3/Gr hybrid MMCs.

2. MATERIALS AND PROCEDURES

Two distinct reinforcing particles, such as nano-sized Al_2O3—Gr with weight percentages of 1, 2, and 3, were used as a foundation for developing hybrid composites. Figure 1 shows the flowchart for preparation and characterization of composite material. The nano-sized Al_2O_3 reinforcement greatly enhances the ultimate tensile strength, hardness, and tribological behavior. Gr in the nanometer size range is utilized to improve the machinability of composite materials. It enhances the wear resistance of the aluminum composites and functions as a self-lubricating substance. Al_2O_3 and Gr with particle sizes of 80 nm were used as reinforcements in the current investigation. The chemical composition of Al7075 alloy is shown in Table 1 (https://www.pmcc.in/).

The Al7075 alloy hybrid composites with 1, 2, and 3% of varying Al_2O_3 and 1% of constant graphite particles and 2 and 3% of varying graphite and 1% of constant Al_2O_3 particle composites were synthesized using a stir-casting technology. In a separate crucible, the Al_2O_3 and Gr were preheated to 350 °C. Hard reinforcing Al_2O_3 and soft Gr preheated particles were added into the molten metal after the base material was melted in a Coke furnace. At 100 rpm, the stirring process was performed constantly. Continuous pours of the molten melt were made into the heated metal mold and allowed to cool. Figure 2 shows the complete casting process of composites by using stir-casting technology. The hybrid composite samples underwent 2 h of solutionization at 510 °C, followed by individual cooling. In this case, two types of quenching agents, ice cubes and water, were utilized. The same samples were quenched and underwent a 4 h age-hardening process at a specific temperature of 160 °C before being cooled to room temperature. Enhancing the grain refinement of the stir-casting-produced hybrid metal matrix composites is necessary. Heat treatment can refine the grain to improve its wear and mechanical properties.

The type of cooling agent and the functions of the material were used to define the heat treatment method. In the heat treatment process, quenching typically plays a significant role.[36] Additionally, the samples were machined in line with ASTM specifications for the hardness, tensile, and wear tests, as shown in Figure 3.

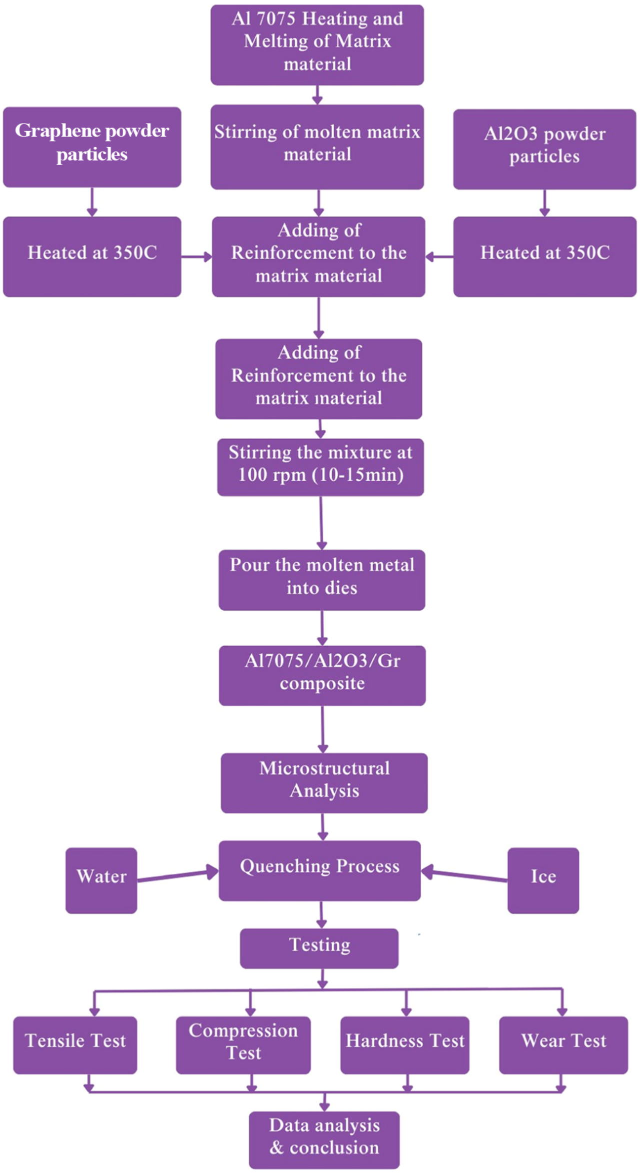


Figure 1. Flowchart for the preparation and characterization of composite material

According to the ASTM E384 standard, hardness was measured using a specimen size of 20 mm in ϕ and 20 mm thickness. The hardness was evaluated using Vicker's microhardness testing equipment by employing a 10 mm ball indenter at a steady stress of 0.5 kg for 30 s. To calculate the average values of composite hardness, the hardness of developed MMCs was examined at three different regions on the test sample's surface.

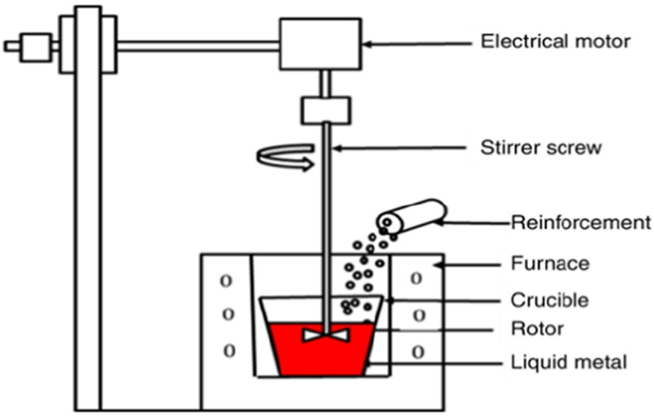
An Electronic Tensometer with a 20 KN maximum load capacity was used for the tests. According to ASTM E8 specifications, tensile samples were tested with a gauge length of 16 mm, and a gauge ϕ of 4 mm was produced.

The created hybrid MMCs were subjected to compression strength tests. According to ASTM E9 standards, samples with a 10 mm ϕ and a 25 mm thickness were used for the compression test specimens.

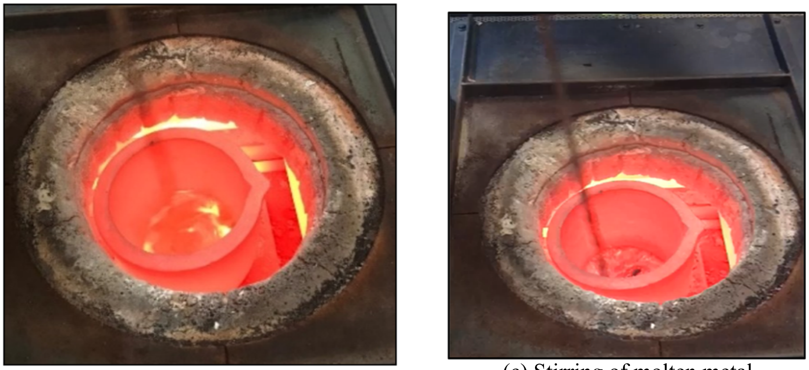
By performing tests in accordance with ASTM G99 requirements at a continuous sliding speed of 1.66 m/s and a force of 30 N against the steel disk, wear behavior was

Table 1. Chemical Composition of Al7075 Alloy with wt %

content	Cu	Mg	Si	Fe	Mn	Ni	Pb	Sn	Ti	Zn	Al
Wt. %	1.48	2.30	0.05	0.25	0.05	0.05	0.02	0.01	0.05	5.42	rest



(a) Stir casting process



(b) Melting of aluminum

(c) Stirring of molten metal

(d) Solidification

(e) Removal of casting

Figure 2. (a) Schematic of stir-casting setup, (b) melting of aluminum, (c) stirring of molten metal, (d) solidification, and (e) removal of casting (“Photograph courtesy of ‘R, Babu E’ Copyright 2023/2024”).

examined (grade: EN-32). Using CNC machining, test samples with a 32 mm length and 8 mm diameter were created. The loss of weight approach was used to calculate how much the created hybrid MMCs will wear out.

3. RESULTS AND DISCUSSION

3.1. Microstructure Analysis. Uniform dispersals of reinforcements improve the wear and mechanical behavior of produced composites. Figure 4a shows the base alloy’s microstructure without reinforcing content. The microstructure of Al7075 is reinforced with 3% Al_2O_3 and 1% Gr with a homogeneous distribution, as depicted in Figure 4b. Near the grain boundaries, the reinforced particles in the formed hybrid composites are visible. It is noted that the particles lack accumulation, which is often caused by the stir-casting technique utilized in the production of hybrid MMCs. The distribution of hard particles in the matrix is a crucial requirement for enhancing the mechanical and wear behavior of the developed hybrid composite. It is widely acknowledged that reinforcing hard ceramic particles in the Al base matrix improves grain refinement. Microstructural studies reveal that the grains around the hard reinforcement particles are significantly finer than those surrounding the reinforcement’s free base alloy. Hard particles can, therefore, accelerate an aluminum alloy’s recrystallization by accelerating particulate nucleation between the reinforcements and base matrix. The

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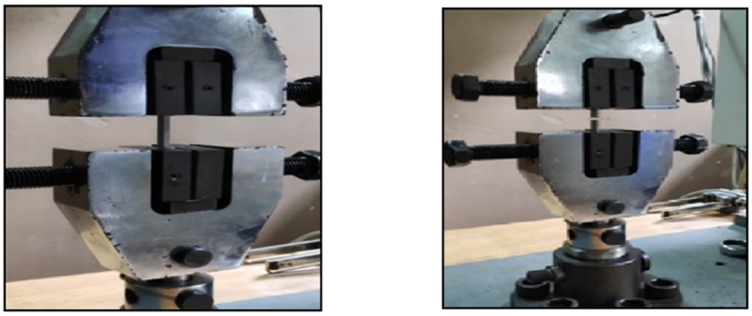
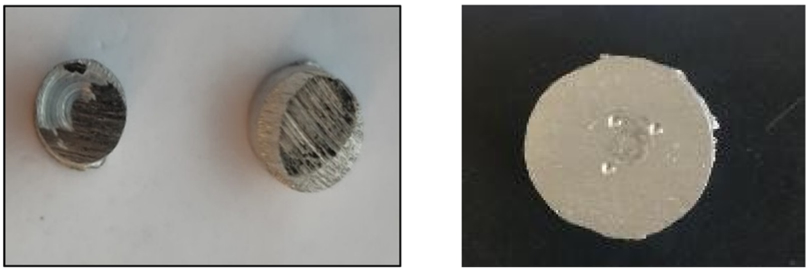
(a) Tensile Specimen



(b) Specimen fixed (c) Broken specimen



(d) Wear Specimen (e) Hardness Specimen

Figure 3. Samples align with ASTM specifications for the hardness, tensile, and wear tests (“Photograph courtesy of ‘R, Babu E’ Copyright 2023/2024”).

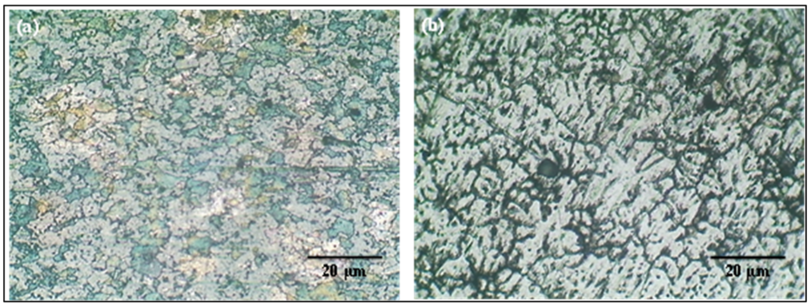


Figure 4. Microstructure of (a) Al7075 (base matrix) and (b) Al7075−3% Al_2O_3−1% Gr.

hardness, strength, and plasticity of metal matrix composites with homogeneous architectures have been developed with excellent results. Researchers have demonstrated how to reinforce metal matrix composites with scattered structures, and fine and coarse grain patterns. Greater bonding results from the fine grain structure of the composites and its interaction with the matrix phase, as opposed to the coarse grain structure. The tensile and hardness strength have also increased noticeably. Similar outcomes were found by other researchers,[12,37] and it is assumed that the Al grain usually hardens adjacent to the hard particles, weakening the barrier to grain refinement.

3.2. Hardness. Figure 5 illustrates the hardness of produced heat-treated hybrid composites with different quenching mediums. Al_2O_3 hard particles were added to the aluminum matrix to increase the composites’ hardness.[38] Higher hardness numbers are seen in Figure 5 due to an increase in Al_2O_3 content and slightly decreased at a higher % of graphite content, demonstrating how adding alumina particles improves the hardness value of the developed hybrid MMCs. The homogeneous dispersion of hard particles in the base material substantially impacted the hardness values of the test samples in composites.

Other researchers[39] have reported similar outcomes. Also, it was determined that the improvement in hardness may be caused by the existence of reinforced particles, which make dislocation movement within the base matrix more challenging. The grain refining based on the Hall−Petch process is primarily responsible for the increase in the hardness value. Additionally, particles can have a particle-strengthening effect,

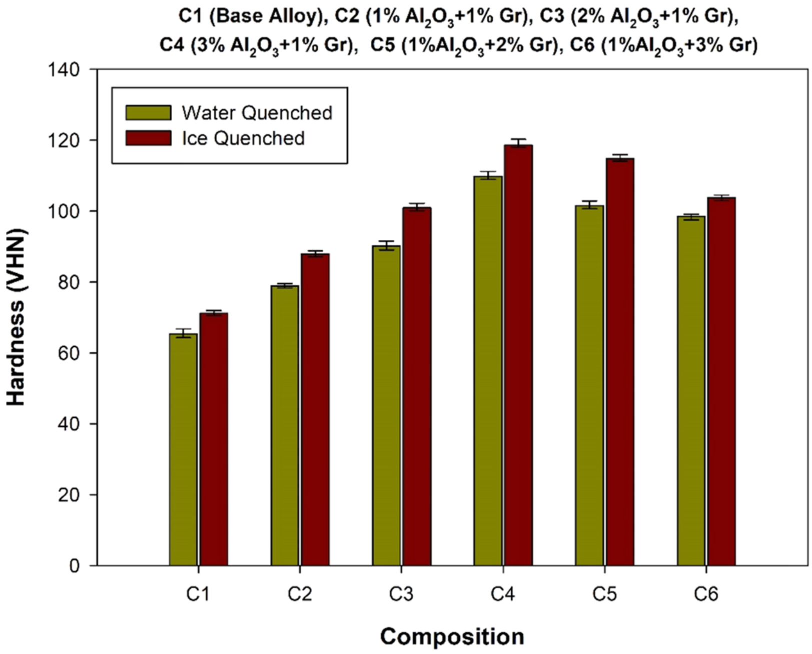


Figure 5. Hardness with varying % of Al_2O_3 and Gr.

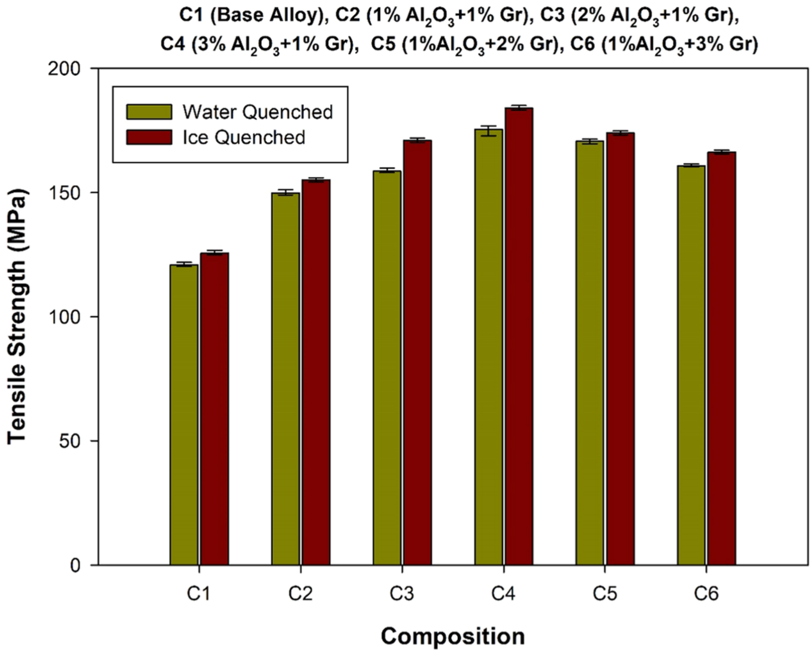


Figure 6. Tensile strength results for varying content of Al_2O_3 and Gr.

which increases the hardness value while preventing dislocations from moving. The kind, size, quantity, and dispersion of ceramic particles all affect how hard something is. The main causes of the sample's greater hardness value are mechanical churning that breaks -Al dendrites and using Al_2O_3 particles as reinforcements.[7]

Additionally, as the Gr content was increased, the hardness of the hybrid composites gradually reduced in the case of 2 and 3% Gr and 1% alumina composites. The high lubricating properties of the Gr particles, which cause grain movement, are the source of the drop in hardness caused by an increase in Gr particulates.[40]

Figure 4 shows that the heat treatment technique increased the hardness values. The improvement of the hard phase brought about by precipitate age-hardening accounts for the increase in hardness after heat treatment. Comparing composites quenched in ice cubes to samples quenched in water reveals enhanced hardness. Solutionizing treatment suggests the emergence of intermetallic phases that produce harder materials. Density enhancements in the dislocation in heat-treated MMCs are brought on by a thermal mismatch between the base materials and reinforcement. As a result of a general gradual resistance to plastic deformation, this ultimately leads to an enhanced hardness. The enhanced bonding between the base matrix and the reinforcement

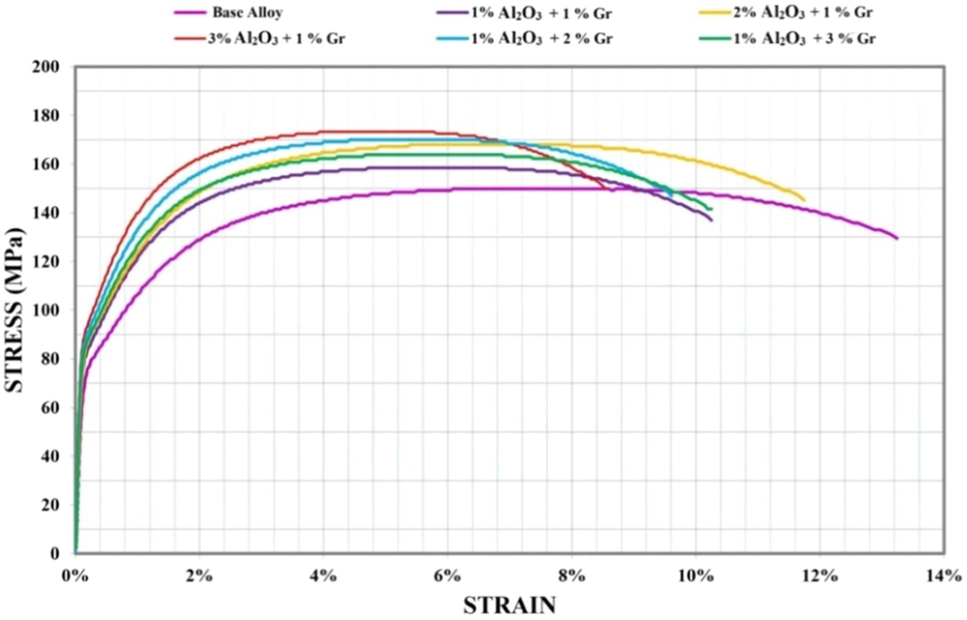


Figure 7. Stress−strain curve for the samples quenched in ice cubes.

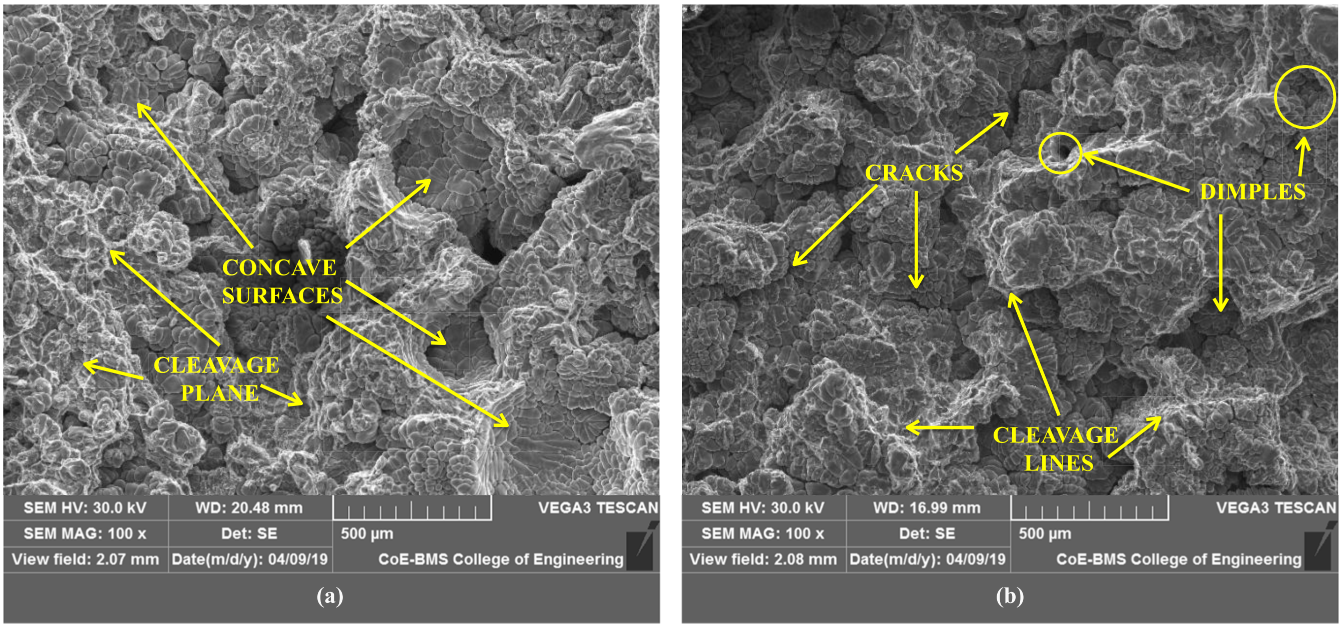


Figure 8. Tensile fractured surface of hybrid MMCs (3% Al_2O_3 + 1% Gr) quenched in (a) water and (b) ice cubes.

materials increases the hardness of the ice-quenched composite. The intermetallic phases within the matrix material stabilized, contributing to the increase in hardness. High cooling rates caused deformation, contributing to the hybrid composites' hardness. This phenomenon significantly impacts the hardness of the developed hybrid MMCs and generally influences distortion created by slip dislocation. Bharath et al.[41] studied the impact of alumina particle addition on the hardness of Al2014 alloy with and without the heat treatment process. Heat-treated Al2014 alloy with alumina-particle-reinforced composites exhibited superior hardness.

3.3. Tensile Strength. Figure 6 displays the tensile strength graphs for the manufactured hybrid MMCs. The results demonstrate that adding Al_2O_3 improves the hybrid composites' tensile strength. This often occurs because the created composites contain hard particles. It is also demonstrated that the tensile strength of newly produced hybrid reinforced composites by hard ceramic particles is improved by their resistance to dislocation. The sort of hard particles is, in general, the key element boosting material strength.[23,24] The correlation between the hard particles and the dislocation boosts the strength of the resulting composites. Dong et al.[20] asserted that the increase in ultimate tensile strength was caused by the addition of hard Alumina particles to the Al7075 matrix, which boosts the strength of AA7075. Tensile strength values increased as the amount of Al_2O_3 increased because of the low porosity and homogeneous dispersion of Al_2O_3 particles. Al_2O_3 particles are thought to have contributed to the formation of refined grains by providing some heterogeneous nucleation sites during solid-

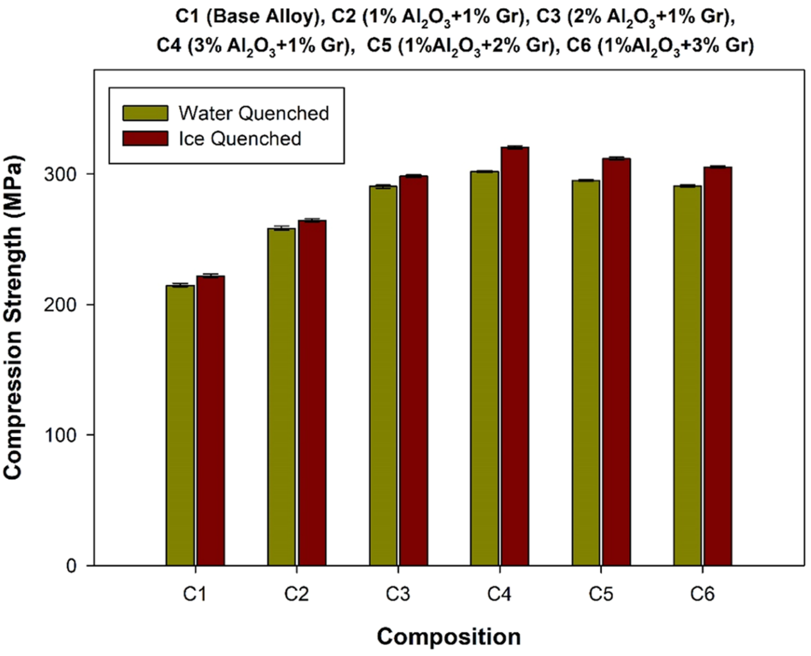


Figure 9. Compression strength with varying % of Al_2O_3 and Gr.

ification. As a result, the grain size can be responsible for improving the tensile characteristics. The AA7075 matrix gains strength from the hard Al_2O_3 particles through load transfer from the matrix to the reinforcement particles.

By adding more Gr, the tensile strength was slightly decreased and higher than the base matrix. The proposed hybrid composites may experience a reduction in tensile strength due to the likelihood of crack propagation and particle pullout caused by the presence of Gr particulates. This may also develop due to solid lubricant particles that cannot properly convey any load.

It has been discovered that the heat treatment method has the potential to improve coherent precipitates. Precipitates and the hosting matrix create a coherent lattice up to a specific temperature; afterward, the lattice vibration leads to incoherent precipitates in the host matrix. It is well known that aging treatment causes fine precipitates to form on a soft matrix (Al), which enhances the composite's characteristics. The strength of the MMCs produced is improved due to the interaction of numerous small, hard ceramic particles and thermal alteration during heat treatment. More robust than expected hybrid MMCs were observed after being quenched in ice cubes in Figure 5. Patil et al.[42] studied the impact of heat treatment on the mechanical behavior of Al7075 alloy reinforced with beryl and graphene on the nanoscale. The ultimate tensile strength and yield strengths were improved in the case of heat-treated composites compared to the non-heat-treated and base Al7075 alloy matrix.

The development of intermetallic precipitates, which frequently act like a barrier for the displacement's pinning down, causes the generated composite materials exposed to heat treatment to significantly increase in strength. The tensile strength of the created hybrid MMCs is significantly increased due to this occurrence, which restricts the dislocation's mobility and lowers the degree of plastic deformations. Figure 7 displays the tensile stress−strain profiles of the stir-casting-produced composites. The tensile strength of 3% Al_2O_3 and 1% Gr particle-reinforced hybrid composite quenched in the ice shows the highest of all of the created composite specimens. As a result, all of the points on a stress−strain curve are displayed for samples quenched in ice. The stress−strain curve shows that the toughness has improved in addition to strong tensile strength. This matters a lot. Meanwhile, ductility is reduced in the majority of ways to increase strength.

The fractography of the AA7075 alloy with 3% Al_2O_3 and 1% graphite particle hybrid specimens quenched in water and ice cubes, respectively, is shown in Figure 8a,b, respectively. Surface fracture tests were carried out after evaluating tensile properties to investigate the fracture behavior between the base matrix and the reinforcements. The SEM image of the cracked surface of the heat-treated samples was taken at a constant magnification, as shown in Figure 8a,b. This study investigates how the microstructure of hybrid composites affects their tensile properties. Hybrid composites are typically brittle. Fracture development is linked to a dimple rupture carried on by the ensuing generation of microvoids.[43] The reinforcement provided by ceramic particles dramatically changes the fracture process.[44]

A study of fractured surface structures was conducted to investigate the broken region. This investigation aids in locating the beginning of microcracks and places that have been too loaded to determine an appropriate degree or amount of fracture features.[25] When compared to fractured surfaces of composite samples quenched in water, dimple sizes on fractured surfaces quenched in ice cubes are significantly lower; the size of the dimples directly correlates with the strength of the formed composite.

3.4. Compression Strength. Figure 9 depicts the compression strength of the AA7075 alloy with varying percentages of alumina and graphite composites with heat treatment quenched in different mediums. The compression strength of the AA7075 alloy increased as the % of alumina particles increased to 3% with 1% of graphite particles in both water and ice quenching agents. With more Al_2O_3, the produced MMCs demonstrated noticeably high compression strength. This result may be mostly attributable to the stir-

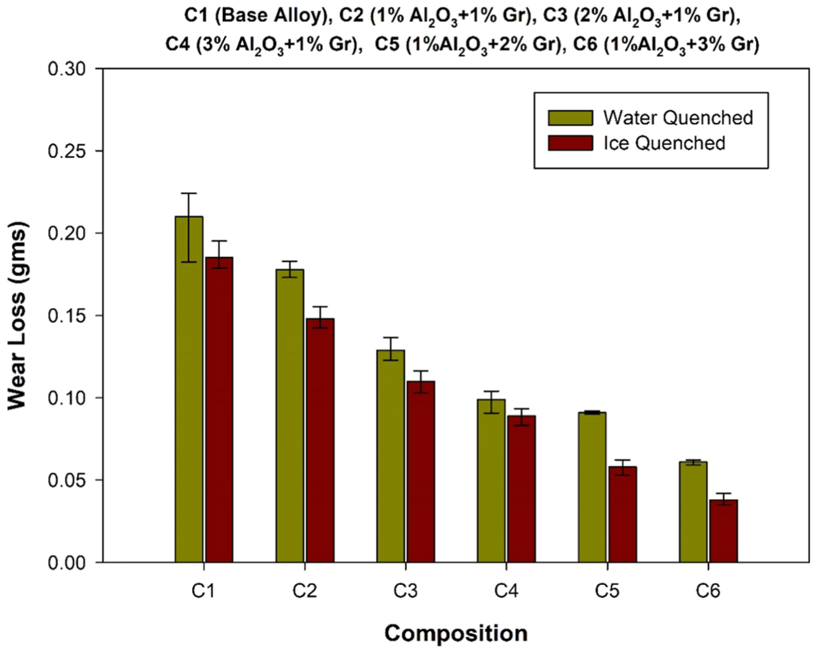


Figure 10. Wear loss with varying % of Al_2O_3 and Gr.

casting procedure and homogeneous reinforcement distribution. The porosity was often reduced due to the bonding between the reinforcement and base matrix.[29] The most frequent reason for alloy strength in MMCs is uniform reinforcement dispersion.

Alumina can act as a barrier to dislocation throughout the base matrix, which improves the mechanical properties of AMMCs. In general, there was a direct correlation between the materials' compressive strength and hardness. Therefore, the increased hardness may be responsible for MMCs' high compression strength. Singh et al.[12] demonstrated that, during the casting stir process, the value of compression strength is greatly increased when we increase the content of alumina reinforcement. Additionally, it has been found that increasing the amount of alumina reinforcement causes a significant increase in the metal matrix's compressive strength during the casting stir process. Compressive strengths increased as the sintering temperature and Al_2O_3 content were raised. The analysis also revealed that compressive strength dramatically declined as reinforcing and sintering reached their ideal levels. Compression strength grew as reinforcement particle value and sintering temperature increased until they reached their maximum values. Then, there was a rapid drop with a further increase in the alumina Al_2O_3 reinforcement and temperature.

Additionally, Figure 9 demonstrates that the compression strength of the generated hybrid MMCs decreased when the Gr content increased. Researchers[45] claimed that solid lubricant particles significantly impact compression stability. However, the unfavorable results affect robustness. According to the current research, particle pullout and crack propagation caused by the presence of Gr particles may be to blame for the decline in compressive strength.[46] The results demonstrate that the test samples quenched in ice cubes have a higher compression strength. This enhancement results from the production of intermetallic precipitations, which normally prevent the pinning down of the dislocation motion, restrict the extent of plastic deformations, and significantly increase the compression strength of the resulting hybrid composites.[47]

3.5. Wear Loss.

Wear tests were carried out on the AA7075 alloy with alumina and graphite at a sliding speed of 1.66 m/s and a force of 30 N against the steel disk. The wear loss of the hybrid composite is depicted in Figure 10. The graph shows that due to the combined effect of alumina and graphite particles, the wear resistance of the AA7075 alloy was increased. Further, heat-treated composites quenched in ice exhibited more wear resistance in all of the prepared composites. High wear resistance results from ceramic hard Al_2O_3 particles being present in the Al matrix. Al_2O_3 particles often cause an increase in the transition load because of the strengthening process. The Al_2O_3 particle reduces interparticulate spacing and functions as a mobility barrier dislocation. The increased hardness of the hard particles is primarily responsible for their capacity to carry a heavy weight. Additionally, the hard disk is rubbed by the shattered Al_2O_3 particles, which generally results in improved wear resistance of the produced hybrid composites. Al_2O_3 particles in the Al matrix grab the applied load, and Gr produces a lubricating coating that reduces plastic deformations. Gr is essentially a sustainable particle, and its presence increases wear resistance.[48] The lubricating qualities of the reinforcements make them ideal for use in MMCs. Gr, a solid lubricant, exhibits improved wear resistance in the produced MMCs. Wear resistance in MMCs is increased by the production of a rich film layer on the wear surface due to dry sliding behavior, which typically restricts the plastic deformations in a produced composite. Tribo layers are produced by these MMCs and are brought about by the existence of a Gr content. Usually, the layers that form just on a pin will stop the aluminum from directly contacting the steel disk.

Creating strain fields around the reinforcements also leads to a higher wear rate. The fine distribution of the reinforcement inside the base matrix is the main component for optimizing the wear behavior. A consistent dispersion of the reinforcements prevents dislocations in material constructions.[49] The increased hardness of the MMCs produced under the T6 heat treatment conditions can inhibit the formation of Al debris and

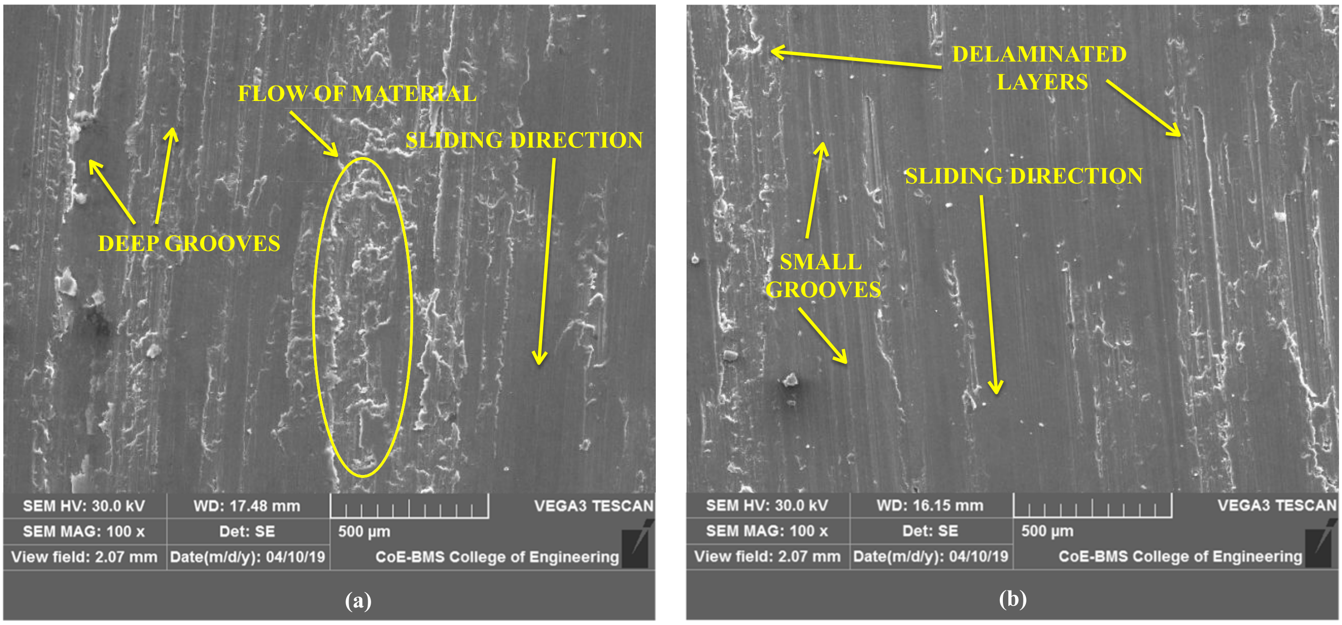


Figure 11. SEM analysis of worn-out surface samples of 3% Al_2O_3 + 1%Gr (a) quenched in water and (b) quenched in ice cubes.

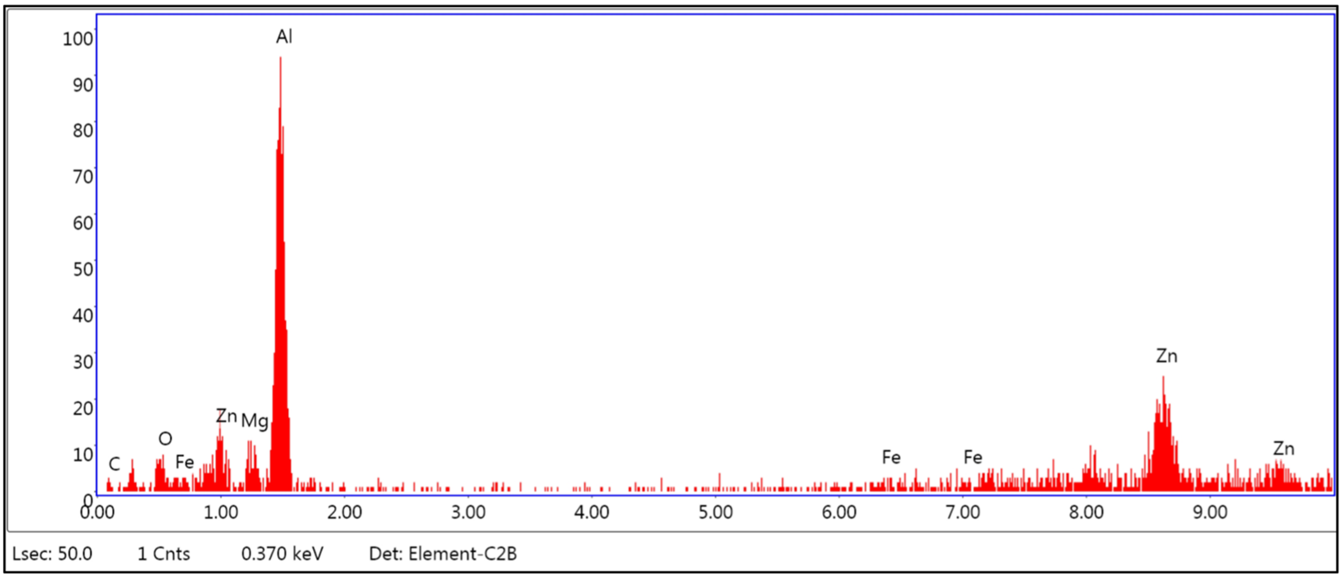


Figure 12. EDS of developed hybrid MMCs (Al−3%Al_2O_3−1%Gr).

reduce its transmission to the surface of steel.[50] According to the wear study, the composite materials were heat-treated at 510 °C and quenched in ice cubes to produce the high hardness of the base matrix. It has been revealed that heat treatment under the T6 condition increased hardness, increasing wear resistance in MMCs.[51,52] As a result, it was decided that for better control of wear of hybrid composites, emphasis should be given to the particle sizes and shapes of the matrix material (Al), ceramics reinforcement (Al_2O_3), and lubricant (Gr), in addition to bonding properties of these various components. Alumina particulates, whose hardness is significantly higher than the Al matrix, are the most significant property of the hybrid composites under investigation. These particles harden the Al matrix and offer the matrix significant protection during the abrasive slide.

The worn surface of the AA7075 alloy with 3% Al_2O_3 and 1% graphite particle hybrid specimens quenched in water and ice cubes, respectively, is shown in Figure 11a,b. Figure 11 displays SEM images of the cracked surface of the specimens that were (a) cooled in water and (b) cooled in ice. It was feasible to infer through SEM analysis research on the wear tracks that the path was not uniform but nonuniform, showing wear surface areas with deep grooves in the direction of sliding and plastic deformations.

Usually, grooves are produced by the reinforcing particles. It can be seen that the specimen surface protection applications have been stripped away and are now present as thin sheets of detritus. The SEM analysis of the surface roughness revealed that the plastic flow of the alloy with the accumulation of components caused wear damage.[53] It was revealed from the SEM pictures of worn-out surfaces that the sample quenched in ice cubes exhibits fewer surface grooves and scratches. The particles caught between the sliding surfaces when the samples' surface and the hard steel disk came into contact are typically to blame for this. Continuous sliding increases the likelihood of debonding of the particulates by causing them to separate from the base matrix and adhere to sliding surfaces. And because of this, samples experience only brief periods of abrasive wear. Increased wear resistance is the outcome of this. In Figure 12, according to an EDS investigation, Fe, Zn, Mg, O, and C are among the primary components of Al_2O_3/Gr reinforced hybrid composites that were found. The presence of the oxygen (O) may be attributable to the presence of alumina (Al_2O_3) content,[54] and the presence of "C" confirms the presence of the glass (Gr) content in the created hybrid composite.[55,56] The results show that the Al_2O_3/Gr reinforced Al hybrid composite composition is trustworthy.

3.6. Implications of the Study. The findings and insights from this research have several important implications across various fields and industries:

- Materials Science Advancements: The efficiency of stir casting in manufacturing high-performance aluminum metal cast composites (AMCCs) reinforced with nano-sized Al_2O_3 and graphite particles is demonstrated in this work. These findings can be used to help design innovative materials with superior mechanical characteristics for various applications.
- Automotive and Aerospace Industries: Improved mechanical properties, such as greater hardness and tensile strength, have immediate consequences for the automotive and aerospace industries. These industries frequently demand lightweight, high-strength materials for components and structures, and the created hybrid composites may find use in these fields.
- Biomedical and Electronics: The study shows that these hybrid composites can be utilized in biomedical and electrical applications. Improved mechanical characteristics and wear resistance are critical for component lifespan and performance in these applications.
- Resource Efficiency: The finding of self-lubricating behavior in hybrid MMCs suggests using resource-efficient materials. Reduced wear on contact surfaces can result in longer component life spans and lower maintenance costs, making these materials both environmentally and economically advantageous.
- Optimized Quenching Methods: The research emphasizes the significance of quenching procedures in determining material properties. Understanding the impacts of various quenching agents can help improve production processes and material performance in various applications.
- Microstructural Insights: The microstructural study reveals important information on hybrid composites' fracture and wear behavior. These findings may be used to influence material design and engineering efforts to improve the performance and durability of comparable composite materials.
- Sustainable Materials Development: The study demonstrates the possibility of developing innovative materials with superior qualities, which coincides with the increased emphasis in modern companies on sustainable and efficient production methods.
- Future Research Directions: The findings pave the way for more study into composite materials. Researchers may investigate various reinforcing materials and compositions to acquire specific material qualities for customized applications.

The implications of this exploration are broad, including prospects for creating new materials that can improve the performance, durability, and sustainability of products and components in various industries.

4. CONCLUSIONS

In the current study, stir casting was successfully used to develop hybrid composites of Al7075 reinforced by nano-sized Al_2O_3+Gr. The mechanical, wear, and microstructural analyses of generated hybrid MMCs were assessed using different quenching agents with heat treatment. The results are listed below:

- With an increase in Al_2O_3 concentration, the created hybrid composites became harder. Additionally, including nano-sized Gr particles made the hybrid MMCs malleable and decreased their microhardness. Further, heat-treated Al7075 alloy with alumina and graphite composites quenched in ice exhibited superior hardness compared to the water-quenched samples.
- Nano-sized Al_2O_3 particles increased the hybrid composite's tensile and compression strength. However, when the weight percentage of nano-sized Gr particles increased, the tensile and compression strength of the material decreased.
- The results also show that by increasing density dislocation, created hybrid composites can become stronger. According to the findings, composites quenched in ice cubes exhibit superior material characteristics than those quenched in water and samples chilled to room temperature.
- According to the results of the fractography investigation, samples quenched in ice have smaller dimple sizes than those quenched in water or chilled at ambient temperature. In general, the relationship between composite strength and dimples' sizes is exactly proportionate.
- The created hybrid composites experience less wear due to the nano-sized Al_2O_3 and Gr particles on the contact surfaces. It is clear from the study that the hybrid MMCs produced exhibited self-lubricating behavior, resulting in resource-efficient materials.
- Nano-sized Al_2O_3 and Gr particles influence hybrid composites' wear behavior in the worn-out surface's SEM pictures. Due to the presence of alumina (Al_2O_3) in the developed hybrid composite, the EDS analysis was able to identify the oxygen content (O), and "C" indicates the presence of Gr content.

■ ASSOCIATED CONTENT

Data Availability Statement

Data used in the present work.

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Notes

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