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Article

Study on the influence of aluminium nitride particulates on the dry sliding wear behavior and mechanical properties of aluminium 6061 alloy developed using stir casting method

Raghavendra Subramanya[1,*], Manjunatha Kuntanahalli Narayanappa[2], Nagesh Devareddy[3], Madusudhana Shettykothanuru Vemanna[4], Ravikumar Mukundaiah[5], Chandra Shekar Anjinappa[6], Thyagaraj Narasapura Rajanna[2], Arun Kumar Rudrappa[7]

[1] Department of Mechanical Engineering, Sai Vidya Institute of Technology, Bangalore 560064, India
[2] Department of Mechanical Engineering, Sri Jagadguru Chandrashekaranatha Swamiji Institute of Technology, Chickballapura 562101, India
[3] Department of Aeronautical Engineering, Sri Jagadguru Chandrashekaranatha Swamiji Institute of Technology, Chikaballpura 562101, India
[4] Department of Aerospace Engineering, Sri Jagadguru Chandrashekaranatha Swamiji Institute of Technology, Chikaballpura 562101, India
[5] Department of Mechanical Engineering, B.M.S College of Engineering, Bangalore 560019, India
[6] Department of Robotics and Artificial Intelligence Engineering, Bangalore Institute of Technology, Bangalore 560004, India
[7] Department of Mathematics, Sai Vidya Institute of Technology, Bangalore 560064, India
*** Corresponding author:** Subramanya Raghavendra, rvs.sdly@gmail.com

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Abstract: Aluminium matrix composites (AMCs) reinforced with hard ceramic particles is currently being widely used as a composite material for a range of industrial and technical applications. In the current study, melt stirring was employed to incorporate Aluminium nitride (AlN) particulates into the aluminium 6061 alloy. In this study AlN particles in different proportions 2%, 4%, 6%, and 8% wt were used with Al6061 alloy. Scanning electron microscopy (SEM) and x-ray diffraction were used to characterise the stir cast composites and the base alloy. SEM analysis confirmed the uniform distribution of AlN particles within the Al matrix. The impact of AlN concentrations on the mechanical properties of Al6061 matrix composites was investigated. Pin on disc machines were utilised to examine the dry sliding wear properties of the composites that were manufactured. The presence of very hard AlN elements in the Al6061 matrix alloy significantly improved the mechanical and wear characteristics of the AMCs. As compared to the Al6061 base alloy, the test results showed that the Al6061 with 8% weight percentage AlN composites had better wear resistance and hardness yield strength and the alloy with 2% AlN showed highest tensile strength of 368 MPa. The good interfacial adhesion between fillers and matrix prevents cracking and allows for effective load transmission to the reinforcing phase. This is mainly because AlN is a highly strong and stiff material, and its incorporation gives strong reinforcement as well as increased tensile, flexural, and hardness strength to the composite. This enhancement in mechanical properties suggests potential applications in high-wear industries such as automotive and aerospace.

Keywords: aluminium nitride; stir casting; wear analysis; tensile; flexural

1. Introduction

In modern engineering applications, especially in aerospace and automotive industries, materials with enhanced mechanical and wear properties are in high demand. Aluminium matrix composites (AMCs) offer tuneable mechanical and physical properties, making them suitable for various engineering applications. These applications include aerospace automobile components such turbine blades, engine parts, and wings [1,2]. Furthermore, AMCs have a wide range of uses in the automotive sector, including synchronizers, brake drums, piston rings, and many more [3,4]. It is well known that the final desired properties of the manufactured AMMCs have a significant influence on the reinforcement selection process, the type and proportion of reinforcement determine the composite's strength, hardness, and wear resistance.

Researchers consistently choose the use of particle and fiber reinforcements in composites because of their ability to give the metal matrix great strength, toughness, wear resistance, and fatigue resistance [5]. Particles, due to their ability to disperse uniformly within the matrix, often provide superior strength and toughness compared to fibers. However, due of their ease in fabrication and cheap modelling cost when compared to other reinforcements, research have concentrated more on investigating particle-based reinforcements.

Due to its multiple applications in fields such as semiconductors, electronics, aircraft, and corrosive chemical handling vessels, aluminium nitride (AlN) coating has garnered significant attention [6,7]. AlN has a wide range of applications due to its high hardness, high electrical resistivity, low coefficient of thermal expansion, outstanding physical and chemical stability—even at quite high temperatures—and great resistance to wear, abrasion, and corrosion. These properties make AlN an ideal candidate for reinforcement in AMCs, which this study aims to explore.

Sager et al. [8] examined the application of AlN particles as reinforcement in metal matrix composites and the way they affected the corrosion behaviour of the materials. The findings indicate that adding AlN reduces grain sizes and improves the matrix materials' resilience to corrosion [8]. The behaviour of stir-cast AlN reinforced AA7075 composites were elucidated by Mohanavel et al. [9]. They discovered that flexural strength, UTS, and hardness improved significantly with an increase in the weight percentage of AlN. Furthermore, it was clear from the SEM study that the particles were equally dispersed throughout the composites [9]. However, while their work focused on AA7075, the behavior of Al6061 composites remains underexplored, particularly with varying AlN concentrations. After examining the behaviour of AlN-filled Al composites, Min Zhao et al. [10]. came to the conclusion that the strong interfacial interaction between AlN and Al matrix was the reason for the significant rise in UTS [10].

The Al-AlN composites were fabricated by Lii et al. [11], and the results showed that the addition of AlN reinforcement significantly increased the composites' compressive strength, hardness, and fracture strength [12]. The addition of AlN content to magnesium alloy considerably enhanced its mechanical properties, such as yield strength, UTS, and plasticity, as reported by Khrustalyov et al. [13]. The impact of Al_2O_3 reinforcement on the wear-resistance (WR) of AA6061 and its composites reinforced with 10 vol% Al_2O_3 was documented by Pramanik et al. [14]. After undergoing direct chill casting, both aluminium alloy and composites were hot-extruded into bars. Results indicated that WR was greater in AA6061/Al_2O_3 composites than in base alloy.

Utilising the stir casting method, Pazhouhanfar and Eghbali [13] developed the AA2024 matrix composite reinforced with Al_2O_3 particles of different sizes, namely 16, 32, and 66 μm. The smaller particles (16 and 32 μm) led to agglomeration and segregation of the particles and porosity, whereas the coarser size (66 μm) had a more uniform dispersion. The Al dendrites' early solidification during the composite's solidification was warranted. As the number of Al_2O_3 particles present grew and the particle size decreased, so did the tensile strength and hardness.

Tribological properties of aluminium 6061 alloy reinforced with hybrid composites of graphite and boron particles have been investigated by Nagesh et al. The Al6061 alloy is melted in a graphite crucible in an electrical furnace at a temperature of 720 ℃. In order to eliminate gases and prevent a temperature decrease during casting, the boron and graphite particles are warmed to 600 ℃. When the samples were put through a wear test, the hybrid composite outperformed mono composites in terms of wear resistance under the specified conditions [15].

Kumar et al. [16], carried out research on composites made of Al6061-SiC and Al7075-Al_2O_3. The liquid metallurgy method is used to create the composites, and 2–6% of the particles are distributed throughout the basic matrix. As the amount of filler in the composites grew, the microhardness of the Al6061-SiC and Al7075-Al_2O_3 composites rose as well, reaching 60-97VHN and 80-109VHN, respectively. Al6061-SiC composites have better tensile strength qualities than Al7075-Al_2O_3 composites, and the composites' tensile strength properties are found to be greater than those of the basic matrix. The composites had greater wear resistance, and SiC also made a substantial contribution to the Al6061-SiC composites' increased wear resistance.

The literature study that is quoted clarifies the important role that ceramic reinforcement—specifically, nitrides and Al_20_3—plays in aluminium-based composites. When this reinforcement is included into materials based on aluminium, it produces a strengthening effect that makes the composite material more resilient to deformation and failure. Reinforcement particles alter the material's behaviour by improving its mechanical characteristics, making it more suitable for a variety of situations needing increased strength.

Building upon these insights, the present study explores the effect of varying AlN concentrations in Al6061 composites. In particular, the application of aluminium nitride as reinforcements in casting-synthesised aluminium matrix composites is not as well documented. However, there is still limited research on the effects of AlN on the microstructural, mechanical, and tribological properties of Al6061 composites. This study aims to fill that gap by investigating the behavior of Al6061 composites with varying AlN content. Ultimately, this study aims to create and analyze Al6061 composites reinforced with AlN, focusing on optimizing their wear resistance, hardness, and compressive strength. Squeeze casting was used to precisely create Al6061 matrix composite enhanced with AlN in order to accomplish this challenging goal.

2. Materials and methods

The alloys for the investigation were produced using stir casting technique. Electric Furnace make VM10L1200 was used for the melting and casting procedures, aluminium alloy 6061 (AA6061) used as the base matrix alloy. Melting was carried out at 800 ℃ in a heat-resistant steel crucible. The graphite blade spinning at 400 rpm was used to agitate the molten metal for ten minutes when AlN reinforcing particles (density 3.26 g/cm^3) of average diameter 10 μm were introduced. The blade was adjusted horizontally and vertically throughout the process to ensure even particle distribution and prevent dead zones in the melt. After that, samples were prepared in accordance with ASTM standards by pouring the molten composite into a cylindrical steel mould, which was preheated to 250^{0}C to avoid thermal shock and ensure a uniform cooling rate during solidification. The cast alloys produced had nominal percentages of 0%, 2%, 4%, and 6% AlN. ASTM-E8 standards were used to produce the tensile samples, ASTM-E10 standards were used for the hardness test, ASTM-E23 standards were used for the flexural test, and ASTM-G99-95 standards were used for the wear samples. The chemical compositions of Al6061 are shown in **Table 1**.

Table 1. Chemical composition of Al6061 and AlN.

Al6061	Elements	Cr	Cu	Mg	Zn	Fe	Mn	Si	Ti	Al
	Actual value %	0.35	0.40	1.20	0.25	0.70	0.15	0.80	0.15	95.85
AlN	Elements	O	N	Al						
	Actual value %	1.46	32.26	66.28						

2.1. X-ray diffraction analysis of Al6061 and AlN

X-ray diffraction assessment was achieved to evaluate the occurrence of Al and AlN reinforcement in the composite. XRD spectrum exhibits the occurrence of dual peaks related to Al6061 and AlN which are depicted in the **Figure 1**. XRD data obtained using a Cu-Ka source (wavelength of 0.1540598 nm) X-ray.

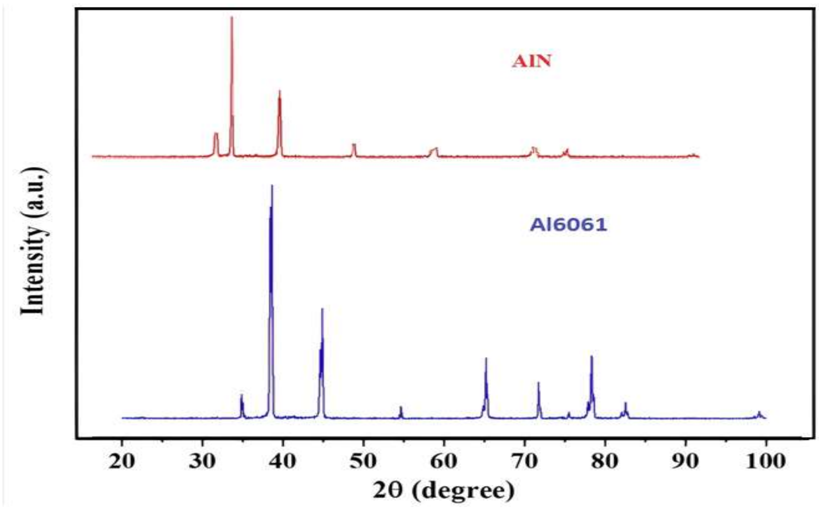

Figure 1. XRD peaks of A6061 and A1N.

Figure 1 shows the XRD pattern of sputtered AlN. The main peaks of the aluminium nitride are observed at Bragg's as 33.3°, 36.0°, 37.5°, and 42.6° corresponding to the crystallographic planes (100), (002), (101), and (220), respectively. The highest peak intensity was found for AlN with (002) orientation. A comparison of observed and standard values of the work investigated by Park and Kim [17]. The XRD showed the compounds present in the aged composites.

Aluminium having the highest peak, Mg and Si elements was present, confirming that it is a 6061 aluminium alloy.

2.2. Tensile, hardness and flexural strength

In the current study, prepared specimens were subjected to a tensile test on a universal testing machine (UTM), the samples were prepared using ASTM-E8 standards. Tensile tests were carried out on KIC-2-1000c machine, and at a test speed of 1 mm/min.

According to the results of the tensile tests as shown in **Figure 2**, the ultimate tensile strength of the alloy increases as the AlN weight percentage rises. Adding ceramic reinforcing AlN functions as a nucleation site and facilitates the crystallisation of the aluminium matrix in the AA6061 matrix. The dislocation motion of aluminium composites is robustly mediated by the improvised grain boundaries. Grain size has decreased as a result of the confined dislocations that are constantly moving across the matrix. This prevents the dislocation motion that builds up the composites' strengthening effect. This reduction in grain size impedes dislocation movement, thereby strengthening the composite. The spatial arrangement of reinforcement in the matrix alloy and the grain refinement seen in the microstructure are the reasons for the rise in hardness of composites. When compared to aluminium alloy, it is also discovered that the increased weight % of AlN acts as a constraint to resist the motion of dislocation, producing a higher hardness. The higher concentration of AlN particles creates more obstacles for dislocation movement, resulting in an increase in hardness.

The flexural test was also conducted on KIC-2-1000c UTM machine with cross head speed of 2 mm/min, the specimen was fabricated as per ASTM E23 standard, Similar trend is observed flexural test also (**Figure 2**), the alloy flexural strength increased as the AlN wt% increases. One of the main factors lowering the ductility is the ceramic-reinforced particles' brittle behaviour. The ductile matrix content can be decreased by increasing the weight percentage of AlN particles in the composites, which can counteract the aluminium matrix's capacity to flow. The flexural strength is calculated using Equation (1).

$$\sigma = (M/I)Y \tag{1}$$

where

σ: Bending stress

I: Moment of inertia

M: Bending Moment

Y: Young's Modulus

Arık et al. [18] studied the mechanical characteristics of B4C-reinforced MMCs with an Alumix-13 matrix, generated using hot compaction. They tested the hardness and three-point bending strength of the aged and non-aged composites. According to the results of the researchers' three-point bending tests, the B4C reinforcement material significantly increased the three-point bending strength of the powder metallurgical composite materials, while the composites containing 10% B4C decreased in strength. As a cause for this finding, they proposed that the increased tendency of fracture formation with the higher B4C ratio restricted the deformation during the three-point bending test and most likely demonstrated a trend towards a cleavage fracture.

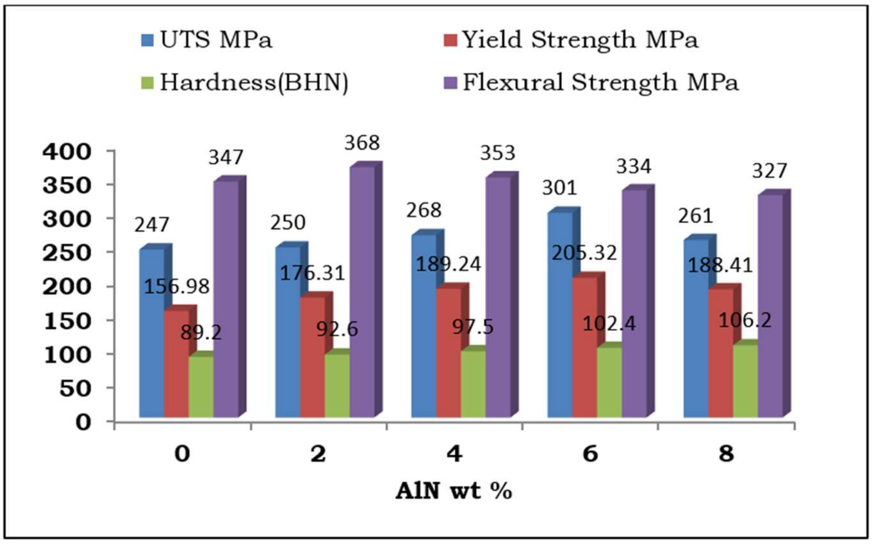

Figure 2. Tensile strength, hardness strength and flexural strength of AlN reinforced Al6061 alloy.

The hardness experiment was conducted using a main load of 100 kgf on a Rockwell hardness testing equipment, with the B scale selected. The specimen with 0% weight AlN had a hardness of 89.2 BHN; linear increases in hardness were achieved by adding 2%, 4%, and 6% weight AlN. The highest BHN recorded in 8% wt reinforced specimens was 106.2. These increases have been identified for enriching the weight proportion of the hard and brittle modes of the AlN particles in the Al6061 aluminium alloy. In a similar work, Hillary et al.'s [19] study examined the mechanical behaviour of Al6061 with silicon carbide (SiC) and titanium diboride (TiB_2) composites. The composite was made with 5 wt% SiC and 2/8 wt% TiB_2 using the traditional stir casting technique. The experiment's results demonstrated increases in micro hardness, tensile strength, and flexural strength of 8.18%, 20.19%, and 9.46%, respectively. Hard particles like SiC and TiB_2 boosted the hybrid composite's load-bearing capacity, which enhanced the mechanical performance of the as-cast Al-6061 composite.

This might be related to an increase in the quantity of hard ALN particles in the aluminium matrix, as well as their high hardness. The incorporation of reinforcement particles into the aluminium matrix increases their surface area while decreasing the size of the aluminium matrix grains. The presence of these hard surface regions on ALN particles provides significant resistance to plastic deformation, resulting in increased hardness of manufactured AMCs [20]. Furthermore, the presence of hard and brittle ALN particles in the soft and ductile Al6061 matrix decreases the ductility content of fabricated AMCs due to the low ductile content of matrix metal in the composite, which significantly improves the hardness of manufactured AMCs, the same phenomena were observed in the obtained result as shown in **Figure 2**.

The dispersion of the strengthening phase and bonding strength of ALN particles in the matrix significantly impact the ultimate tensile strength. This is a well-known dispersion-strengthening mechanism. As a result, the observed undesirable decrease in ultimate tensile strength is mostly due to the creation of small AlN agglomerations inside the matrix. These AlN agglomerations often decrease the interfacial area between the reinforcement and the matrix. Furthermore, the existence of pores within the matrix caused by the overlapping of the AlN particles has a detrimental influence on the material's strength, resulting in fracture initiation in the composite under loading. This reduces interfacial energy bonding between reinforcement and matrix particles, this leads to reduce in the strength of the composites [21].

3. Wear analysis

Dry sliding tests were chosen to simulate real-world conditions where lubrication might be absent, such as in high-temperature environments. The wear test was performed with a 'Pin-on-Disc' wear testing equipment, using specimens with a diameter of 6 mm and a length of 40 mm, a dry sliding wear test was performed in accordance with ASTM-G99-95 standard, against a revolving EN32 steel disc with a hardness of 65 Rc. Testing was conducted using a Pin on-Disc wear test machine (Make: Ducom Instruments Pvt. Ltd., Model: TR20LE), whereby wear and tangential frictional force were tracked with the use of electronic sensors.

The parameters for tribological experiments include load 20 N, 40 N, and 60 N, as well as sliding velocity 1.5 m/s at intervals of 0.5. **Figure 3**, displays the results of the wear tests conducted on the produced composites and illustrates the relationship between the particular wear rate and the quantity of reinforcement in terms of sliding distance and applied load. The wear rates of all the alloy samples are clearly lower than those of the Al6061 alloy, as shown in **Figure 3**. The composite with 8 weight percent AlN has the lowest wear rate, the wear resistance of the 8 wt% AlN composites can be attributed to the uniform distribution of hard AlN particles that resist surface deformation and material removal during sliding. There are several reasons for the increased wear rate in the Al6061 alloy, including the presence of reinforced AlN, the uniform distribution of the reinforcement, the interfacial bonding between the reinforcement and matrix material, and the increased strength attained by

Smaller grains prevent dislocations from moving and lessen the likelihood that a fracture will spread, which is why this happens. AlN, on the other hand, is usually stronger and harder than the matrix material. These hard particles can withstand wear and distortion when included into a softer matrix, hence boosting the composite's overall hardness and wear resistance. Ensuring a consistent distribution of AlN inside the aluminium matrix enhances the composite's resilience to wear. This uniform distribution contributes to the development of a microstructure with several hard phases, which can lessen friction and stop wear tracks from forming.

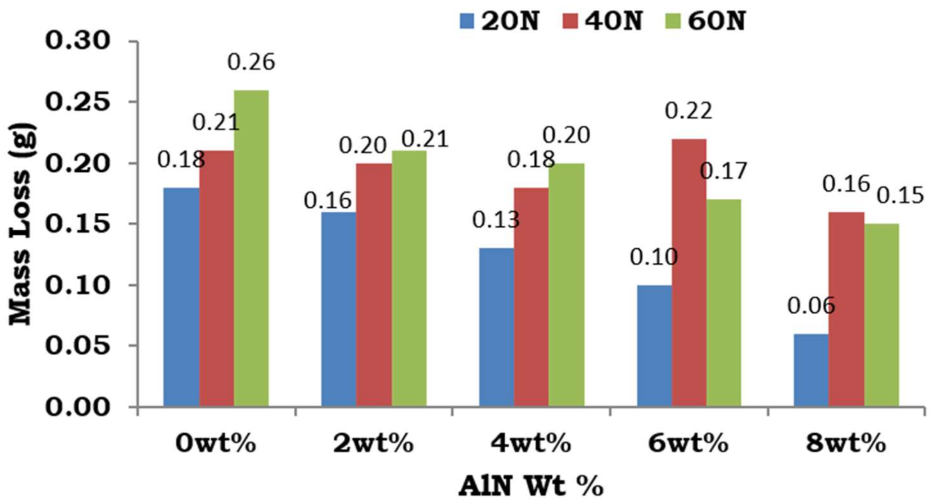

Figure 3. Mass loss of AlN reinforced Al6061 alloys at 20 N, 40 N and 60 N load conditions.

The impact of AlN weight percentage on wear weight loss during the wear test under various load circumstances, such as 20 N, 40 N, and 60 N, is shown in **Figure 4**. The weight loss is calculated using Equation (2).

$$\text{Weight loss(gm)} = \frac{\text{intial weight} - \text{final weight}}{\text{intial weight}} \quad (2)$$

The AlN composites with 8 weight percent reinforcement had the lowest mass loss, whereas the Al6061 matrices had the highest mass loss. It is evident that hard Nano AlN particles reinforced with Al6061 matrix result in a significant increase in mass loss.

The relationship between the rise in wear rate seen in both the Al6061 alloy and the AlN reinforced alloy and the increase in normal load is shown in **Figure 3**. The resistance provided by the brittle asperities and the combined surface effects of ploughing and delamination brought on by the increased load are the causes of this phenomena. Ultimately, the wear rate rises considerably as a result of this higher stress. Moreover, a rise in stress might cause subsurface micro cracking, which would alter or reduce the surface asperities which can be seen from SEM images in **Figures 5** and **6**. Aluminium alloy contains hard alloy particles, which combine to form a mechanically mixed layer (MML) that is made up of a strong layer and a stretchable aluminium base matrix. The resultant lower rate of wear is due to this multi-layered material's effective ability to limit material exchange from the surface, maintaining a mild wear regime primarily controlled by an oxidative process.

Similar findings were reported by Raviraj et al. [22] in their investigation of the aluminium, zinc, and magnesium alloy as well as Verma and Singh [23], when they investigated wear analysis of aluminium matrix composite reinforced with high entropy alloy particles.

3.1. Specific wear rate and co-efficient of friction

Because of the presence of AlN particles, which withstand the applied stress, the contact surface between the produced composite pin sample and the counter steel disc is less than in the parent alloy. Furthermore, when sliding, the AlN reinforcement material cannot separate from the aluminium matrix due to the high integrity between the reinforcement particle and the Al6061 matrix. Consequently, in comparison to the monolithic alloy, the Al6061/8 weight percentage AlN composites exhibited the lowest wear rate. The effect of normal force on the wear rate of the Al alloy without reinforcement and the Al6061/AlN alloy is shown in **Figure 4**. The chart clearly shows that the produced AMCs and plain matrix Al's wear performance increased linearly with an increase in normal load. An increase in load results in a higher WR for Al6061.

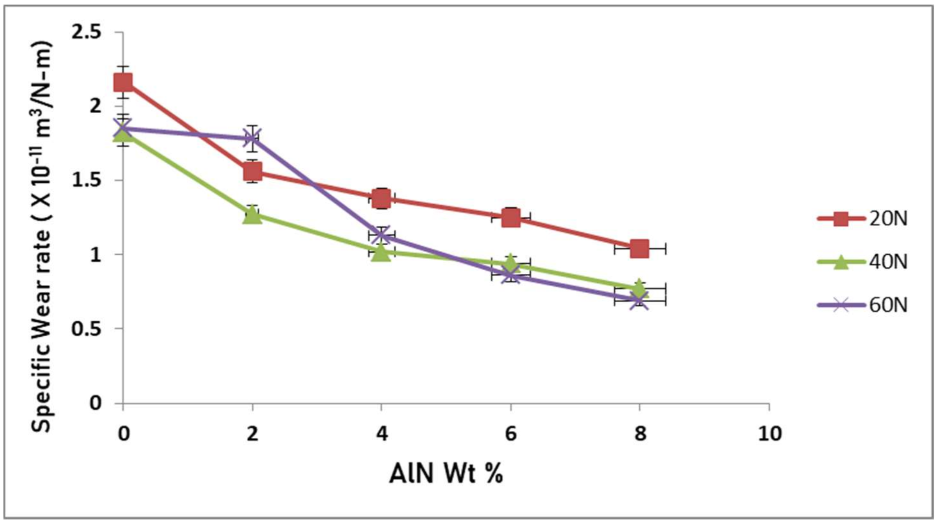

Figure 4. Specific wear rate of the AlN reinforced Al6061 alloy for different load conditions.

The surface material softens as a result of intense frictional heating brought on by increased applied stress. The hard asperity penetration much improves, leading to an increase in the composite material's plastic deformation. Consequently, these actions ultimately cause the composite's wear rate to increase.

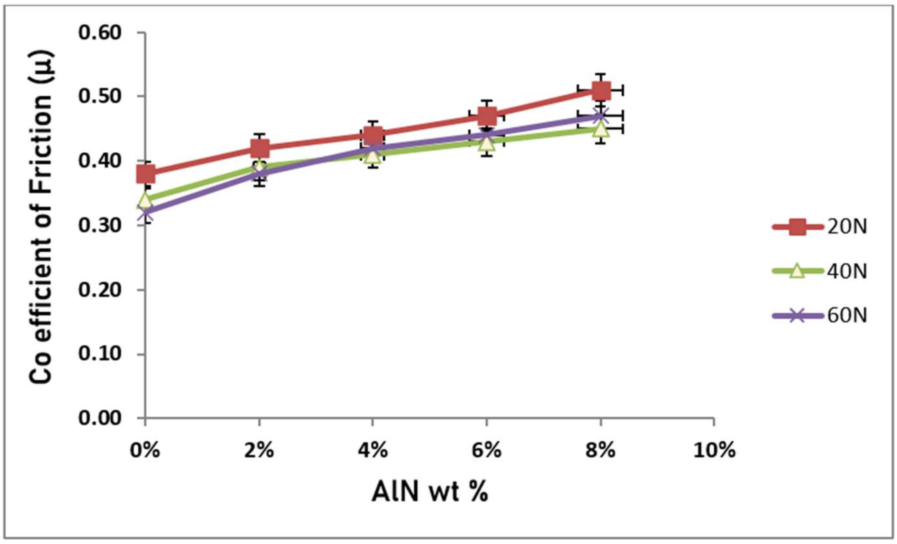

Figure 5. Friction coefficient of the AlN reinforced Al6061 alloy for different load conditions.

Figure 5 illustrates that the Al6061 has a lower coefficient of friction than the AlN-reinforced Al6061 samples. Variations in the degree of localised plastic deformation at actual contact locations might be the cause of variations in the friction coefficient. Because the AlN surfaces are tougher, it is anticipated that there would be less plastic deformation and reduced friction.It is clear that AlN reinforced alloys had less adhesive and abrasive wear because of their increased hardness and somewhat lower coefficient of friction, respectively.

A conductive epoxy composite with two hybrid filler reinforcement systems was created by Choi and Kim [24]. There are two types of systems: one with large-sized AlN particles and small-sized Al_2O_3 particles, and another with small-sized AlN particles and large-sized Al_2O_3 particles. At equal volume contents, this composite shows a higher packing density and a smaller surface area. The mechanical, electrical, and thermal characteristics of a modified AlN filled polyetherimide (PEI) composite were examined by Wu et al. [25]. With increased AlN levels, the tensile modulus, strength, thermal stability, and electrical characteristics improved. The values of the tensile strength are raised by 27% when 12.6 vol% AlN is added to the PEI matrix. The highest tensile modulus of the PEI matrix filled with 33.6 vol.% modified AlN fillers is 563.29 GPa, which is 300% more than the value of the pristine PEI matrix.

3.2. Morphology of worn-out surfaces

In order to comprehend the wear mechanism, it is necessary to examine the worn surfaces. At the sliding distance traversed with applied load condition, the worn surface topography is shown under SEM in **Figure 6**, showing prominent characteristics including asperity fragmentation, wear debris creation, fracture development, and delamination. Both the al6061 and the composite having AlN wt% Al6061 have more noticeable sliding grooves as a result of the asperities' abrasive ploughing effect on the tougher steel surface.

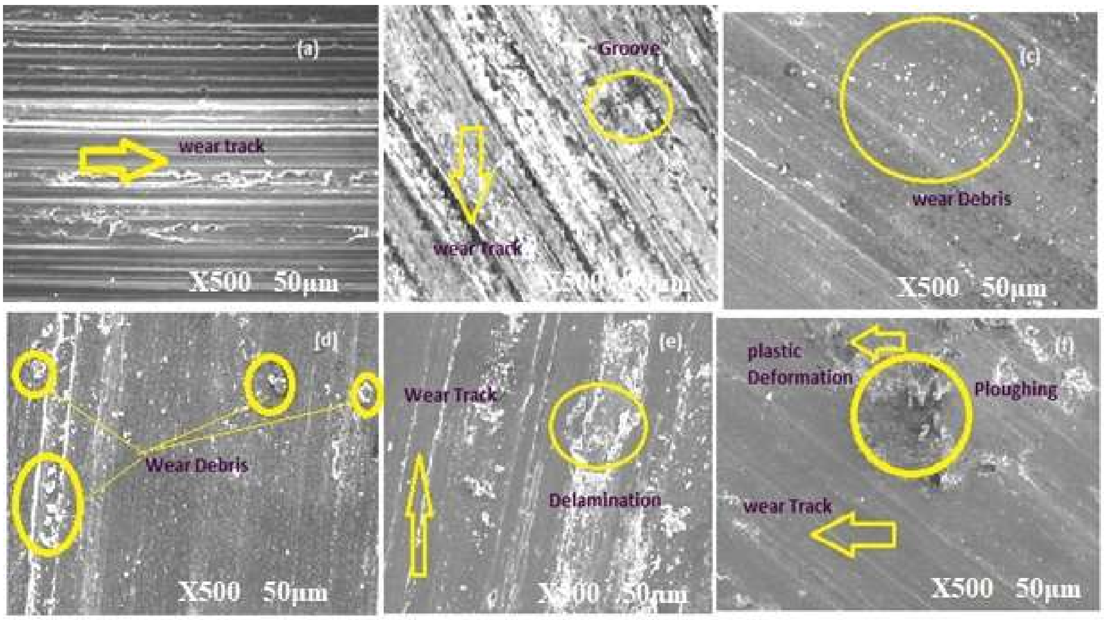

Figure 6. SEM morphology of worn out surfaces.

According to research by Tyagi et al. [26], the classification, geometry, and percentage of the reinforcing materials have a significant impact on the wear characteristics of Al-based composites.

In a study on the sliding wear performance of a hybrid Al2219/Grp/B4Cp composite, Rabindranath et al. [27] found that as load, speed, and travel distance rose, so did the wear in all the materials. On the other hand, the hybridised composite exhibited greater resistance to wear, most likely as a result of the presence of ceramic particle reinforcements. The pace at which material was removed from the composite's surface decreased as a result of the particles' strong resistance to the abrasive's micro-cutting of the composite.

Kumar et al. [28] investigated the wear response of an Al430-based composite including MgO and SiC. Investigators observed that the material wear increased as the reinforcing content increased. Maintaining a 2.5% reinforcement concentration at 600 rpm resulted in a 40% reduction in weight loss. Furthermore, a 45% and 91% wear decrease was seen at higher reinforcement concentrations of 5% and 7.5%, respectively. Additionally, compared to the basic alloy, the composite wear rate was reduced at different loads and speeds.

Delamination, adhesive, abrasive, and fretting wear modes can all affect Al-based MMCs. The relationship between each mechanism and surface morphology is discussed here. The Al6061/AlN alloy sample exhibits a mix of adhesion wear mechanism and deep grooves aligned in the sliding direction, indicating a plastic deformation caused by abrasion. As the two surfaces' interacting asperities fracture and undergo plastic deformation, fractured particles are created that serve as abrasive particles during sliding. As can be seen, these fragmented particles leave the surface and create voids. There have been reports of severe wear in several Al alloys in the past.

4. Conclusion

Al6061 alloy matrix composite reinforced with 0%, 2%, 4%, 6%, and 8% aluminium nitride (AlN) was successfully made using the stir cast approach and exhibited excellent qualities due to an efficient integration of the Al alloy and reinforcement components.

- The enhanced mechanical properties with higher AlN loading make these composites ideal for applications requiring high wear resistance and durability.
- For AlN reinforcement concentrations, the hardness values are progressively improved, ranging from 89.2 BHN at 0 wt% to 106.2 BHN at 8 wt%. Compared to plain matrix, the produced composites have a higher level of hardness.
- Al6061 with 6 wt% AlN alloy reveals 19.70% greater tensile strength when compared to Al6061 plain matrix alloy. Al6061/AlN composites achieves a peak yield strength of 205.32 MPa at 6% wt% AlN reinforcement.
- The wear rate reduced gradually when AlN was added, reaching a minimum at 8 wt% of AlN reinforcement.
- The adhesive mode of features for Al6061 matrix alloy and the abrasive mode of characteristics for Al6061/AlN AMCs are revealed by worn surface morphology. The composites made of Al6061/8 wt% AlN are ultimately shown

to have the best mechanical and wear characteristics. This makes Al6061/8 wt% AlN composites highly suitable for use in demanding environments such as automotive components or industrial machinery. Future studies could explore the long-term durability of these composites in various operational environments.

Author contributions: Conceptualization, SR and RM; methodology, MKN and MSV; software, CSA; validation, CSA and AKR; formal analysis, TNR and ND; investigation, SR, RM and CSA; resources, MKN and ND; data curation, RM and SR; writing—original draft preparation, SR; writing—review and editing, SR and RM; visualization, TNR and MSV; supervision, SR.

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