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MECHANICAL AND WEAR PERFORMANCE OF END CHILLED ALUMINIUM -2024 MATRIX COMPOSITES REINFORCED WITH AL_2O_3 NANO PARTICLES

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Abstract

In recent years, the use of lightweight materials with improved mechanical and tribological qualities has significantly advanced. This study aims to develop an aluminum 2024 matrix alloy reinforced with 0, 3, 6, 9, and 12 weight percent of Al_2O_3 using the stir casting technique. The alloy was melted at approximately 700°C, mixed with preheated Al_2O_3 particles, and cast into a sand mold with various end chills, including graphite, mild steel, copper, brass, and cast iron, to facilitate directional solidification. Mechanical testing revealed that the copper-chilled MMC achieved the highest hardness and strength at reinforcement levels of 9% and 12% by weight, respectively, with increases of 9.88% in strength and 16.66% in hardness compared to the base alloy. Micro structural examination showed uniform dispersion of nano alumina particles, contributing to improved wear resistance. The copper-chilled MMC exhibited high friction and modest wear at lower stresses but significant wear under higher loads. The incorporation of Al_2O_3 nanoparticles and the chilling effect enhanced the mechanical and tribological properties, resulting in a finer microstructure and better bonding between the reinforcement and matrix.

***Keywords**:* Alumina nano particles, Stir casting, Solidification, End chills, Wear resistance

1. Introduction

Aluminum matrix composites (AMCs) are distinguished by the reinforcement of hard particles into the matrix, such as nitrides (AlN ,TiN) oxides (Al_2O_3), or carbides (SiC ,TiC ,Al_4C_3) [1]. The incorporation of nanoparticles into the metal matrix produces mechanical and physical qualities that are not inherent in the matrix alone. Therefore, to manufacture high-performance composites, smaller particles, typically in the submicron to nanoscale range, must be introduced into the aluminum matrix for reinforcement.

Aluminum 2024 matrix is widely utilized in the aviation industry due to its favorable properties, finding applications in military equipment, shafts, gears, and aircraft fittings. Despite their superior tribological qualities, achieving a fully homogenized microstructure can be challenging for aluminum alloys and aluminum matrix composites [2]. Adhesive wear, characterized by material transfer between sliding surfaces, typically occurs due to local plastic deformation caused by the load between contacting asperities [3]. Microstructure variances can occur due to change in phase, which arises from differences in the potential energies of various phases and their distinct rates of dealloying [4]. Aluminum MMC consist of a matrix and reinforcements, typically manufactured using specialized production methods such as powder metallurgy or fluid cast metal technology. Despite the drawbacks of powder metallurgy, such as high processing costs and limitations on component size, stir casting is considered as an effective technique for MMC's [5].

This process produces the nanocomposite by melting the matrix alloy and stirring it with reinforcement particles. To reduce porosity, particle clustering, oxide inclusions, and interfacial reactions, stir casting involves adjusting several stirring parameters, such as reinforcement content, casting temperature, stirring time and stirring speed [6]. Careful selection of parameters is essential to ensure a high level of microstructural consistency in the stirring and melting technique [7]. Aluminum alloys with a wide solidification temperature range are challenging to feed during solidification, often leading to dispersed porosity. This issue can be effectively mitigated using chills, which are favored by foundry engineers for their ability to promote directed solidification and enhance heat dissipation, resulting in reliable and high-quality castings. Several studies [8][9] have investigated the impact of chilling on the integrity and solidification of alloys. As demand rises for top-notch composites, it becomes crucial to produce defect-free aluminum composites. According to recent literature, there is limited research on the mechanical characterization, tribological behavior, and microstructure of MMCs that include Al_2O_3 and Aluminum 2024 nanoparticles. Additionally, there is a lack of comprehensive studies on the tribological characterization of these composites when produced through cold casting. This study aims to bridge these knowledge gaps, particularly considering the significance of MMCs fabricated via cold casting in industries such as aerospace and automotive. This study provides a comprehensive review of the current state-of-the-art regarding the microstructure, mechanical properties, and tribological characterization of cold-cast MMC's reinforced with Al_2O_3 nanoparticles.

2. Literature Review

In the late 1980s and early 1990s, concentrated efforts were made on aluminum and titanium matrix composites, particularly focusing on aluminum MMCs cast with discontinuous reinforcements [10].
A strong worldwide push to develop materials that were both lightweight and strong led to extensive research on lightweight MMC's. Aluminum emerged as the primary matrix metal, with titanium also playing a significant role. Both continuous and discontinuous materials were employed to reinforce these matrices [11]. High volume percentages of powder reinforcements were incorporated into metal matrices [12], yielding composites that found utility in electronic packaging [13], where precise heat control was essential. Subsequently, a shift was observed from composites featuring continuous reinforcement to those with discontinuous reinforcement. Metal matrix composites (MMCs) with discontinuous reinforcement have proven advantageous in a broader range of applications due to their increased affordability and ease of processing [14]. The emergence of nanocomposites around 2000 marked a significant breakthrough in composite materials. There has been a notable increase in global research on metal matrix composites (MMCs) reinforced with nanoparticles, particularly carbon nanotubes, which are extensively blended into various metal matrices. Researchers have also investigated the production methods and heat treatment of nanocomposites [15]. During this period, the growing demand for MMCs that could be mass-produced for various applications led to significant attention being focused towards the nanometal matrix composites.
Subsequently, attention turned to developing techniques for joining titanium and aluminum matrix composites, with a specific emphasis on friction stir welding. Several advanced methods were pioneered, including the drilling of SiC particle-reinforced aluminum matrix composites, the milling of magnesium matrix composites, and the spark plasma sintering of titanium matrix composites [16][17][18].
Research into developing the next generation of MMCs using rare earth ceramic particles in aluminum alloy matrices has remained a focal point in the twenty-first century. Advanced ceramic materials are enhanced with additions of elements such as alumina, beryl, neodymium, yttrium, and cerium. These rare elements, including

alumina, yttrium, cerium, and beryl, have significantly enhanced the wettability, mechanical properties, and wear resistance of MMCs. Despite the common use of rare elements as reinforcements in MMCs, there is limited research on the application of Al_2O_3 nanoparticles to strengthen chilled aluminum alloys [21][22].

3. Experimental Procedures

Al2O3 nanoparticles, averaging 20–30 nm in size, were chosen to reinforce the aluminum 2024 matrix. A nano-composite forming apparatus was employed alongside the stir casting process to ensure an even distribution of nanoparticles throughout the Al 2024 matrix. The production process involved the following steps:

1. Aluminum 2024 ingots with specified dimensions were selected for production after heating nano-alumina particles to 200°C in a crucible.
2. The Al 2024 ingots and varying weight percentages of nano-alumina particles were heated to 700°C in a furnace.
3. To ensure uniform distribution of the nano-alumina particles throughout the matrix, the molten alloy was stirred using a mechanical stirrer.
4. Multiple end chills were incorporated into the sand casting mold to control the direction of solidification.
5. Sand casting technique was utilized to prepare the specimens.
6. The resulting mold specimens were machined according to ASTM requirements for characterization.

Process Parameters:

1. Stirring speed: 300 rpm
2. Stirring temperature: 700°C
3. Reinforcement preheating temperature: 200°C
4. Stirring time: 10–12 minutes

After melting, the aluminum 2024 matrix material was heated to 700°C. Preheated Al_2O_3 nanoparticle reinforcement was uniformly added to the molten alloy using a specialized attachment, raising its temperature to 200°C. To ensure thorough and even mixing of the reinforcement into the matrix, the mixture was vigorously agitated at 300 rpm. The melted reinforced was poured into the mold cavity, which held the end chill, and allowed to solidify [23][24]. In this study, the testing specimens exclusively from the cooler end, as determined by copper end chills. Each specimen contained varying amounts of reinforcement, ranging from 3 to 12 weight percent in 3 weight percent increments.

3.1 Mechanical Properties

The mechanical properties of Al2024 cast samples reinforced with Al_2O_3 nanoparticles were evaluated, including hardness, wear resistance, yield tensile strength, and ultimate tensile strength.

Tensile test

Tests were conducted to evaluate the mechanical characterization of both cast Al2024 and the resulting nanocomposites. Aluminum Matrix Composites (AMCs) were cast, and according to ASTM standard E8/E8-09 As shown in Figure 1, the test specimens were ready for the tensile test [25][26].

Due to their impressive strength-to-weight ratio, MMC's find extensive application in structural, automotive, and aerospace industries. This is attributed to their ability to transfer applied loads to the harder reinforcements through a softer, more ductile matrix metal. This study implemented a crucial chilling process to ensure a dense, solid composite free of microporosity and to promote robust interfacial bonding between the composite phases. The differences in the coefficients of thermal expansion between the reinforcement and matrix are widely recognized to increase dislocation density. Dislocations encounter greater resistance to movement between grains and require more energy (or loading) to remain mobile when they accumulate near grain boundaries. The addition of reinforcement can increase the Ultimate Tensile Strength (UTS) by up to nine weight percent. However, strength may decline if the particle concentration exceeds the 9 weight percent threshold. This is likely due to particle agglomeration and segregation as they approach the eutectic phase. The clustering of particles can locally weaken the structure, leading to fractures and a subsequent reduction in strength.

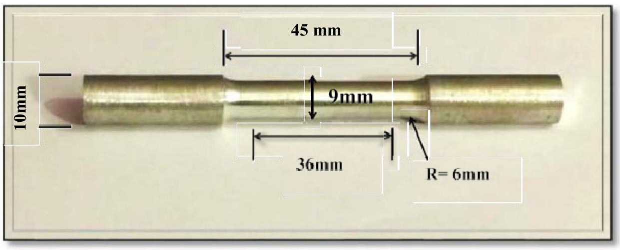

Figure 1: Specimen for Tensile test based on ASTM (E8/E8-E9)

Tensile tests were conducted using a WDW/200E universal testing machine with a 200 kN capacity on specimens measuring 9 mm in diameter and 36 mm in gauge length. Figure 1 illustrates the specimens' dimensions. The ultimate tensile strength, tensile characteristics, elongation percentage and were calculated.

Hardness Test

The depth of penetration under a constant external force is a widely recognized factor influencing the hardness test. In this study, the hardness of Al 2024 reinforced with 3, 6, 9, and 12 weight percent of Al_2O_3 nanoparticles was determined using a Brinell Hardness Tester equipped with a steel ball indenter and a 1.96 N load.

Wear test

For the wear testing, a sliding distance of approximately 660 meters was employed. To ensure proper contact with the steel disc, the pin samples, measuring 12 mm in diameter and 30 mm in length, surfaces were polished with 80-grit emery paper before the test, as depicted in Figure 2.

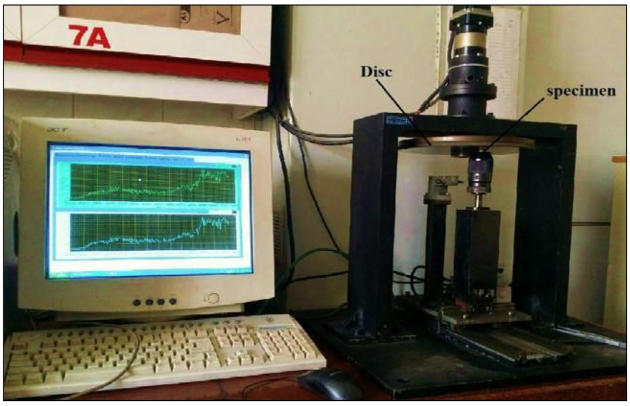

Figure 2: The wear rate setup

4. Results and discussion

Microstructure of the chilled composite

The amount of reinforcement and the rate of cooling are two critical factors in the solidification process that have a substantial impact on the microstructure of the composite that was created in this study.

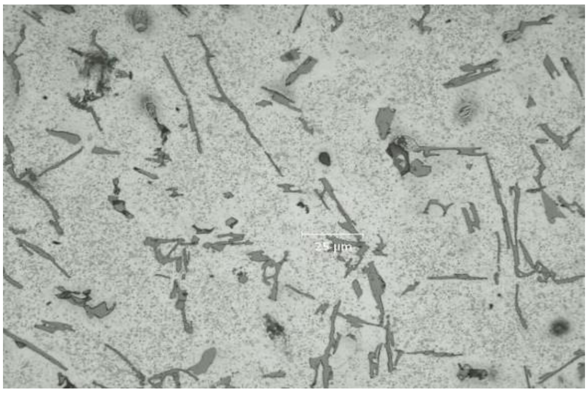

Figure 3: The microstructure of a composite with three weight percent reinforcement cast using a copper chill.

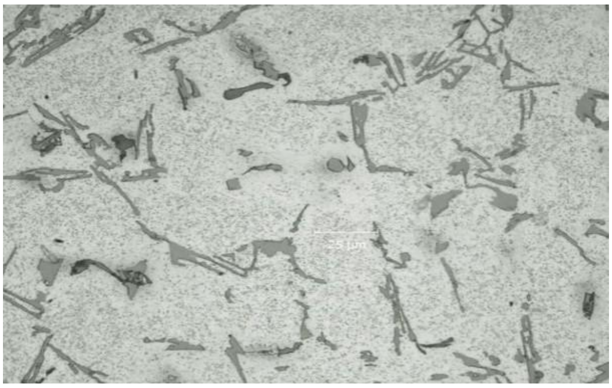

Figure 4: The microstructure of a composite cast with 6wt.% reinforcement using a copper chill.

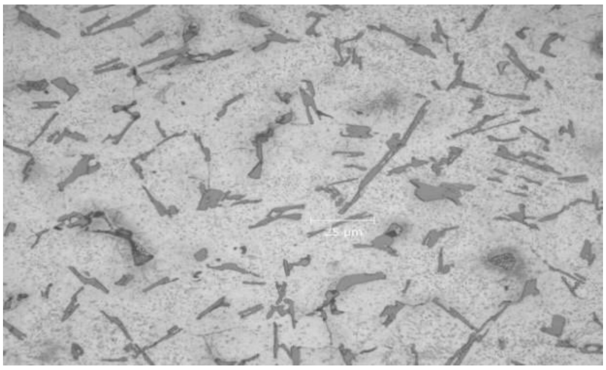

Figure 5: The microstructure of a composite cast with 9 wt.% reinforcement using a copper chill.

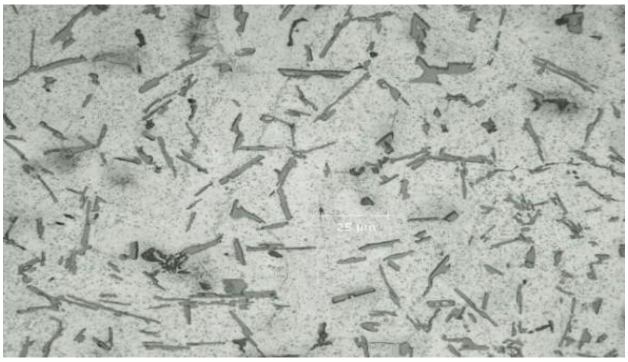

Figure 6: The microstructure of a composite cast with 12 wt.% reinforcement using a copper chill.

Figures 3-6 display photomicrographs of etched specimens with varying weight percentages of reinforcement (3, 6, 9, and 12), cast with a copper end cold and magnified at 500×. According to the microstructure study, as the chill thickness decreases, the grain fineness increases. The fine grain structures of the MMCs cast with a copper cold are associated with beneficial mechanical properties. However, segregation or clustering of the reinforcement particles occurs at higher percentages of reinforcement addition (beyond 12 weight percent), particularly near the grain boundaries, although this is not evident in the microstructure images. The micrographs reveal a equal dispersion of particles in the interdendritic zones of the chilled composites with reinforcement levels of 3, 6, and 9 weight percent. In contrast, the composite with 12 weight percent reinforcement shows fewer particles in the interdendritic region. The settling and/or clustering of reinforcement particles may occur due to a larger density difference in the matrix at higher reinforcement levels. Therefore, increasing the reinforcing content beyond 12 weight percent does not yield the intended outcome.

The photomicrographs indicate a roughly linear relationship between the weight percentage of reinforcement and its uniform distribution within the matrix alloy. A microstructure analysis of cooled MMCs also assesses the distribution of reinforcement and bonding at the reinforcement- matrix interface. The absence of segregation or clustering near the grain boundaries in chilled MMCs with lower reinforcement contents (3 and 6 wt%) suggests good integrity between the reinforcement and matrix. The weight of the reinforcement particles, the specific stirring technique employed, and the ability of the molten matrix to effectively wet the heated reinforcement can all contribute to this outcome.

Microstructure studies reveal that the finely grained structure of MMCs created with a copper chill is primarily attributed to the sharp temperature gradient experienced during solidification. This gradient enables a robust, porosity-free bond by promoting the proper flow of liquid metal into the interdendritic regions. Detailed examination of the photomicrographs reveals a microstructure characterized by finely dispersed, dark gray eutectic silicon throughout the interdendritic area (appearing as a light gray matrix) and finely precipitated alloying elements in the aluminum solid solution matrix. Additionally, grain refinement contributes to the observed fine grain structure, which is particularly pronounced in MMCs cooled with copper.

The size and shape of dendritic arm spacing are heavily influenced by the rate of solidification. Chilling leads to sharper and faster cooling rates, resulting in a reduction of dendritic arm spacing relative to the size of the reinforcing particles. This phenomenon restricts the motion of the reinforcement within the matrix, thereby minimizing segregation during solidification. To ensure an equal distribution of reinforcement within the matrix, the dendritic arm spacing should match or be smaller than the particle size. Microstructural investigations suggest that reinforcing particles are typically trapped between dendrites during solidification.

This phenomenon is particularly evident in the initial secondary branches and the trailing edge of the dendritic tip. As dendritic growth continues, particles within the secondary branches remain trapped between them. Additionally, particles that accumulate at the trailing edge of the tip after solidification often become situated at the base of the dendrite.

Tensile Test Results

Tensile testing was used to establish the ultimate tensile strength and yield tensile strength. Figure 3 illustrates the stress-strain curves obtained from testing pure aluminum 2024 and aluminum 2024 reinforced with 3, 6, 9, and 12 weight percent Al_2O_3 nanoparticles.

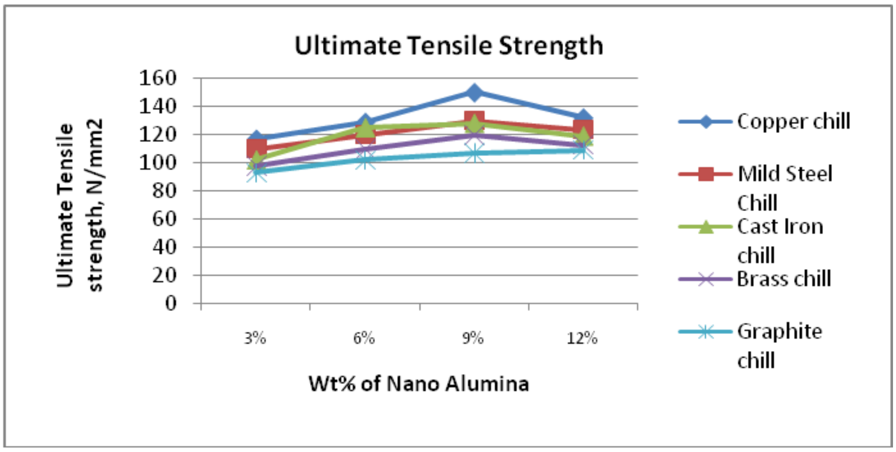

Figure 7: wt. % reinforcement Vs UTS for MMCs using different chill

Figure 7 illustrates the impact of reinforcement content on the Ultimate Tensile Strength (UTS) of various MMCs cast with different types of chills. Among all the chills examined, the composite cast with a copper chill exhibits the highest UTS (158 N/mm2), while the graphite chill displays the lowest UTS (105 N/mm2). Additionally, the findings of the strength test indicate that even though the reinforcement is dispersed equally, an increase in reinforcement content can improve UTS by up to 9 weight percent before cluster formation results in a reduction. Clusters formed under tension concentrate at their location, impeding load transfer and resulting in strength loss. However, in this study, the improvement in mechanical characterization was achieved.

The observed increase in Ultimate Tensile Strength (UTS) indicates a positive influence of both cooling and Al_2O_3 nanoparticle reinforcement on the composite. Previous studies have shown that several parameters, including the type of reinforcement, particle size and distribution, and the interfacial bond between reinforcement and matrix, affect the composite's strength. Through careful control of the casting process, including the chilling process for a fine grain structure, the stir casting method, and preheating of the reinforcement, the current study achieved a significant enhancement in Ultimate Tensile Strength (UTS). Microstructural examination revealed that the chilled MMCs were denser and free of microporosity. The mechanical evaluation of Al_2O_3 and Al 2024 nanoparticles MMCs indicated that both the amount of reinforcement and the chilling effect influence the strength.

Hardness Test results

Aluminum alloys pose a challenge in abrasive or wear environments due to their lower strength, ductility, and softness compared to ferrous materials. To enhance their tribological characterization, MMC's are often reinforced with strong ceramic elements. In this study, aluminum 2024 was combined with Al_2O_3 nanoparticles to create composite specimens for the hardness test.

Hardness tests were conducted on the test samples after undergoing the aging heat treatment process, as composites age more rapidly than matrix alloys. Following the solution treatment, the hardness of MMCs cast using chilling was measured over various aging times to determine the optimal aging conditions. The amount of reinforcement was found to significantly influence the ideal aging conditions. It was observed that as the aging period increased, the hardness of each MMC initially increased to a peak value before decreasing. With increasing reinforcement content, the peak aging time generally decreased, as the additional reinforcement increased the number of pre cipitation nucleation sites. Consequently, an increase in reinforcement content resulted in higher MMC hardness at a constant aging temperature and duration, given that the reinforcement particles are significantly harder than the aluminum alloy matrix.

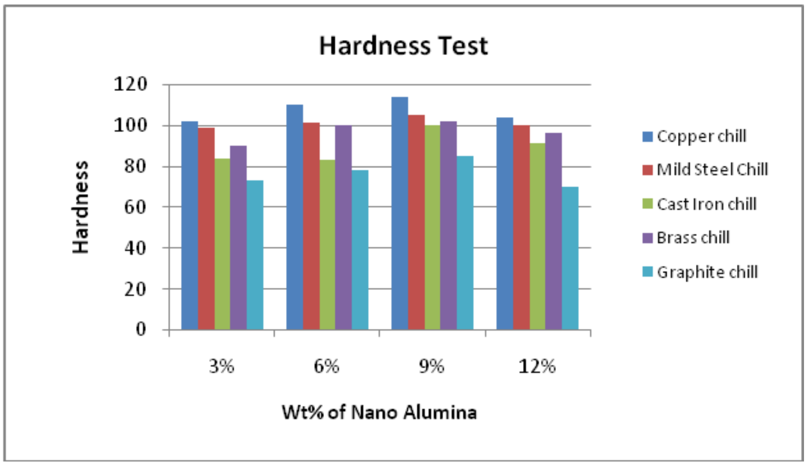

Figure 8: wt. % reinforcement Vs Hardness for different MMCs
Using different chills

Figure 8 displays the hardness of chilled Metal Matrix Composites (MMCs) cast with chills. Studies on the microhardness of chilled MMC samples showed that enhanced matrix hardness was correlated with higher degrees of reinforcement (up to 9 weight percent). Furthermore, the findings of the hardness test showed that the composite's hardness was influenced by the chill's thickness. This significant enhancement in hardness is mainly attributed to the smaller grain size of Al_2O_3 nanoparticles in the matrix resulting from rapid cooling, which provides stronger resistance to localized deformation during indentation. The mechanical characterization of the reinforcement and the matrix in ceramic-reinforced composites often exhibit significant differences. This leads to a high density of dislocations near the interface between the matrix and reinforcement, as well as incoherence. Incoherence induces rapid precipitation processes, and nucleation of heterogeneous precipitation may occur at sites with increased dislocation density.

The hardness of the composite rises with increasing reinforcement content by about 118 BHN (up to a 9 weight percent addition), according to the results of the hardness test. Among the composites produced with different chills, the composite cast with a copper chill exhibited the highest toughness. This increase in hardness enhances the composite's wear resistance, making it suitable for automotive applications. Nevertheless, microstructural studies showed that hardness decreases when reinforcement of segregation and cluster formation occurs, even at 12 weight percent addition of Al_2O_3 nanoparticles. Among all the copper chills used, the composites chilled with copper exhibited the highest hardness, attributed to its strong heat extraction capability. Moreover, the highest hardness was consistently observed towards the cooler end and decreased towards the riser end for each composite. This further highlights the impact of chilling on toughness.

Wear test results

Tribological studies were conducted to examine the wear characteristics of Al2024/ Al_2O_3 composites using a pin-on-disk machine. Wear tests were performed on Al2O3 with varying weight percentages (0, 3, 6, 9, and 12 wt%) using a pin-on-disc wear tester.

Effect of load

The induced stress significantly influences the observed wear resistance during wear testing. The figure illustrates the variation in weight loss of the composite (with 9 weight percent reinforcement cast using different chilling processes) as a function of sliding distance, tested at weights of 10, 20, 30, 40, and 50 N, respectively. At the lowest load (10 N), all tested composites consistently exhibited a high coefficient of friction, indicating mild wear. In contrast, under higher loads (50 N), the composite with 12 weight percent reinforcement and a 10 mm thick chill displayed significant wear but showed better performance.

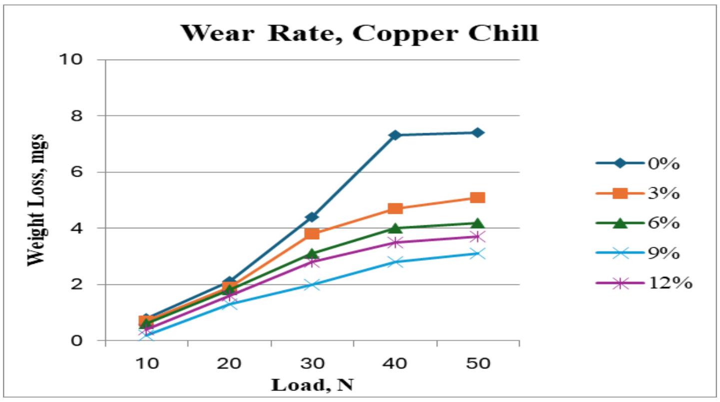

Figure 9: The impact of the load on the copper chill wear rate

Figure 9 illustrates the impact of load fluctuation and the weight fraction of Al_2O_3 nanoparticles on composite weight reduction. The graph depicts the weight loss variation for samples containing 9 weight percent Al2O3 nanoparticles with a copper chill. It is evident that as the load increases from 10 N to 50 N, the weight loss increases for all weight percentages of Al_2O_3 nanoparticles. However, compared to the higher loads of 40 N and 50 N, the rate of weight loss was less pronounced up to 30 N. Furthermore, as the weight percentage of reinforcement increased, weight loss decreased, particularly up to 9 weight percent garnet. The presence of Al_2O_3 nanoparticles reduces weight loss by preventing wear and limiting dislocation movement. Additionally, the Al_2O_3 nanoparticles strengthen the softer matrix alloy, reducing deformation on the sliding surface.

Worn Surface morphology

Following wear testing, the surface morphology of pure Al 2024 and Al 2024/ Al_2O_3 9 wt% composite samples was examined using scanning electron microscopy, as illustrated in Figure 10.

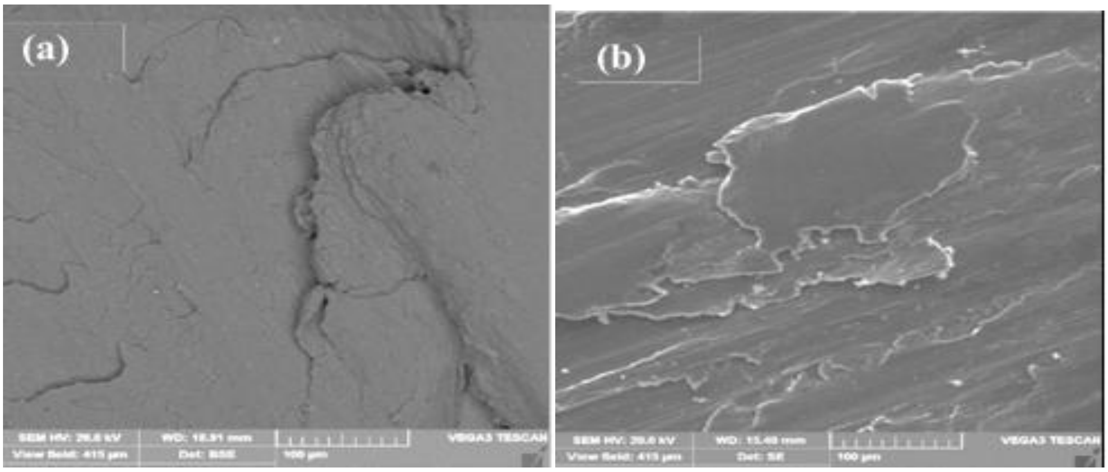

Figure 10: SEM of worn surface for composite Al 2024, loads 50 N, at (a) 0 wt%, (b) 9 wt%.

To enhance their wear resistance, the composites were reinforced with hard Al_2O_3 particles. Wear track analysis of the pure alloy Al 2024 revealed oxide wear, indicating an abrasive wear mechanism likely due to high friction and temperature. These findings suggest that Al 2024 reinforced with Al_2O_3 particles exhibits superior wear resistance compared to Al 2024 alone.

5. Conclusion

Using the stir casting technique, a composite of Al 2024 reinforced with Al_2O_3 nanoparticles (average particle size of 20–30 nm) was fabricated. Experimental research was conducted to assess the ultimate tensile strength, hardness, and wear rate behavior of the composite. The following conclusions can be drawn:

1. The wear resistance and mechanical characteristics (hardness and ultimate tensile strength) of the Al2024 composites were greatly improved by the inclusion of Al_2O_3 nanoparticles.
2. The greatest advancement was observed when the weight percentage was increased from 3% to 9%. Microstructural analysis revealed that the chilling process contributed to the excellent bonding and fine grain structure. Additionally, the analysis indicated a uniform distribution of reinforcement throughout the matrix. Compared to the unchilled steel composite, the matrix alloy of the chilled composites exhibited finer grains due to the randomly oriented Al_2O_3 nanoparticles.
3. The inclusion of Al_2O_3 nanoparticles in the aluminum alloy enhanced the wear resistance of the chilled composite. At lower loads, the chilled composites exhibited a high coefficient of friction and underwent mild wear. However, at higher loads, they surpassed the matrix alloy in terms of resistance to severe wear.

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A Brief Author Biography

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