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EXPLORING THE TRIBOLOGICAL BEHAVIOR OF ALUMINUM MATRIX COMPOSITES REINFORCED WITH WC NANOPARTICLES

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ABSTRACT
The current study investigates the effects of WC nanoparticle content on aluminum matrix composites' microstructure, hardness, wear, and friction behavior. Al-WC nanocomposites with varying weight percentages of WC (0%, 1%, 1.5%, and 2%), are made using ultrasonic methods. stir-casting with cavitation assistance. The microstructure of the nano-composite samples is examined using optical microscopy and scanning electron microscopy. Analysis with energy dispersive X-rays reveals the elemental composition. Vicker's microhardness test is performed with a load of 50 gf and a dwell time of 10 seconds at several locations on the composite sample's surface. Using a pin-on-disk tribotester, the wear and friction properties of the composites during dry sliding are examined. The normal loads vary from 10 to 40 N, and the sliding speeds range from 0.1 to 0.4 m/s. There is no discernible clumping on the composite surface, and the nano-WC particles are distributed uniformly. The addition of nano-WC particles to the composite reinforces its wear resistance and improves its frictional behavior. It is observed that when the weight percentage of nanoparticles increases, the hardness increases correspondingly. The formation of layers on the surface made up of oxidized waste and particles from the counter-face affects the wear properties of composites. As the weight proportion of hard nanoparticles rises, the wear mechanism changes from adhesion to abrasion.

Keywords:
Wear, stir casting, and nano-composite

I. Introduction

It is possible to create Metal Matrix Composites (MMCs) with low-tech, low-cost fabrication techniques. The primary focus of research on Metal Matrix Composites (MMCs) has been on improving their mechanical properties and optimizing their performance capabilities as compared to uniform metals and alloys. High specific strength and stiffness, superior performance at high temperatures, and a low coefficient of thermal expansion are required for Metal Matrix Composites' (MMCs') mechanical properties. Since aluminum can provide a wide range of mechanical characteristics at a relatively low cost of production, it is frequently utilized as the matrix in metal matrix composites. Numerous technological industries, including aerospace, automotive, marine, and military, use these composites extensively [1].
Advanced engineering uses aluminum matrix composites (AMCs) as key materials. They are widely used in many different industries, including the military, automobile, aircraft, and structural engineering. The production process and the chemical compatibility of the reinforcement and matrix are key factors in determining the optimal conditions for achieving the highest attributes. Al-based metal matrix composites' properties are mostly determined by the volume %, morphology, size, and form of the reinforcement. Metal matrix composites (AMCs) based on aluminum are widely acknowledged as high-performance structural materials with a variety of industrial uses [2]. Because of their excellent strength to weight ratio, aluminum alloys are widely used in a wide range of

applications. Unfortunately, their poor tribological performance, moderate ductility, and restricted thermal stability limit their usage in many industrial applications. Through the addition of carbon-based or ceramic reinforcing particles, AMCs overcome the limitations of aluminum alloys. In the automotive or transportation industries, AMCs control a large portion of the aluminum goods market. The enhanced mechanical and tribological properties of AMCs reinforced with oxides (Al_2O_3, SiO_2), carbides (SiC, TiC, WC, B_4C), borides (TiB_2ZrB_2), and other materials are well documented in the literature. However, when the size of the reinforced ceramic particles varies in microns, the effect of fatigue and fracture on AMCs is negligible. External forces have the potential to produce stresses that are specifically directed towards larger particles, hence adversely affecting the fracture behavior of AMCs. Large or medium-sized particles also adversely affect the tribological performance of AMCs. This is due to increased wear on the counter-face material caused by the hard phase of AMCs, primarily via abrasion [3]. Consequently, it is difficult to choose a proper material combination that minimizes wear and an adequate cutting tool for machining the composite due to the exceptional tribological features of AMC. A higher weight percentage of reinforcement in micro-particulate reinforced AMCs causes the molten metal to become more viscous, the wettability to decrease, the possibility of cluster formation to increase, and difficult reactions to occur at the particle-matrix interface. Aluminum-based metal matrix nano-composites (AMNCs) are emerging as a novel material type to solve these limitations. These composites exhibit a remarkable combination of properties, including as ultimate tensile strength, resistance to creep, and ductility, all with a lower weight percentage of reinforcements [4,7]. It is expected that the effects of nanoparticles on the properties of aluminum alloys will balance out. Nemati has demonstrated that AMNCs have better tribological properties than both AMCs and Al alloys [5,6]. The integration of nanoparticles like Al_2O_3, SiC, TiC, AlN, and WC into pure aluminum or alloys has been well documented in recent studies. The mechanical performances of composites reinforced with 1 volume percent or more of nanoparticles are on par with or even better than those of composites treated with 10 volume percent or more of microparticles. Hosseini demonstrated that increased hardness and wear resistance may be obtained by adding up to 3 vol.% of nano-Al_2O_3 to AMNC. Moreover, wear resistance and hardness are negatively impacted by particle size increases.

II. Literature Analysis

Arivukkarasan et al.'s study [8] looked into the experimental analysis of a composite material made of tungsten carbide (WC) as the reinforcing material and an aluminum LM4 alloy matrix. The stir casting technique was used to create the composite specimens. We introduced 5, 10, and 15% weight percentages of WC particles to a molten aluminum LM4 alloy (AALM4) and swirled. Once the composite has solidified, the samples are prepared in accordance with the relevant ASTM guidelines and put through testing to evaluate their mechanical properties, such as hardness, impact resistance, and tensile strength. Moreover, the pin-on-disc wear test instrument was employed to investigate the tribological behavior of the composite. To look at the various elements in the composites, an X-ray diffraction (XRD) analysis was done. The investigation using a scanning electron microscope (SEM) verifies that the WC particles are evenly distributed throughout the aluminum LM4 alloy matrix. A higher weight % of WC particles in the LM4 matrix improved the mechanical characteristics of hardness, impact strength, and tensile strength. Compared to the other composites tested, only the composite containing 15% weight percentage of WC exhibited a decrease in mass loss during the wear test. A growing number of applications, including infrastructure, sports, aviation, and ground transportation, are using composites based on aluminum (Al) because of its improved properties, which include a high strength to weight ratio and resistance to fatigue, corrosion, and wear. Exceptional wear and frictional performance are required for many applications involving dynamic contact forces in order to increase the lifespan. Over the past ten years, lab-scale tribological experiments have consistently demonstrated that nanocomposites perform better than microcomposites and alloys. The literature on the tribological behavior of particulate-reinforced Al nanocomposites by dry sliding was reviewed by Shinde et al. [9]. System characteristics like wear and friction are observed to be influenced by inborn components like microstructure, manufacturing method, and reinforcement. Furthermore, the tribolayer formed inside the system and extrinsic characteristics like load, speed, and contact conditions are all related. Aluminum matrix composites (AMCs) are a novel class of materials that may be tailored and created to have specific qualities that are needed for particular applications. Advanced engineering materials, or AMCs, are a unique class of materials with improved properties over regular aluminum alloys. Superior hardness, increased yield strength, favorable strength-to-weight ratio, increased thermal conductivity, decreased coefficient of thermal expansion, and increased resistance to wear and corrosion are just a few of the desired qualities of AMCs. Consequently, there has been an increase in interest in the potential applications of this material in the automotive, aircraft, and other structural areas in recent decades. Because AMCs have better mechanical, tribological, and physical properties than conventional metal matrix composites, their utilization has been growing over time. Considerable attention has been devoted to the study of Metal Matrix Composites (MMCs) based on aluminum. Srinivas et al. [10] have studied a wide range of alloys and reinforcing types in detail, employing a variety of synthetic techniques to produce materials with certain desired properties. A wide range of property combinations can be obtained by applying reinforcement and metal matrix in the right way. The effects of WC nanoparticle content on the microstructure, hardness, wear, and friction behavior of aluminum matrix composites were investigated by Pal et al. [11]. Al-WC nano composites with varying weight percentages of WC (0, 1, 1.5, and 2) are produced using the ultrasonic cavitation assisted stir-cast method. Optical and scanning electron microscopy are used to investigate the microstructure of the nano-composite samples. Using energy dispersive x-ray analysis, the elemental composition is determined. The Vicker's microhardness test is carried out using a load of 50 grams of force and a dwell time of 10 seconds at different locations on the surface of the composite sample. Using a pin-on-disk tribotester, the wear and friction properties of the composites during dry sliding are investigated. The study looks into various sliding speeds between 0.1 and 0.4 m/s and normal loads between 10 and 40 N. There is no clumping visible on the composite surface, and the nano-WC particles are distributed uniformly. The addition of nano-WC particles to the composite reinforces its wear resistance and improves its frictional behavior. It is observed that when the weight percentage of nanoparticles increases, the hardness increases correspondingly. The formation of layers on the surface made up of oxidized waste and particles from the counter-face affects the wear properties of composites. As the weight proportion of hard nanoparticles rises, the wear mechanism changes from adhesion to abrasion. The wear properties of hybrid nanocomposites with Al-10 weight percent, SiCmicro-x weight percent, and SiCnano (x = 0, 1, 3, 5, and 7) were investigated by Arif et al. [12]. The effects of sliding distance, applied force, and nano-silicon carbide (SiC) addition were examined using a factorial design (5 × 3 × 2) of testing. The effects of SiC, the sliding distance, and the force applied were found to be, respectively, 42.4%, 42.3%, and 11.3%. The five weight percent nanocomposite reinforced SiC nanoparticles outperformed all other synthesized nanocomposites in terms of wear resistance. Scanning electron microscopy (SEM) and electron dispersive spectroscopy (EDS) were used to analyze the worn surfaces and debris. To further forecast the tribological properties of composites using nano-silicon carbide (SiC) reinforcement, five different regression models were developed. The applied stress and the sliding distance served as the models' inputs. These five commonly used statistical indicators were employed to evaluate the performance of these models.

III. Supplies and Procedures

3.1 Procedure Process

Commercial aluminum 1100 alloy, with an elastic modulus ranging from 70 to 80 GPa and a density of 2.71 g/cm3, serves as the basis matrix for this study. The AA1100 alloy, which has a minimum of 99% pure aluminum in it, is widely utilized in a variety of industries because of its remarkable formability. As shown in Figure 1a, the reinforcement used is tungsten carbide powder (WC), with an average particle size of 80 nm. Under the product code K510, this powder was purchased from Hongwu International Group Ltd. A dry cabinet with minimal moisture content and a temperature of 25˚C is used to store the 99.9% pure WC nano powder. Utilizing a vacuum casting setup, an ultrasonic vibrator, and a bottom-pouring type stir casting furnace developed by SWAMEQIP in India, nano-composites containing WC particles are produced. Three different weight percentages of WC particles are used to create the nano-composites: 1%, 1.5%, and 2%. The fabrication setup's schematic design is shown in Figure 1b. The maximum operating temperature of the furnace is 1000˚C.

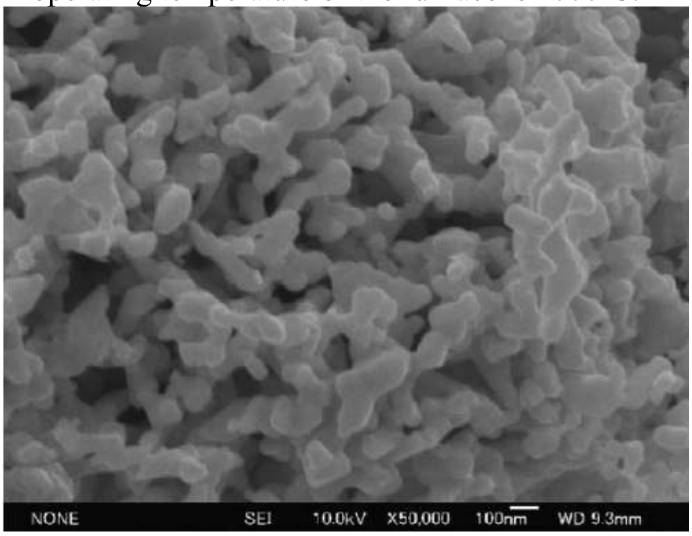

Figure 1a: SEM image of respective WC powder

The Al alloy ingots are first melted within the furnace chamber, where they are kept at a steady 750˚C throughout. Nano-WC particles are added in the proper ratio to the powder pre-heating chamber that is linked to the furnace while the melting process is still in progress. The creation of a layer on the particle surface requires preheating nanopowders to a temperature of 300˚C. An apparatus called a mechanical stirrer creates a vortex when metal melts. In close proximity to the vortex, the heated nanopowder is added to the molten alloy. The liquid is agitated for 15 minutes at 600 revolutions per minute in order to generate a vortex. Following the completion of the particle injection, the mechanical stirring is stopped, and a probe from an ultrasonic vibrator is inserted into the molten metal, penetrating to a depth of approximately two thirds of the liquid metal pool. For fifteen minutes, ultrasonic waves are allowed to flow through liquid metal, all the while keeping the metal pool contained and shielded by inert argon gas. An enclosed container connected to a vacuum pump holds a broken dice. The lowest point of the furnace is where the die is located. To remove the gases from the cast, a vacuum pump is used to achieve a vacuum state of 10-2 mbar. The vacuum pump is turned on when the mixing procedure is finished. The molten material is then poured into the die after the furnace's bottom is opened. The melt is allowed to solidify after the filling is finished. Composites with three different reinforcing ratios—1%, 1.5%, and 2% of WC nanopowder—have been produced.

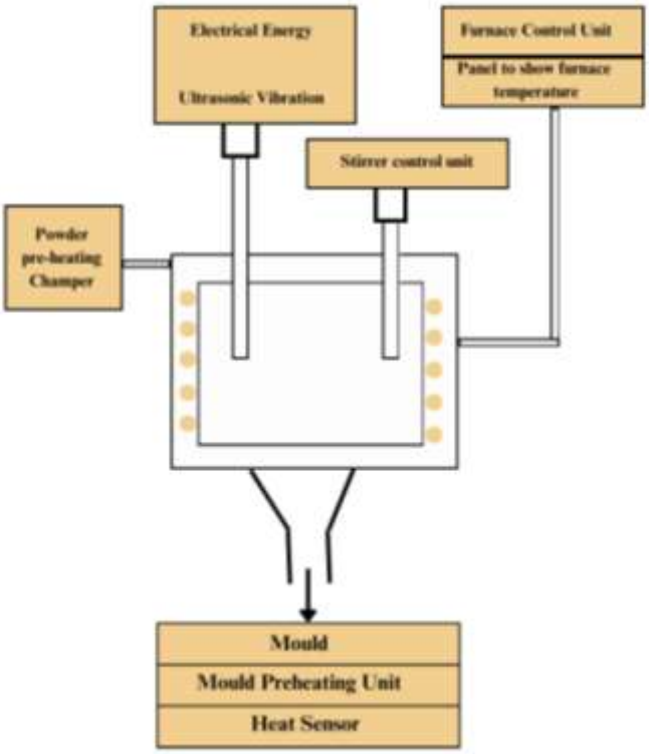

Figure 1b: Diagram illustrating the setup of a stir-casting system with ultrasonic cavitation assistance

3.2 Method of Production

The Archimedes technique, as described in ASTM: B962-08, is used to calculate the density of the alloy and the composites that are created. According to ASTM standard E384-99, the microhardness of the specimens is measured with a Vicker's micro-hardness tester utilizing a diamond indenter with a 50 gf load and a 10-second dwell period.

3.3 Analysis of micro-frameworks

Standard techniques including polishing, etching, and grinding using SiC sheets are used to create metallographic test samples from basic alloys and composites. Before and after wear testing, the materials are characterized using the energy dispersive X-ray analyzer (EDAX), scanning electron microscopy (SEM), and X-ray diffraction method (XRD). An optical microscope made by Leica was used to investigate the microstructure of as-cast composites. The nano-composites are first chemically analyzed using an X-ray diffractometer (Ultima III, XRD, Rigaku Corporation) that uses CuKα radiation after they are fabricated. Next, a field-emission ultra-high resolution scanning electron microscope (JSM-6360 Hitachi, Japan) outfitted with an EDAX setup is used to study the surface texture at a high vacuum of 15KV. To find the presence of WC, an EDAX spectrum was taken from the composite surface.

3.4 Analysis of worn surfaces and wear tests

Using a pin-on-disk tribometer (TR-208-M2, Ducom, India) in dry sliding conditions at room temperature, the wear and friction properties of Al-WC specimens are assessed in accordance with ASTM standard G99-05. The cylindrical specimen, which measures 30 mm in height and 6 mm in diameter, is held vertically in place by a specimen holder against a rotating disk made of EN31 steel that has been hardened to a hardness range of 58–62 HRc. The wear and friction tests were carried out with four different loads—10, 20, 30, and 40N—and four different sliding speeds—0.1, 0.2, 0.3, and 0.4 m/s. The specimens have a 40 mm track diameter and are firmly positioned at a fixed spot. A 10-minute wear test is conducted for each item. By placing inert masses on the loading pan—which is connected to the specimen by a lever—the loads are imposed. Because of the counter disc's higher hardness than the pin sample's average hardness, wear mostly affects the pin sample. A digital balance with a resolution of 0.01 mg is used to measure the mass loss of the pin sample, while frictional values are obtained straight from the setup using a load cell. Volumetric wear is defined as the loss of volume and is calculated using the sample density and mass loss data. Based on the volume loss (m3), sliding distance (m), and applied stress (N), the particular wear rate (m3/N-m) is computed. Acetone is used to wipe the counter disc's surface after every test. The SEM is used to study worn surfaces after wear testing to get insight into wear modes and processes. From worn surfaces, an EDAX spectrum is acquired in order to identify any oxidation or possible tribo-chemical processes that may affect the results of wear.

IV. Experimental findings

4.1 The effect on hardness of adding WC to the AALM4 matrix

The effect of adding WC particles to AALM4 matrix composites on their hardness is seen in Figure 2. It is evident from Figure 2 that the hardness of the composites rises with the weight percentage of WC particles. It is discovered that the LM4–15% WC alloy has a higher hardness than the LM4 alloy without reinforcement. The hardness of the composite is significantly increased by the addition of WC, outperforming that of the unreinforced AALM24 matrix. The rule of mixtures can be used to easily analyze this fact, and the results of this inquiry are consistent with this equation. According to this study, the hardness of the composite increased from 119.03 to 214.77 VHN when the weight percentage of WC increased from 5 to 15 wt%.

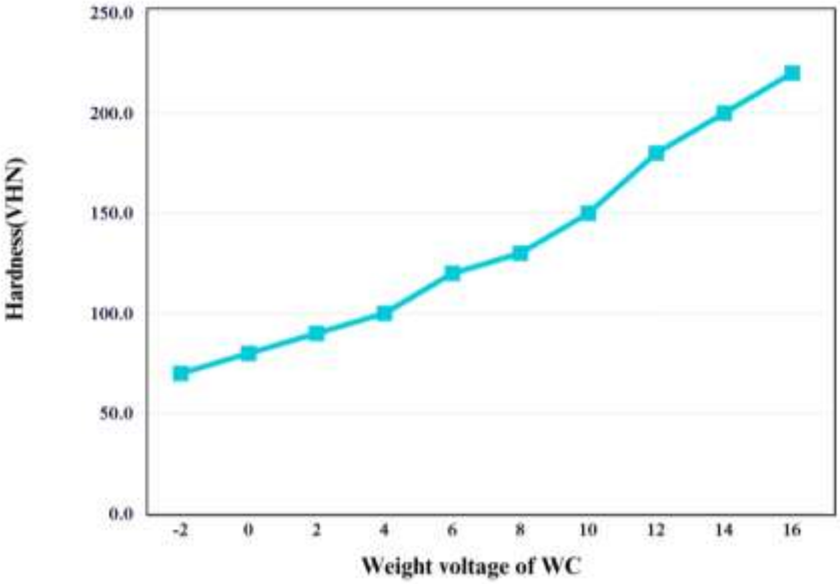

Figure 2: Effect of WC on hardness

4.2 The impact of incorporating WC into the AALM4 matrix on its tensile strength

The effects of WC on the tensile strength and elongation of the stir-cast AALM4-WC composites are shown in Figure 3. The tensile strength of the composites is increased by adding 5 weight percent of WC to the AALM4 matrix. The tensile strength of the AALM4-5wt.%WC composites is greatly increased by increasing the weight percentage of WC particles in them. WC particles use the dispersion strengthening process to impede dislocation motion in the aluminum AA LM4 matrix. Furthermore, increasing the amount of WC causes the distance between the WC particles to decrease. The strength of the composite will be increased by decreasing the space between the WC particles since this will increase the tension required for dislocation movement between the WC particles. The percentage elongation is decreased in the AALM4 and AALM4-WC composites after WC particles are added. This is due to the fact that the soft matrix materials' capacity to deform without breaking is decreased when powerful reinforcements are used.

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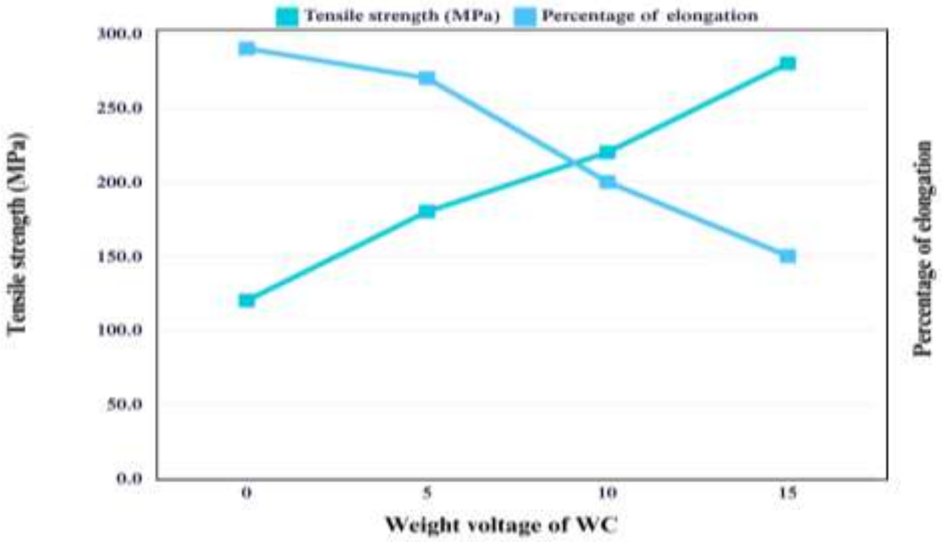

Figure 3: Impact of WC on tensile strength and elongation

4.3 The impact strength of AALM4 matrix is investigated by adding WC

Impact testing, which uses Izod impact testing equipment, is used to determine how much energy a specimen absorbs when subjected to a quick, dynamic force. The consequence of adding WC to the AALM4 matrix is shown in Figure 4. The results of the impact test show that the LM4–15% WC has a high impact strength while the unreinforced LM4 has a low impact strength. The WC particles' natural hardness increases the composites' resistance to impact. The composite showed a maximum impact strength of 6 MPa when it contained 15% WC particles by weight.

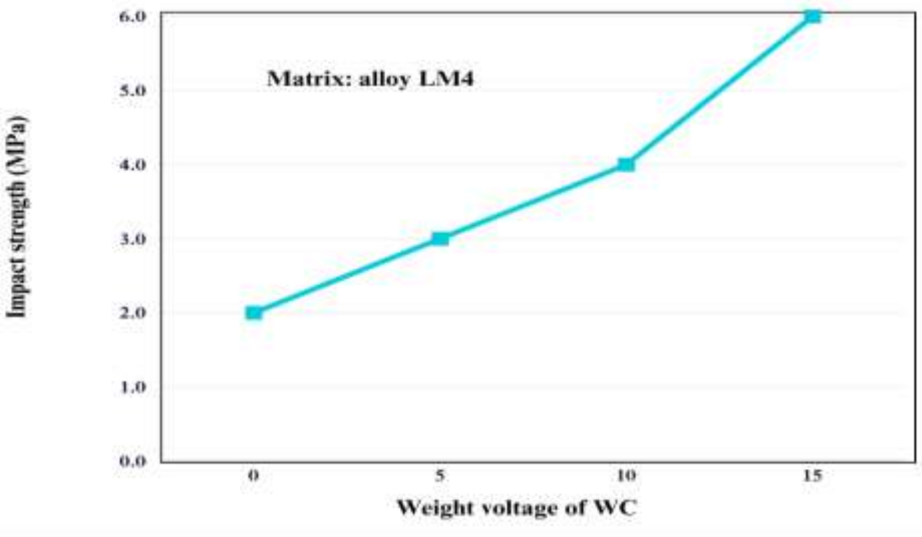

Figure 4: Impact of WC on impact strength

4.4 Wear Properties

The effects of WC particles on the wear properties of the composites are shown in Figures 5 and 6. The weight percentage of WC is shown in Figure 5 in connection to the mass loss noted during the wear test. The AALM4 matrix without reinforcement exhibits the largest mass loss, while the AALM4 matrix with 15% by weight of WC particles records the lowest mass loss. All agree that adding hard particles to aluminum alloys greatly increases the base alloy's resistance to wear. The wear resistance of materials is directly correlated with their hardness, as per the Archad equation. The composite material composed of AALM4 and 15% weighted WC has the greatest enhancement in wear resistance due to the presence of reinforcing particles. It is evident from Figure 5 that the wear rate of the composite decreases with an increase in the number of WC particles. The fact that WC particles are harder than matrix particles is another factor contributing to this phenomenon. Therefore, increasing the amount of strong reinforcing particles could improve wear resistance in line with the concept of mixing.

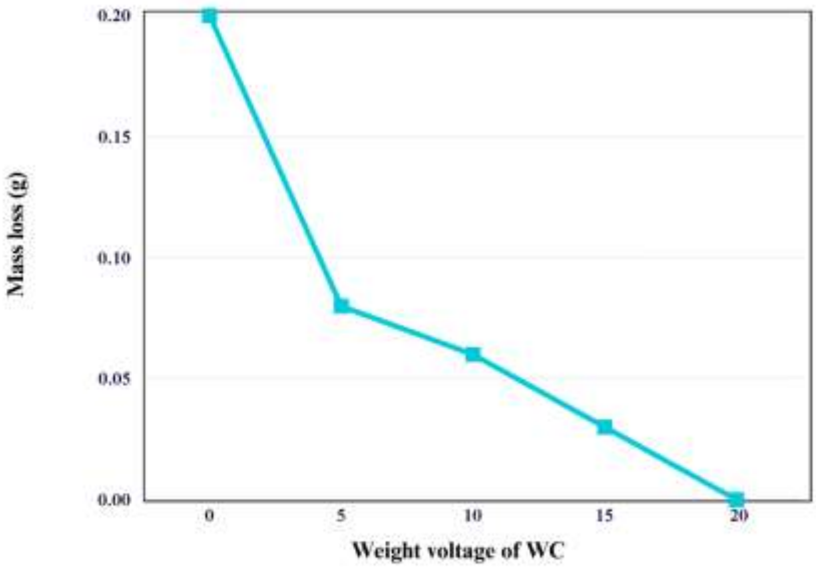

Figure 5: Impact of WC on wear properties

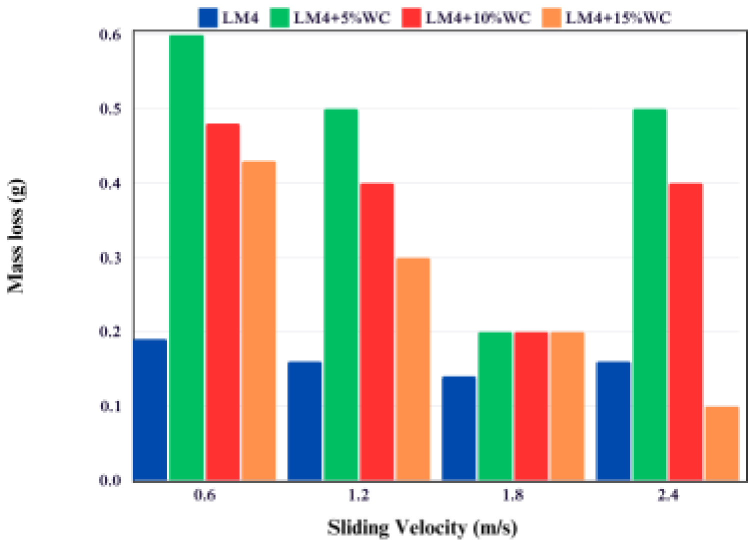

Figure 6: Sliding Velocity vs. mass loss

The relationship between the mass lost in AALM4-WC composites and the sliding velocity is shown in Figure 6. There is less mass loss when the sliding velocity rises from 0.5 to 1.5 m/s. All of the tested alloys and composites see an increase in mass loss when the sliding velocity is increased to 2.0 m/s. The production of higher temperatures at high sliding velocities may be the cause of the mass increase with the sliding velocity of 2 m/s. As the temperature rises, the rate of tension and strain will decrease during sliding.

V. Conclusion

The current effort focuses on employing ultrasonic cavitation assisted stir casting to produce nano Al-WC composites. There is no discernible indication of agglomeration in the optical or SEM micrographs, which show a uniform dispersion of nano-WC particles throughout the aluminum matrix.

Through the use of XRD and EDAX analysis, the existence of nano-WC particles within the matrix is confirmed. Composites' density and hardness increase in direct proportion to the weight percentage of WC reinforcement. The quantity of WC nanoparticles present has a direct correlation with the wear resistance of composite materials. In every working condition, the nano-composites outperform the basic alloy in terms of friction. The wear and friction behavior of composite materials are determined by the sliding speed and applied load, which also play a role in the formation of a mechanically mixed layer, contact with hard ceramic particles, and frictional heat generation. Analyzing SEM images and EDAX patterns of worn surfaces allows for the detection of wear processes. Adhesion and delamination are the main wear mechanisms that affect base alloys. In nano-composites, the abrasion and oxidation of wear debris become increasingly significant, and their influence increases with increased load and sliding speed.

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