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MECHANICAL AND TRIBOLOGICAL PERFORMANCE OF AL7075 METAL MATRIX COMPOSITES REINFORCED WITH NANO Al_2O_3 PARTICLES: AN EXPERIMENTAL INVESTIGATION

Krishna Nandan, Mukesh Kumar

Department of Mechanical Engineering,
Vivekananda Global University, Jaipur, India

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MECHANICAL AND TRIBOLOGICAL PERFORMANCE OF AL7075 METAL MATRIX COMPOSITES REINFORCED WITH NANO Al_2O_3 PARTICLES: AN EXPERIMENTAL INVESTIGATION

Krishna Nandan*, Mukesh Kumar

Department of Mechanical Engineering, Vivekananda Global University, Jaipur, India

Corresponding email id: krishna_nandan@vgu.ac.in

Abstract: *Nanostructured aluminum oxide (Al_2O_3) reinforced metal matrix composites (MMCs) based on Al7075 alloy have emerged as novel structural materials for applications requiring excellent mechanical properties and wear resistance. This research work explores the effect of nano Al_2O_3 reinforcement volume fraction (0-4 wt.%) on the mechanical and dry sliding wear characteristics of stir cast Al7075/Al_2O_3 MMCs. Yield and ultimate tensile strengths, percentage elongation and Vickers microhardness measurements were performed following standard procedures to develop a structure-property correlation. The mechanistic assessment revealed a gradual improvement in mechanical performance with increasing reinforcement content up to an optimum of 3 wt.% Al_2O_3. The microalloyed composite with 3 wt.% Al_2O_3 exhibited the highest yield and ultimate tensile strengths of 202.1 N/mm² Further increase in the reinforcement content, however, led to a slight decrease in mechanical properties, likely due to particle clustering and interfacial defects within the composite. The wear performance of the composite was evaluated in the pin-on-disc configuration over Wear rate studies illustrated that the composite containing 3 wt.% Al_2O_3 reinforcement showed the least rate of wear (2.3×10^{-3} mm³/m) at a 1 An increase in wear rate was observed with rising normal load and sliding distance, while moderately high sliding speed of 350 RPM resulted in the lowest wear rates for all compositions, indicating a shift in wear mechanism from abrasion to adhesion wear. This study demonstrates that 3 wt.% nano Al_2O_3 reinforcement is the optimal composition of Al7075-based MMCs for a combination of improved mechanical and tribological performance, with optimal properties for aerospace, automotive and structural engineering applications.*

Keywords: *Aluminium Metal Matrix Composite (Al-MMC), Nano Al_2O_3 Reinforcement, Mechanical Characterization, Dry Sliding Wear Behavior*

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Introduction

The continuous development of modern engineering industries, especially the aerospace, automotive, defense, and structural industries, has made it urgent to develop lightweight materials with excellent mechanical strength, excellent hardness, and high mechanical toughness. Conventional monolithic aluminum alloys, though having appreciable strength-to-weight ratios, often fail to meet the performance-level demands imposed by the increasingly demanding performance requirements of modern structural and tribological applications. In this regard, aluminum based metal matrix composites (Al-MMCs) have gained significant scientific and industrial interest during the last two decades due to outstanding combination of low density, increased stiffness, wear resistance as well as controllable thermomechanical properties that can be tuned by careful selection of the matrix alloy and the reinforcement phase [1,2]. Among different systems of aluminum alloys have been investigated as MMC matrices, Al7075 alloy, a high strength precipitation-hardened Al-Zn-Mg-Cu alloy system, has been widely recognized as one of the most structurally efficient base material, with some of the inherently high mechanical strengths, good fatigue resistances and excellent machinability, making it particularly suitable for use as a matrix structure for high performance composite systems intended for high performance structural applications [3,4].

Metal matrix composites are usually reinforced using ceramic particles such as silicon carbide (SiC), boron carbide (B4C), titanium diboride (TiB2) and aluminum oxide (Al2O3), which act as load bearing constituents that inhibit dislocation motion, grain refinement and overall mechanical response of the composite system [5,6]. Among these reinforcement materials, Aluminum Oxide, Al2O3, has been extensively investigated for its excellent application in aluminum alloys because of its excellent physical and chemical properties, such as high hardness about 1800-2000 HV, high melting point temperature at 2072 degC, high chemical stability, good interface compatibility with Aluminum matrix, and relatively low cost of production [7,8]. These attributes make Al2O3 a very attractive reinforcement candidate for Al-MMCs, especially for applications where the simultaneous achievement of improved hardness, tensile strength and wear resistance is required. Furthermore, the development of nano-scale Al2O3 reinforcement from the traditional micro-scale has led to a paradigm change in composite performance, because the nano-sized particles provide a much higher surface area/volume ratio, stress distribution and matrix-reinforcement interfacial bond quality, thus imparting a much higher mechanical and tribological performance in the composites even at comparatively lower weight fractions of reinforcement [9,10].

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The fabrication methodology used during the synthesis of Al-MMCs, the microstructures integrity, the homogeneity of particle distribution and the resulting properties of the composite are deeply influenced by such a factor. Stir Casting (also called vortex casting) has become one of the most widely used and commercially viable liquid-state processing for the fabrication of particle reinforced MMCs, mainly because of its simplicity, economy, scalability, and capability of fabricating near-full-shape components with complex geometries [11,12]. The process includes stirring the molten matrix alloy mechanically to create a vortex and introducing reinforcement particles into the vortex, so as to enhance the wettability of the reinforcement particles and achieve the uniform distribution of the particles in the metal matrix. Despite its advantages well documented in literature, stir casting is prone to various problems such as particle agglomeration, porosity formation and segregation at higher reinforcement concentrations which require careful optimization of processing parameters to obtain composites with consistent microstructural quality with reproducible mechanical performance [13].

Extensive experimental investigations have been carried out in order to assess the effect of Al2O3 reinforcements on the mechanical behaviour of aluminum alloy-based MMCs. Prasad and Rama Narayana Reddy [14] have reported significant enhancement in hardness and tensile strength of composites of Al6061 and Al2O3 with varying contents of reinforcement due to good load transfer between matrix and ceramic particles. Similarly, Kumar et al. [15] showed that nano Al2O3 reinforced Al7075 composites had a yield strength and hardness results that were superior to their micro reinforced counterparts, thus emphasizing the positive role of nano scale reinforcement and its refinement of microstructure and its increase of dislocation density. On the other hand, many observations of the tensile behavior of composites indicate that ductility and elongation decreases dramatically with increment of the ceramic content, which has been attributed to the naturally brittle nature of the reinforcement phase and thus consequent to the restriction of plastic deformation in the composite matrix [16,17].

The tribological performance of Al-MMCs under dry sliding conditions is one of the most important design parameters of engineering components with contact loading, friction, and surface degradation. Wearing behavior is governed by a complex interplay of factors including applied normal load, sliding velocity, sliding distance, reinforcement content, particle size and the nature of the tribological interface [18,19]. The pin-on-disc tribometer setup has been widely used as a standardised tribological experimental setup for tests of the dry sliding wear behaviour of MMCs, since it allows systematic variation of tribological parameters in order to

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establish comprehensive maps of wear and the dominating wear mechanisms. Previous investigations have reported that Al2O3 reinforced MMCs have much lower wear rates than unreinforced aluminum alloys, due to the protection offered by the hard ceramic particles to reduce direct metal to metal contact and minimize subsurface plastic deformation [20,21]. However, the relation of reinforcement content, sliding parameters and wear mechanism from the abrasive to the adhesive or delamination wear regimes is still an issue under further investigation, especially for nano reinforced composite systems as the tribological behavior is substantially different from that of conventionally reinforced composites [22].

Despite the abundance of existing literature in Al-MMCs there are few systematic studies that tackle the combined influence of nano Al2O3 reinforcing weight fraction and multi-parametric tribological conditions including variable normal loads (10 N and 15 N), wide range of sliding speeds (150-500 RPM) and large sliding distances (500-1000 m) on the mechanical and wear mechanism of Al7075-based composites which are considered integrated performance characteristics. Most published investigations have been focused either on mechanical characterisation or the tribological assessment individually, without the establishment of a coherent structure-property-performance relationship through the entire range of reinforcement concentrations. Furthermore, the identification of a suitable reinforcement composition to achieve maximum mechanical strength and hardness and tribological resistance while taking into account the loss of ductility with excessive reinforcement loading has not been discussed thoroughly about the Al7075/nano Al2O3 composite systems.

The present investigation is therefore motivated due to the need to bridge these knowledge gaps by carrying out a comprehensive experimental investigation and to systematically evaluate the effect of nano Al2O3 reinforcement content (0-4 wt.%) on the yield strength, ultimate tensile strength, percentage elongation, Vickers microhardness and dry sliding wear rate of stir casted Al7075/Al2O3 MMCs. Tribological experiments have been performed in a matrix of normal loads, sliding speeds and sliding distances to create an in-depth understanding of wear behavior and transition of the wear mechanism as a function of reinforcement content and operating conditions. The results obtained in this research work are expected to offer useful information for science and technology as well as guidelines for practicing engineers for design and optimization of high-performance Al7075-based MMC systems for demanding applications in aerospace, automotive and structural engineering where weight reduction, mechanical reliability and surface durability are of prime importance.

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2. Similar Work

The development and the characterization of metal matrix composites (MMCs) has been a topic of great interest during the past several decades as the demand for advanced engineering materials with the lightweight properties of aluminum alloys combined with the outstanding mechanical and tribological properties of ceramic reinforcements has been ever-present. A global review of the available literature reveals that there has been considerable progress in understanding synthesis, microstructural evolution, mechanical behavior and wear properties of the aluminum MMCs and this provides a strong scientific base on which the present investigation is built.

Aluminum alloys have been well known as preferred matrix materials for composite systems for aerospace, automotive and structural engineering applications, mainly because of their favorable strength-to-weight ratio, corrosion resistance and processability [5]. The reinforcement of aluminum matrices with ceramic particulates such as Al2O3, SiC, TiO2, ZrO2 and B4C has been widely successful to improve the hardness, tensile strength and wear resistance of these composite systems, making them a potential alternative of conventional monolithic alloys in high-performance engineering environments [7,10]. Prasad and Asthana [26] offered a basic insight into the tribological issues involved in aluminum MMCs for automotive applications and established that the use of hard ceramic reinforcements in aluminum MMCs leads to significant reductions in adhesive and abrasive wear mechanisms by creating a protective tribolayer at the contact interface to prolong the operational life of sliding components.

The stir casting process has been widely confirmed as one of the most practical viable and cost-effective fabrication journeys for particle strengthened Al-MMCs. Chandra et al. [12] tested the hardness and toughness of aluminum MMCs by stir casting and showed that the hardness of MMCs can be systematically varied to obtain different levels of tough but only if sufficient wetting is ensured as well as suitable stirring parameters to obtain a homogeneous particle distribution. Complementarily, the experimental validity of casting characteristics in stir-cast aluminum composites was proven by Gowrishankar et al. [11], who determined that processing parameters such as stirring speed, melt temperature and particle preheating have a decisive influence on the microstructural uniformity and mechanical consistency of the fabricated composites. Despite its benefits, the stir casting process is prone to particle agglomeration and voids at high reinforcement fractions as pointed out by Bhargava et al. [13], who stressed that

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it was necessary to optimise nano particle dispersion protocols to reduce agglomeration effects that affect mechanical integrity.

The mechanical behavior of aluminum composites reinforced with Al 2O 3 has been the subject of many systematic investigations. Mazahery and Ostadshabani [16] carried out a detailed investigation about the mechanical properties of nano Al2O3 reinforced aluminum matrix composites, and showed significant enhancement in hardness and tensile strength with increasing amount of reinforcement, which could be attributed to Orowan strengthening, coefficient of thermal expansion mismatch strengthening, and good transmission of loads. AlSalhi et al. [14] reported a comprehensive review of nanoparticles reinforced aluminum alloys in which the authors saw that nano-scale reinforcements enhance the properties much more than their micro-scale counterparts due to an enhanced surface area and an efficient dislocation interaction with matrix dislocations. Similarly, Solanki et al. [15] examined the mechanical and corrosion characteristics of nanocomposites in an aluminum matrix reinforced with nanoparticles and confirmed that the best amounts of reinforcement are necessary so that the nanocomposites have the best combination of strength and ductility, while excessive reinforcement causes degradation in properties due to the accumulation of interfacial defects.

Sadeghi et al. [17] investigated friction stir processed aluminum composite reinforced with bimodal micro- and nano-sized Al2O3 particles to show the combination of the processing method and particle size diversity is critical on the control of biomechanical refinement and mechanical consider response. Their results underlined the excellent tribological performance possible with nano-reinforcement strategies, a conclusion which was supported by the results from Shuvho et al. [31], who characterized the mechanical behavior of aluminum MMCs reinforced with nano Al2O3, SiC, and Ti2O2 particles and reported a final finding of enhanced surface integrity and wear resistance compared to mono-reinforced composites for nano-reinforced systems. The tribological characterization of Al-ZrO2 composites reviewed by Parveen et al. [20] further supported the positive use of ceramic reinforcement in wear rate and friction coefficient reduction under dry sliding conditions, confirming the importance of the type and morphology of the reinforcement to the resulting tribological results.

The dry sliding wear behaviour of aluminum MMCs has been tested in a wide variety of parametric conditions, and these have been reported in many published investigations. Samal et al. [28] examined the dry sliding wear behaviour of an MMCs made with Al6082 matrix reinforced with red mud particles and they concluded that the wear rate is proportional to the

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applied normal load and sliding distance and is non-monotonic function of the sliding velocity which is consistent with mechanism transitions from the abrasive and adhesive to oxidative wear regimes. Omrani et al. [27] reviewed the tribological properties of graphite reinforced aluminum MMCs and emphasized the importance of self lubricating reinforcements in green tribology applications, which showed that reinforcement selection greatly affects the dominating wear mechanism. Shuvho et al. [30] conducted a tribological investigation of MMCs based on aluminum 6063 reinforced with hybrid SiC-Al2O3-TiO2 particles, and provided the following details: Multi-reinforcement system showing complex wear behavior controlled by synergistic interaction between individual reinforcement phase and aluminum matrix based on contact conditions.

Investigations on the machining and surface characteristics of Al-MMCs have provided additional information about the performance of materials when loaded. Srivastava [10,19] evaluated the mechanical properties and EDM machinability of stir cast Al6063/SiC MMCs and found correlations between the amount of reinforcement, surface integrity and material removal rate are relevant to the practical deployment of MMC component in precision engineering applications. Haque et al. [37] investigated the tribological behavior and microhardness characteristics of Al6063/nano Al2O3 MMCs manufactured by powder metallurgy, and it has been confirmed that nano reinforced composites for a range of process parameter combinations have superior hardness and wear resistance characteristics than those of the unreinforced variants. Kamrani et al. [25] investigated systematically the effect of reinforcement volume fractions on the mechanical properties of Al-SiC nanocomposites manufactured by the mechanical alloying technique, reporting that the best reinforcement fractions maximize the strength while minimizing the loss of ductility, which is of direct relation to the present study for optimizing nano Al2O3 content of Al7075 composites.

The action of reinforcement type and hybrid combinations on MMC performance have been studied further by a number of other researchers. Kaviyarasan et al. [7] has compared the mechanical properties of Al6063 alloy incorporating different types of reinforcing ceramics particle and showed that the hardness and tensile strength improvements of Al6063 alloy with Al2O3 reinforcing ceramics is competitive with other ceramic systems. Danappa et al. [48] examined dry sliding wear behaviour of Al7075/Gr/nano TiO2 hybrid MMCs by using response surface methodology and found out that sliding speed, normal load and reinforcement content are the most important parameters affecting the wear rate and optimum combination results in lower wear rate by about 45-55% compared with that of unreinforced alloys.

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Bhuvanesh and Radhika [39] ruled the tribological behavior of silicon nitride reinforced aluminum MMC's experimentally and confirmed the ultimate importance of reinforcement hardness in resisting subsurface deformation and tangential material transfer at the tribological interface.

Collectively, the reviewed literature establishes the fact that nano Al2O3 reinforcement in aluminum alloy matrices has great potential for simultaneous improvement of mechanical and tribological performance with the optimization of the reinforcement content being the key to achieving the desired property balance. However, comprehensive studies comprehensively addressing Al7075/nano Al2O3 composites under wide ranges of tribological parameters included multi-level normal loads, sliding speeds and sliding distances are still comparatively scarce which justify the systematic experimental investigation undertaken in the present work.

3. Material and Methods

3.1 Research Methodology Overview

The present investigation followed a systematic experimental methodology to fabricate and characterize Al7075-based metal matrix composites (MMCs) reinforced with nano sized aluminum oxide (Al2O3) particles at different weight fractions in the range of 0 to 4 wt.%. The fabrication was performed by the stir casting process which was chosen because of cost-effectiveness, scalability and based on its ability to produce reasonably uniformly reinforced composites. The global research workflow included raw material procurement and characterization, composite manufacturing, microstructural investigation, mechanical testing and tribological evaluation in a multi-parametric pin-on-disc wear testing set-up.

3.2 Matrix Material: Al7075 Alloy

The base matrix material used in present investigation was Al7075 aluminum alloy which is a high strength precipitation hardenable alloy of Al-Zn-Mg-Cu series, procured from a certified material supplier at Jaipur, Rajasthan, India. Al7075 is well known in aerospace, automobile and structural engineering industries for its excellent combination of high tensile strength, good fatigue resistance, moderate corrosion resistance and good machinability. The alloy owes its strength to the fact that the majority alloying elements are zinc and magnesium that facilitate the formation of MgZn2 precipitates during an ageing heat treatment process contributing significantly to PH. The addition of copper further improves the strength while trace amounts of chromium give better resistance to stress corrosion cracking.

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Figure 1. Cutting of Al7075 raw material for purification

Prior to composite fabrication, the section of the as received Al7075 billets were cut into suitable charge weights using a precision band saw as shown in Figure 1. The sectioned pieces were then subjected to an initial stage melting process carried in a graphite crucible resistance furnace up to about 780 degC temperature to burn off surface oxides and other impurities, and to ensure a clean melt with uniform chemical composition, as shown in Figure 2. The chemical composition and original mechanical properties of the Al7075 alloy for this study that is verified are shown in Tables 1 and 2, respectively.

Figure 2. Al 7075 furnace activity to remove the impurities

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Table 1 Chemical Composition of Al7075 Alloy Used in the Present Investigation

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	Al
Composition (wt.%)	0.40	0.35	1.52	0.03	2.51	0.19	5.68	0.06	0.05	Balance

Table 2 Mechanical Properties of Al7075 Alloy and Nano Al_2O_3 Reinforcement

Property	Al7075 Alloy	Nano Al_2O_3
Density (kg/m³)	2810	3960
Vickers Hardness (HV)	182.1	~2000
Elastic Modulus (GPa)	71.7	380
Yield Strength (N/mm²)	73.8	—
Ultimate Tensile Strength (N/mm²)	106.8	—
Elongation (%)	2.39	—
Melting Point (°C)	477–635	2072
Particle Size (nm)	—	50–100

3.3 Reinforcement Material: Nano Al_2O_3 Particles

The reinforcement material used in this research was commercially sourced nano sized aluminum oxide (a-Al2O3) powder as fine as 50 - 100 nm in mean particle size purchased from a certified nano-materials supplier. Nano Al2O3 was used as the reinforcement phase due to its exceptional physical and chemical properties, excellent hardness (around 1800 - 2000 HV), high melting point (2072 degC), high chemical stability at high temperature, high thermodynamic compatibility with aluminum matrices and relative low price with respect to other types of ceramic reinforcements including SiC or B4C. The nano-scale particle size is responsible for providing much higher surface area-to-volume ratio as compared to micro-scale counterparts, thus resulting in more efficient load transfer, enhanced matrix reinforcement

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interfacial bond and superior dislocation pinning effects, which contribute to the marked improvement in mechanical and tribological performance of the composite.

Table 3 Physicochemical Properties of Nano Al_2O_3 Reinforcement

Property	Value
Chemical Formula	Al_2O_3
Phase	Alpha (α-Al_2O_3)
Particle Size	50–100 nm
Purity (%)	≥ 99.5
Density (kg/m³)	3960
Hardness (HV)	~1800–2000
Elastic Modulus (GPa)	380
Melting Point (°C)	2072
Thermal Conductivity (W/m·K)	30
Crystal Structure	Hexagonal (Corundum)
Surface Area (m²/g)	45–65

Prior to inclusion within the melt, the nano Al2O3 powder was pre-heated in a muffle furnace at 300 degC for 2 hours to eliminate adsorbed moisture, surface contaminants and enhance wettability to the molten aluminum matrix. Figure 4 shows the particle size distribution of the nano Al2O3 reinforcement which confirm a basically uniform distribution of particle size within the range 50-100 nm, which is an indicative of the good quality of the procured reinforcement material. The physicochemical properties of nano Al2O3 are summarized in the table 3.

3.4 Composite Fabrication by Stir Casting

The Al7075/nano Al2O3 MMC specimens were produced by a conventional stir casting method which was chosen because of the well-documented advantages of this method which include utilization of simple operation and cost-effectiveness, the ability to use various weight

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fractions of the reinforcing elements, and the ability to produce near-net-shape composite castings with reproducible microstructural characteristics. The stir casting equipment consisted of the following: resistance heated graphite crucible furnace with a mechanical stirrer assembly containing the graphite-coated stainless steel impeller designed to create a stable vortex of molten metal.

Table 4 Stir Casting Process Parameters for Al7075/Nano Al_2O_3 MMC Fabrication

Process Parameter	**Value / Condition**
Matrix Material	Al7075 Alloy
Reinforcement	Nano Al_2O_3 (α-phase)
Reinforcement Weight Fraction (wt.%)	0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0
Particle Size of Reinforcement (nm)	50–100
Melt Temperature (°C)	820
Pouring Temperature (°C)	720
Stirrer Speed (RPM)	450
Stirring Duration (min)	10
Particle Preheating Temperature (°C)	300
Particle Preheating Duration (h)	2
Mold Material	Permanent Steel
Mold Preheating Temperature (°C)	250
Casting Geometry	Cylindrical Rod (Ø20 mm × 200 mm)

The fabrication procedure was started by placing the pre-weighed Al7075 billets inside the graphite crucible and heating the furnace to 820C approximately 40C above the liquidus temperature of the alloy to ensure the complete melting of the alloy with appropriate melt fluidity. Once a fully molten state was reached and the melt temperature stabilized, the mechanical stirrer was then introduced in to the melt and operated at a rotational speed of 450 RPM to create a controlled vortex. The preheated nano Al2O3 powder with corresponding

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target reinforcement weight fraction (0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5 and 4 wt.%) was introduced incrementally into the vortex with a controlled feed rate of about 5-8 g min-1 using a vibration assisted powder feeder in order to minimize particle clustering and ensure progressive and uniform dispersion in the melt. Stirring was continued for 10 min after completion of the addition of powder to ensure uniform mixing of powders and homogeneous distribution of nano particles throughout the melt volume.

The melting temperature was then lowered to 720C before pouring to minimise the effects of turbulence on porosity and control the solidification behaviour. The composite melt was then gravity poured into preheated (250degC) permanent steel molds with a cylindrical shape (diameter: 20mm, length: 200mm) to form the composite rods that were later used to prepare the specimens. Upon complete solidification the cast rods were removed from the molds and undergo visual and dimensional inspection and sectioned out to test specimens with appropriate geometries as per the relevant testing standards. Table 4 summarises the fabricating process parameters used during stir casting of artefacts of Al7075/nano Al2O3 composites.

3.5 Mechanical Testing

Mechanical characterization of the fabricated composites was performed following the set up international testing standards. Tensile specimens were prepared from cast rods according to the standard of ASTM E8/E8M, the length of gauge length is 50 mm and the length of diameter is 12.5 mm, which are tested by universal testing machine (UTM) at the speed of 2 mm/min to determine yield strength, ultimate tensile strength and percentage elongation. Vickers microhardness measurements were made on an applicable load of 1 kgf (HV1) at a dwell time of 15 seconds, five indentations were made per specimen at randomly selected points on polished cross-sectional surfaces and the average value was reported.

3.6 Tribological Testing

Dry sliding wear tests were carried out in a pin-on-disc type tribometer in compliance with the requirements of the ASTM G99 standard. Cylindrical wear pins with dimensions of 8 mm diameter and 30 mm length were fabricated from each composite composition and each wear pin was tested against a hardened EN32 steel disc (hardness: 62 HRC). The following tribological parameters were studied: The results of these studies can be summarized in Table 5.

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Table 5 Tribological Test Parameters for Pin-on-Disc Wear Testing

Tribological Parameter	Levels / Values
Normal Load (N)	10, 15
Sliding Speed (RPM)	150, 250, 350, 500
Sliding Distance (m)	500, 750, 1000
Track Diameter (mm)	80
Pin Diameter (mm)	8
Pin Length (mm)	30
Disc Material	EN32 Steel (62 HRC)
Lubrication Condition	Dry (Unlubricated)
Wear Rate Unit	$mm^3/m \times 10^{-3}$
Ambient Temperature (°C)	25 ± 2
Relative Humidity (%)	45 ± 5

4. Fabrication Steps

4.1 Overview of Fabrication Procedure

The fabrication of Al7075/nano Al2O3 metal matrix composites was performed using stir casting technique which represents as one of the most widely employed liquid state processing methodology used for manufacture of particle reinforced MMCs due to its inherent advantages like process simplicity, cost-effectiveness, scalability, and ability to produce composites with a reasonable distribution of reinforcement across a variation of weight fraction. The fabrication procedure was done following a series of well-defined sequential steps including raw material preparation, melt processing, reinforcement incorporation, mechanical stirring and solidification casting. Each step has been carefully controlled to ensure the consistency of the microstructure, reduce the formation of porosity, and obtain reasonable matrix-reinforcement interfacial bonding in all nine compositions of the composite investigated in the present study.

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4.2 Preparation of Matrix Material

The Al7075 alloy billets, which were obtained as extruded rods, were first cleaned with wire bristle and acetone solvent to remove surface grease, oxide layers and other substances which may have adverse impact on the melt quality. The cleaned billets were then cut into uniform charge pieces of about 50 g per piece by a precision band saw as shown in Figure 1 for uniform and controlled melting in the graphite crucible. The total charge weight for each casting batch was kept at 500 g of Al7075 alloy with the addition of the nano Al2O3 noted as reinforcement calculated as a percentage of this base weight in accordance with the target composition of the composite.

The sectioned Al7075 pieces were loaded into a high-density isostatic graphite crucible that was set inside an electric resistance furnace. The furnace temperature was ramped at a controlled rate of 10C min-1 and the charge was heated to 820C, which is about 40C above the liquidus temperature of Al7075 (~477-635C solidus-liquidus range) to ensure a complete melting with a good melt fluidity to bring out the stirring and casting operations. Once the complete melting was achieved based on visual observation and temperature stabilization through thermocouple monitoring, drossing was carried out by skimming the oxide-rich surface layer from the molten metal via a preheated dross skimmer made of stainless steel to remove the floating impurities to guarantee a clean melt before the addition of reinforcement, as shown in Figure 2.

4.3 Preparation of Nano Al_2O_3 Reinforcement

Prior to the introduction into the aluminum melt, a thermal pretreatment process was used for the nano Al2O3 powder with the aim of an improved surface condition and better wettability to the melted matrix of the alloy. Precisely weighed amounts of nano Al 2 O 3 powder as reinforcement weight fractions of 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 and 4.0 wt.% were placed in alumina crucibles and preheated in a muffle furnace at 300degC for 2 hours. This preheating treatment had the dual advantages of removing adsorbed surface moisture which may cause hydrogen porosity in the melt and partially oxidizing the surface of the particles to advance chemical bonding on Al2O3-Al interface. The preheated powders were moved as soon as possible to the casting station in sealed containers to avoid re-adsorption of atmospheric moisture before melt was added. The results of the physicochemical properties of the nano Al2O3 reinforcement and the preparation parameters are shown in Table 4.

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4.4 Stir Casting Process

The stir casting operation was performed with a motorised stir casting machine with a graphite-coated stainless steel impeller and the capability to rotate with controlled speed from 100 to 600 rpm. The impeller was positioned at about 1/3 of melt depth from the bottom of the crucible to produce an efficient and stable vortex without excessive splashing of the melt or entrainment of air as shown in figure 2.

The fabrication process was carried out in two different stirring stages to achieve the progressive and homogeneous incorporation of nano Al2O3 particles in the Al7075 melt. In the first stage, the molten Al7075 at 820 degC was stirred at a speed of 200 RPM for 300 seconds to form a uniform vortex and homogenize the temperature of the molten Al7075 before the addition of particles. The preheated nano Al2O3 powder was then added incrementally into the vortex at a controlled feed rate of 5-8 g/min with the help of a vibration assisting powder feeder to avoid clumping of the particle being added.

Figure 3. Stir casting machine used for making the composite

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After adding the reinforcement powder completely, the melt temperature increased to a superheated condition of 780 +- 10 degC and the stirring speed increased to 450 RPM for 650 seconds more to insure good dispersion and wetting of nano al2o3 particles in the molten matrix. The increased stirring rate in the second stage facilitated mechanical de-agglomeration of the nano particles and enhanced the interface contact between the ceramic reinforcement and the aluminum melt, and thereby ensured a homogeneous composite slurry before casting. Throughout the stirring process, the crucible was kept in a semi inert atmosphere by firing a controlled flow of argon gas over the surface of the melt to minimize oxidation and hydrogen pickup. The full two stage stirring procedure is described in Table 6.

Table 6 Two-Stage Stir Casting Process Parameters

Parameter	Stage 1 (Pre-Addition Mixing)	Stage 2 (Post-Addition Mixing)
Melt Temperature (°C)	820	780 ± 10
Stirring Speed (RPM)	200	450
Stirring Duration (seconds)	300	650
Impeller Material	Graphite-Coated SS	Graphite-Coated SS
Impeller Position	1/3 from crucible bottom	1/3 from crucible bottom
Atmosphere	Argon Gas Purge	Argon Gas Purge
Reinforcement Feed Rate (g/min)	—	5–8
Purpose	Melt homogenization	Particle dispersion and wetting

4.5 Casting and Solidification

Upon completion of the second stage stirring, the composite slurry temperature was carefully decreased to the optimal pouring temperature of 720C by controlled cooling of the furnace. This temperature decrease before pouring was important in the minimization of melt turbulence, shrinkage on solidification and particle segregation and settling in the casting

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operation. The composite melt was degassed by using hexachloroethane (C2Cl6) tablets which were introduced to the melt at 0.2 wt.% of the melt weight with an aim to minimize the amount of dissolved hydrogen and reduce the porosity in the solidified casting.

Table 7 Casting and Solidification Parameters

Parameter	Value / Condition
Pouring Temperature (°C)	720
Mold Type	Permanent Steel Mold
Mold Preheating Temperature (°C)	250
Mold Geometry	Cylindrical (Ø20 mm × 200 mm)
Degassing Agent	Hexachloroethane (C_2Cl_6)
Degassing Agent Quantity (wt.%)	0.2
Cooling Condition	Ambient Air Cooling
Atmosphere During Pouring	Argon Gas Purge
Number of Composite Batches	9 (one per reinforcement fraction)
Post-Casting Inspection	Visual + Dimensional

The degassed composite melt was gravity poured into preheated permanent cylindrical shape steel molds, shown in Figures 4. The molds were preheated to 250C before pouring to minimize the thermal gradient between the melt and mold walls to minimize solidification cracking, cold shuts, and misruns and to promote the more uniform development of grain structure throughout the casting. After pouring, the molds were left to cool to room temperature with ambient cooling before they were demolded. The solidified composite rods were removed from the molds and visually inspected for surface defects and were labelled systematically in accordance with their weight fraction of reinforcement for the subsequent specimen preparation and testing. The casting parameters used are summarized in Table 7.

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Figure4. Mold filled with composite liquid material

4.6 Specimen Preparation

Following the solidification and demolding process, the cast composite rods were machined to the required dimensions of the specimens by a cnc lathe and surface grinding machine. Tensile test specimens machined following the standards of ASTM E8/E8M with gauge length of 50 mm & diameter gauge of 12.5 mm. Wear test pins of 8 mm diameter & 30 mm length were prepared using each composite composition. Hardness test specimens were then sectioned from the cast rods, mounted in epoxy resin, and metallographically polished to a mirror finish with silicon carbide emery papers of successively higher grades (320, 600, 800, 1200 and 2000 grit) followed by 1 um diamond paste polishing. The prepared specimens were etched using Keller's reagent (2 mL HF + 3 mL HCl + 5 mL HNO3 + 190 mL H2O) for 15--20 seconds to expose the grain boundaries and microstructure for optical microscopy. The specimen dimension and preparation standards used in each characterization technique are summarized in Table 8.

Table 8 Specimen Dimensions and Preparation Standards

Test Type	Standard	Specimen Geometry	Dimensions
Tensile Testing	ASTM E8/E8M	Dog-bone (cylindrical)	Gauge Length: 50 mm, Gauge Ø: 12.5 mm
Vickers Hardness	ASTM E384	Polished cross-section	15 mm × 15 mm × 10 mm

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Test Type	Standard	Specimen Geometry	Dimensions
Wear Testing (Pin-on-Disc)	ASTM G99	Cylindrical pin	Ø8 mm × 30 mm
Microstructural Analysis	ASTM E3	Metallographic mount	Ø25 mm × 10 mm
Density Measurement	ASTM B962	Irregular chunk	~10 g per sample

5. Result and Discussion

5.1 Mechanical Properties

5.1.1 Yield Strength and Ultimate Tensile Strength

The variation of yield strength and ultimate tensile strength (UTS) of Al7075/nano Al2O3 composites with reinforcement content is given in Fig. 5. A systematic and progressive improvement in both yield strength and UTS was observed with increasing the weight fraction of nano Al2O3 upto the optimum concentration of 3 wt.% beyond which a measurable decrease in both the properties was recorded. The unreinforced Al7075 base alloy had a yield strength of 73.8 N/mm2 and UTS of 106.8 N/mm2. Upon incorporation of nano Al2O3 at 3 wt.%, these values increased significantly to 202.1 N/mm2 and 301.5 N/mm2 respectively with absolute improvements of about 174% and 182% as compared to the base alloy. These substantial enhancements are attributed to synergistic operation of several strengthening mechanisms attributed to nano scale ceramic reinforcement, i.e., Orowan dislocation bypass strengthening; Hall-Petch grain boundary strengthening due to grain refinement induced by nano particle-matrix interactions; load transfer from ductile aluminum matrix to the stiffer phase of the ceramic reinforcement; and coefficient of thermal expansion (CTE) mismatch strengthening due to greatly different thermal expansion behavior of Al2O3 (8.1 * 10-6 /oC) and Al7075 (23.6 * 10-6 /oC), which generates geometrically necessary

Beyond 3 wt.% reinforcement, both yield strength and UTS showed a progressive decrease and the yield strength and ultimate tensile strength of the composite (4 wt.% reinforcement) were 181.3 N/mm2 and 259.8 N/mm2, respectively. This resulting deterioration in mechanical performance at increased reinforcement fractions should basically be attributed to the

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increasing tendency of nano Al2O3 particles to agglomerate in the aluminum matrix at elevated weight fractions and to form particle clusters, which are acting as local stress concentration sites and initiate premature fracture under tensile loading. Additionally, the higher likelihood of interfacial void formation and particle matrix debonding at higher reinforcement contents is responsible for the decline in load transfer efficiency and subsequent drop in tensile properties. These observations agree with those found in the literature on previously reported nano-reinforced Al-MMC systems, and confirmed the presence of an optimum reinforcement concentration that can maximize mechanical performance of the systems.

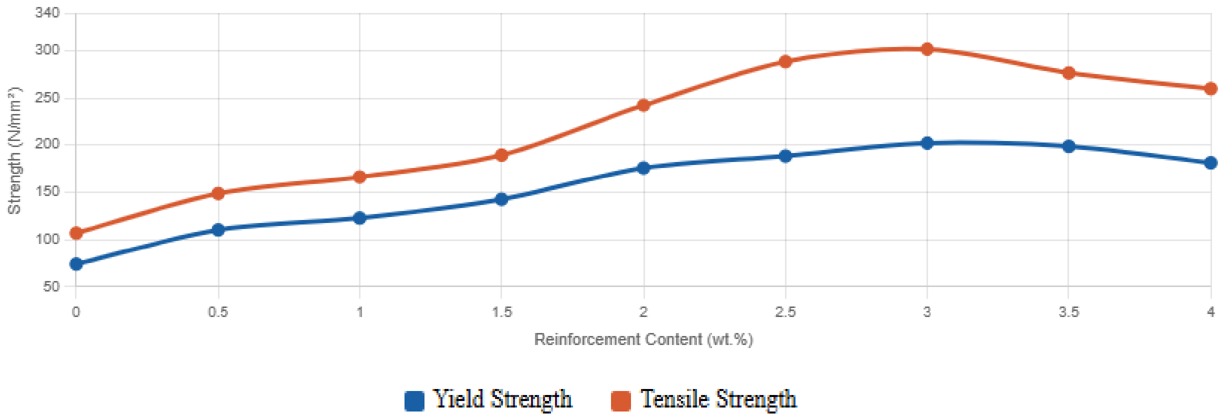

Figure 5 Variation of yield strength and ultimate tensile strength with nano Al_2O_3 reinforcement content (wt.%) in Al7075 MMCs.

5.1.2 Vickers Microhardness

The variation of Vickers micro hardness with nano Al2O3 reinforcement content is shown in fig. 6. Hardness showed a monotonic increase from a value of 182.1 HV for unreinforced Al7075 base alloy to a maximum value of 221.3 HV at 3 wt.% Al2O3 which represents an improvement of approx. 21.5%. The progressive increase of hardness with reinforcement content is fundamentally owed to the intrinsically high hardness of nano Al 2O 3 particles (~1800-2000 HV), which can efficiently resist plastic indentation in the hardness testing by limiting dislocation movement in the surrounding matrix material. The nano-scale size of the reinforcement particles means a higher number density of particles is achieved per unit volume as compared to micro-scale equivalents at the same weight fraction and this can be used to maximize the Orowan strengthening contribution of the particle system and in turn improve the overall resistance to localized plastic deformation.

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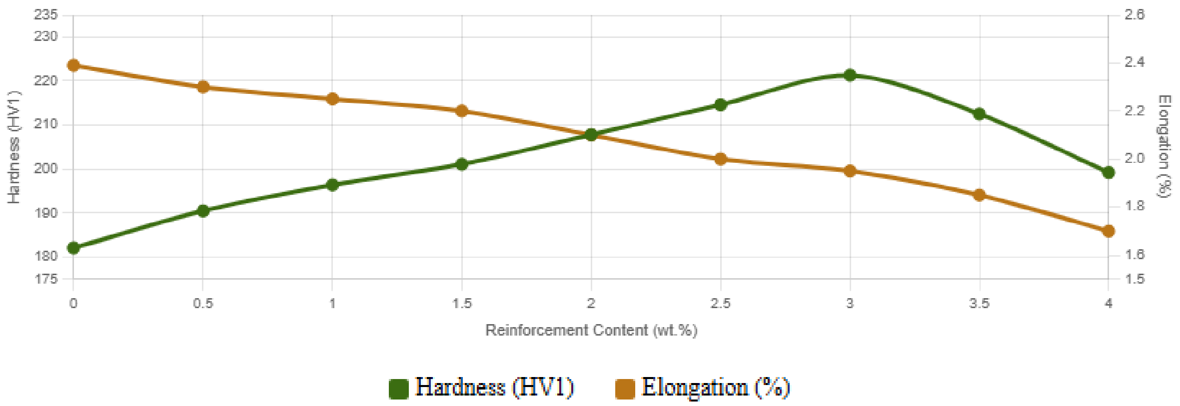

Figure 6 Variation of Vickers hardness (HV1) and percentage elongation with nano Al_2O_3 reinforcement content.

At reinforcement content more than 3 wt.%, the hardness decreased to 212.5 HV and 199.2 HV at 3.5 and 4 wt.%, respectively. The decrease in hardness beyond the optimum reinforcement fraction is related to particle agglomeration (agglomerate particle reduces the number of effective reinforcement matrix contact interfaces and creates softened areas in the agglomerate-rich zone in which the effect of individual nano particles as constraint is reduced). These results confirm 3 wt.% as the critical reinforcement content for the maximisation of hardness for Al7075/nano Al2O3 composites.

5.1.3 Percentage Elongation

As demonstrated in Fig. 6, percentage elongation showed a regular and progressive decrease with increasing nano Al2O3 reinforcement content in the whole range investigated. Elongation decreased from 2.39 for the unreinforced alloy to 1.70% for the 4 wt.% composite. This diminution of ductility is an expected result of ceramic reinforcement and is mainly controlled by the intrinsically brittle character of Al2O3 particles, which limit plastic deformation in the composite by hindering the gliding of the dislocations and inducing stress concentration at the particle-matrix interface. The progressive degradation of elongation observed through the reinforcement range without any reversal at higher values of reinforcement indicates that ductility degradation is a cumulative function of reinforcement content and is not recovered even in the case of agglomeration induced strength deterioration. While the decrease in elongation is a trade-off with the pronounced increase in strength and hardness obtained, the non-dimensional values of elongation are still in the technically acceptable range for structural engineering applications where stiffness and wear resistance are more important than ductility.

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5.2 Tribological Performance

5.2.1 Effect of Reinforcement Content on Wear Rate

The wear rate behavior of Al7075/nano Al2O3 composites with reinforcement contents, normal load, sliding speed and sliding distances is presented in Figs. 7-10. From the variation of parametric values, the wear rate was generally reduced with the increasing nano Al2O3 content up to 3 wt. %, above the value of which the wear rate increased; similarly for the mechanical properties.

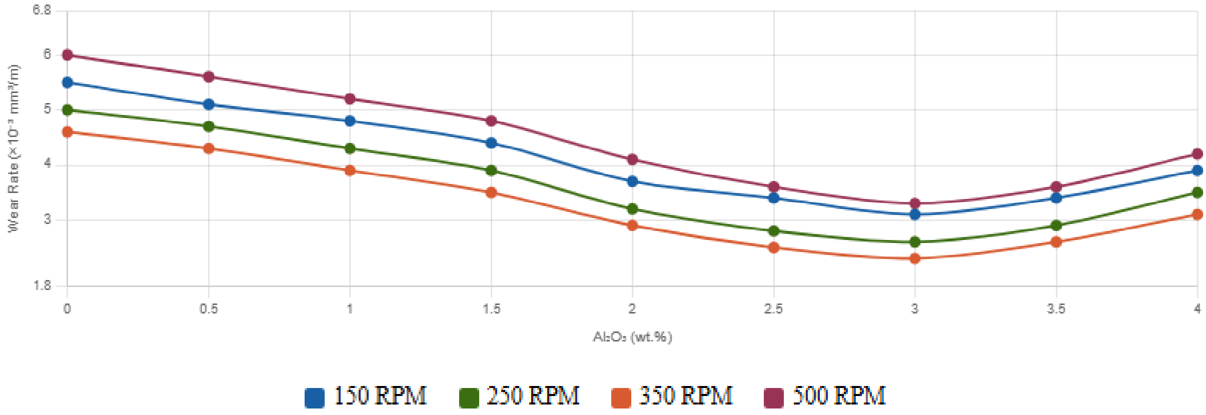

Figure 7 Wear rate ($mm^3/m \times 10^{-3}$) vs. nano Al_2O_3 content at 10N load, 500m sliding distance across four sliding speeds.

Under the conditions of 10N normal load, 350RPM sliding speed, and 500m sliding distance, the minimum wear rate of composite with 3 wt.% achieved 2.3X10-3mm3/m, while the unreinforced alloy wear rate is 4.6X10-3mm3/m, which is about 50%. The superior wear resistance of the composite over the base alloy is mainly attributed to the protection function of nano Al2O3 in the tribological contact region, as they act as load-bearing asperities to decrease the direct contact between metals, form mechanically mixed layer (MML) to inhibit the transfer of adhesive materials, and increase the hardness of the subsurface area of the metal, which reduces wear caused by plastic deformation (delamination wear).

5.2.2 Effect of Normal Load

A comparison of Figs. 7 and 8 (500m sliding distance) and Figs. 9 and 10 (1000m sliding distance) shows that application of normal load of 15N in place of 10N had a significant and consistent increase of wear rate in all composite compositions, sliding speeds, and sliding distances. For 3 wt.% composite material at 350 RPM and 500m wear rate increased from 2.3*10^-3 mm3/m at 10N to 3.2*10^-3 mm3/m at 15N and increased by about 39%. At the

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sliding distance of 1000m which was higher under the same conditions, the corresponding values were 4.3*10^-3 mm^3/m and 5.9*10^-3 mm^3/m for 10N and 15N respectively.

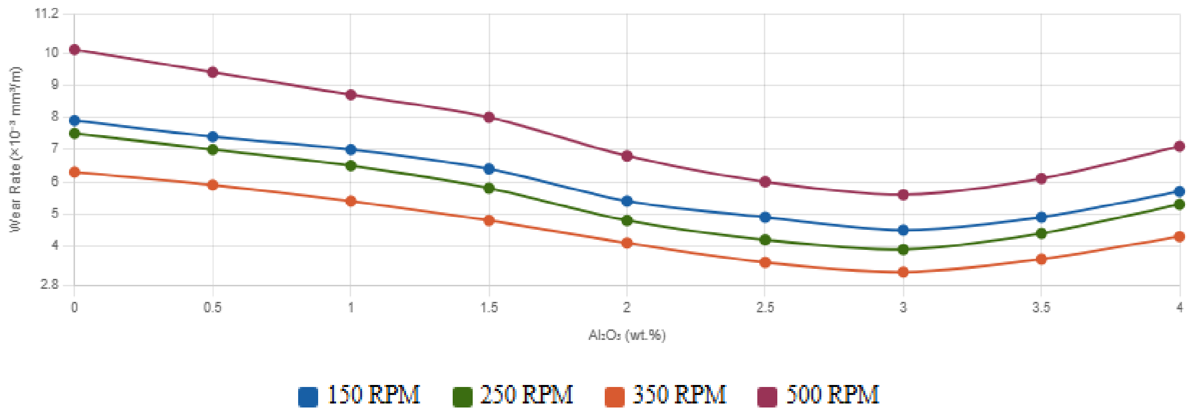

Figure 8 Wear rate ($mm^3/m \times 10^{-3}$) vs. nano Al_2O_3 content at 15N load, 500m sliding distance across four sliding speeds

The reason for wear rate escalation under elevated normal load is attributed to the increased contact pressure at the pin-disc interface due to the plastic deformation of subsurface material that is accelerated, brittle fracture of reinforcement particles at higher stress levels is promoted and adhesive material transfer and abrasive groove formation rate on the worn surface is enhanced. Furthermore, the higher frictional heat at higher loads is conducive to enhance the thermal softening of the aluminum matrix, which results in less resistance for plastic flow and thus increase in material removal rates.

5.2.3 Effect of Sliding Speed

The influence of sliding speed on wear rate showed a non-monotonic behavior which is of high tribological interest, as one can see in Figs. 7 -10. Among four different sliding speeds tested (150, 250, 350 and 500 RPM), the intermediate sliding speed (350 RPM) showed consistently low wear rate values for all those reinforcement compositions and load and sliding distances. Wear rate was rather high at 150 RPM and reduced to a minimum at 350 RPM then increased significantly at 500 RPM. For the unreinforced Al7075 at 10N and 500m, wear rates at 150, 250, 350 and 500 RPM were found to be 5.5, 5.0, 4.6 and 6.0 * 10-3 mm3/m, respectively. This non-monotonic speed dependence is attributed to the competing effects of two mechanisms: at lower sliding speeds (150-350 RPM) the increase in sliding speeds favors the formation of a thermally stable, strain-hardened mechanically mixed layer at the contact surface which acts as a protective tribofilm and reduces direct contact between metal disc at the contact surface lowering the wear rate.

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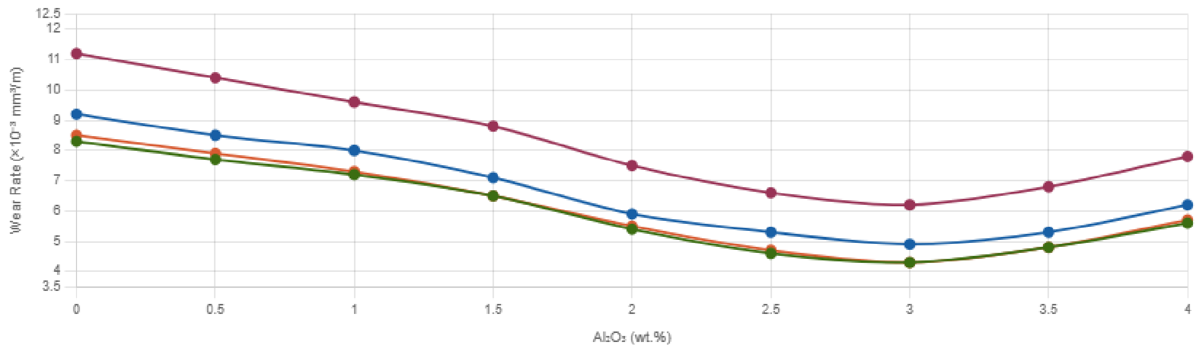

Figure 9 Wear rate ($mm^3/m \times 10^{-3}$) vs. nano Al_2O_3 content at 10N load, 1000m sliding distance across four sliding speeds.

At speeds above 350 RPM, however, the frictional heat generated is in a non-beneficial range, and leads to a thermal softening of the aluminum matrix, destruction of the protective tribolayer, and a change from a mild abrasive to a severe adhesive wear, with a corresponding increase of the material removal rates.

5.2.4 Effect of Sliding Distance

The influence of sliding distance on the wear rate is clearly shown by comparing the result from sliding distances of 500m, 750m, and 1000m at all the parametric conditions. Wear rate increased SWR a linear and substantial with increasing sliding distance was found for all composite compositions and loading conditions. For the 3 wt.% composite at 10N and 350 RPM, wear rate rose from 2.3*10-3mm3/m at 500m to 4.4*10-3mm3/m at 750m and 4.3*10-3mm3/m at 1000m.

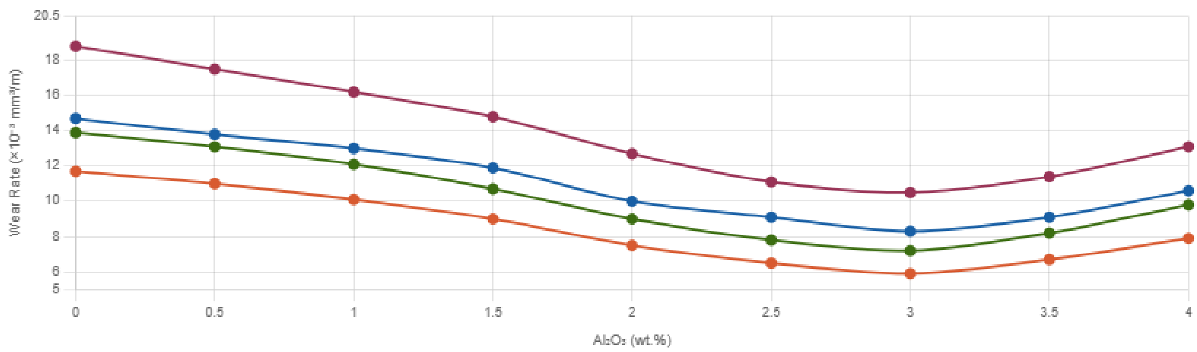

Figure 10 Wear rate ($mm^3/m \times 10^{-3}$) vs. nano Al_2O_3 content at 15N load, 1000m sliding distance across four sliding speeds.

The progressive wear rate increase with sliding distance is related to the gradual degradation and fragmentation of the protective mechanically mixed layer under sustained sliding contact,

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the formation of wear debris accumulation at the contact interface, which naturally functions as a third body abrasive medium, the progressive roughening of the surface due to the repeated deformation and fracture of surface asperities, and the thermal history of the sliding specimen that favors cumulative softening of the subsurface material at long sliding times. Notably, the degree of the relative increase in wear resistance provided by nano Al2O3 reinforcement was similar for the whole sliding distances, demonstrating the sustained effectiveness of the ceramic reinforcement in inhibiting the removal of material under prolonged tribological loading effects. Synthesizing the mechanical and tribological results, the 3 wt.% nano Al2O3 composite can be indisputably identified as the best composition, which has the highest yield strength (202.1 N/mm2), UTS (301.5 N/mm2), hardness (221.3 HV) and least wear rates for the widest range of tribological conditions examined. The post-optimal decrease in properties at 3.5 and 4 wt.% reinforcement confirms the existence of a well defined optimum controlled by the antagonistic balancing of the strengthening resulting from the homogeneous dispersion of particles with the weakening resulting from agglomeration of particles and accumulation of interfacial defects. These findings give definite quantification information for the Al7075/nano Al2O3 composites design used for high-performance engineering applications.

6. Conclusion

The present investigation systematically investigated the mechanical and tribological behaviour of the Al7075 metal matrix composites reinforced with nano-sized Al2O3 particles over a reinforcement range of 0-4 wt.%, which is manufactured using the stir casting technique. Based on the obtained comprehensive experimental results and analysis, the following main conclusions are drawn: The incorporation of nano Al2O3 reinforcement resulted in a progressive and significant improvement in yield and ultimate tensile strength and Vickers micro hardness of Al7075 MMCs up to an optimum reinforcement content of 3 wt.%, at which the highest values of 202.1 N/mm2, 301.5 N/mm2 and 221.3 HV recorded improved by about 174%, 182% and 21.5%, respectively, when compared with unreinforced Al7075 base alloy. These enhancements have been ascribed to the synergetic effect of Orowan strengthening, grain boundary strengthening, load transfer and coefficient of thermal expansion mismatch mechanisms related to nano-scale reinforcement phase. A full and progressive decrease in the percent elongation as a function of incrementation in the reinforcement content was a confirmation of the expanse ductility-strength trade-off expected of ceramic-reinforced MMC systems.

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Tribological investigations performed under a full set of normal loads (10N and 15N), sliding speeds (150-500RPM) and sliding distances (500-1000m) demonstrated that the 3 wt.% nano Al2O3 composite has the lowest wear rates for all the parameteric conditions with a minimum wear rate of 2.3 * 10-3 mm3/m was observed at 10N, 350RPM and 500m sliding distance - which is about 50% lower than the wear rate for Wear rate was found to increase monotonically with both normal load and sliding distance and a non-monotonic speed dependence with a minimum at 350 RPM confirmed a change from mild abrasive to severe adhesive wear mechanisms at fast sliding velocities.

Beyond 3 wt.% reinforcement, real deterioration was noted in both mechanical and tribological characteristics that were attributed to agglomeration of the particles and their formation of interface defects in the composite matrix, and 3 wt.% was the determined optimal reinforcement fraction for Al7075/nano Al2O3 MMC systems. The results of this study offer useful scientific and engineering direction for the development of high-performance light-weight composite materials for aerospace, automotive and structural applications which require good mechanical integrity and tribological durability.

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