Research Article

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Investigation of Mechanical and Tribological Properties of Aluminum Metal Matrix Hybrid Nanocomposites Reinforced with Alumina and Titanium Carbide Nanoparticles

D. Sudarsan[1*], A. Bovas Herbert Bejaxhin[1] and S. Raj Kumar[2]

[1]Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Science, Chennai, TN, India

[2]Department of Mechanical Engineering, Institute of Technology, Hawassa University, Hawassa, Ethiopia

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*dssudersun1976@gmail.com

ABSTRACT

Particle-reinforced aluminum metal matrix nanocomposites (MMNCs) garnered huge attention in recent years, owing to their increased wear properties and mechanical characteristics. Metal matrix composites and alloys often make use of nanoparticles of alumina and titanium carbide for reinforcing purposes. Fewer details are known about hybridized MMNCs that have been fortified with different types of nanoparticles. The characteristics of hybrid nanocomposites are evaluated in comparison to those of nanocomposites reinforced with individual reinforcements. A 100 gmf stress was applied for 10 seconds to test the specimens' Vickers micro-hardness. The hardness increased by 114% and the compressive strength by 60% with the addition of nanoparticles to the metal matrix. Tests were conducted on the specimens' dry wear characteristics at speeds of 550, 600 and 650 rpm with loads of 40, 45 and 50 N. A higher carbon reinforcing level in the metal matrix results in a higher wear resistance.

Keywords: Powder metallurgy; Tribology; Mechanical properties; Wear; Hardness.

1. INTRODUCTION

A composite material combines the physical and chemical characteristics of two or more distinct components. The matrix and the reinforcing phase are the two primary components of a composite material, respectively (Bayraktar *et al.* 2020). Components that may be recognized at tiny levels may be physically and/or chemically joined during the production of composites. MMCs are a type of composite material in which a metal alloy acts as a matrix (Sathiaraj *et al.* 2016; Ramesh *et al.* 2022).Metal matrix composites (MMCs) are considered as cutting-edge materials due to their exceptional qualities compared to those of neat metals or alloys (Kumar and Rai, 2018). The low density and moderate mechanical qualities of aluminum and its alloys make them ideal matrix phases for MMCs. Aluminum matrix composites (AMCs) have several applications in various industries (Mihlyuzova *et al.* 2022). Incorporating various materials into AMCs can enhance their strength and increase their properties. Strong reinforcing phases can be added to the aluminum matrix, such as titanium carbide (TiC), boron carbide (B_4C) or aluminum oxide (Al_2O_3) (Rahman *et al.* 2018; Maurya *et al.* 2020). Carbon-based reinforcements such as graphite, alumina (Al_2O_3) and graphene can be utilized to strengthen aluminum or its alloy matrix (Katundi *et al.* 2020; Meignanamoorthy *et al.* 2020).

There has been research on how TiC particle reinforcement affects the strength and ductility of composites made of aluminum matrix (Sharma *et al.* 2020; Manikandan *et al.* 2023). Their research revealed an 18% improvement in ductility. A hardness of 48 HV was determined by an alternative research group's investigation of nano-TiC reinforcement. Materials utilized in applications requiring wear resistance can benefit from TiC-reinforced composites due to the hardness of TiC, which enhances their resistance to wear (Harouz *et al.* 2022). The TiC-reinforced composites exhibit favorable tribological properties. Using transmission electron microscopy (TEM), the authors (Kumar *et al.* 2020) investigated composites with an aluminum matrix and nano-TiC reinforcements. The microstructure was generally seen as nanocrystalline in the Transmission electron microscope (TEM) images. The finished products suffer from increased porosity due to the higher reinforcing content. The use of hybrid nanocomposites to reinforce an aluminum matrix was investigated by researchers (Srinivasan *et al.* 2023). The materials used during production resulted in increased hardness and reinforcing distribution uniformity. Matrix and reinforcement load transmission was shown to be efficient, leading to improved properties. The authors (Raghav *et al.* 2021) investigated hybrid composites made from inexpensive fly ash and titanium carbide. The composite exhibited a reduced wear rate than the basic material due to its self-lubricating capabilities. Carbon-based nanoparticles have been investigated for their capacity to enhance characteristics in aluminum matrix composites. The process of strengthening of the alumina-reinforced aluminum matrix nanocomposite was revealed by researchers in their study (Manikandan *et al.* 2023). Some hypothesized mechanisms that explain the property improvement of Al_2O_3-strengthened aluminum MMNCs contain load transmission, the system of Orowan looping and displacement production from temperature disparity (Kang *et al.* 2019; Kumar *et al.* 2021).

For improved AMC performance, carbon-based materials, TiC, B_4C and Al_2O_3 can be added as reinforcements. Achieving a uniform distribution, improving hardness and wear resistance and maximizing the equilibrium between ductility and strength have all been primary goals of the research community. The effects of hybridized nano-reinforcements in an aluminum matrix are the focus of this study. Nanoparticles of alumina and titanium carbide are frequently employed as strengthening agents in various alloys and MMNCs. The utilization of various reinforcements in hybridized MMNCs is an emerging sector of study. By combining alumina with nano TiC, a new hybrid nanocomposite with an aluminum matrix has been developed. The specimens were tested for their Vickers micro-hardness under 100 gmf stress for 10 seconds. Specimens were subjected to dry wear tests at speeds of 550, 600 and 650 rpm with weights of 40, 45 and 50 N. Cylindrical specimens were tested for compressive strength using a Universal Testing Machine. Nanocomposites reinforced with separate reinforcements, pure matrix materials and hybrid nanocomposites were compared in terms of their characteristics.

2. MATERIALS AND METHODS

2.1 Materials

Aluminum is chosen as the matrix phase, with nano Titanium carbide (TiC) and alumina (Al_2O_3) selected as the reinforcement phases.

2.2 Preparation of Nanocomposites

Powder metallurgy (PM) was used to create an aluminum composite with Al_2O_3 and nano-TiC. sintering, compaction and mixing are the three main steps in powder metallurgy. Throughout the mixing process, the 8:1 ball-to-powder ratio has been preserved in ball milling. For 2.5 hours, the material was ground using a ball mill operating at 350 rpm. The powder cluster has been thoroughly mixed after being fragmented by the impact of the ball milling. The Universal Testing Machine (UTM) was then used to compress the combined powder with a force of 70 kN. Alumina and nano-titanium carbide were both present in the hybrid nanocomposite at volumetric concentrations of the same amount. The sample was compressed and then sintered at 650 °C in a vacuum furnace. The cylindrical specimen is manufactured with a length of 30 mm and a diameter of 15 mm.

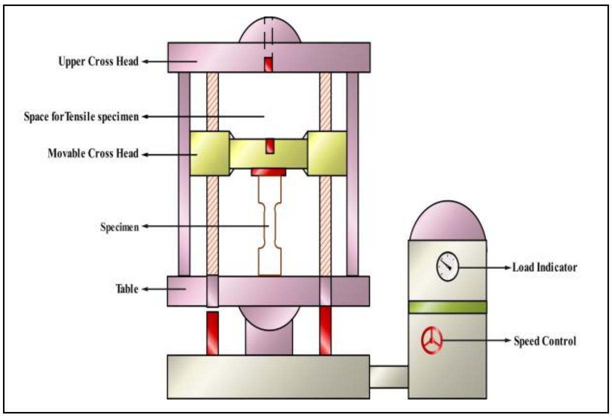

Fig. 1: Schematic view of Universal Testing Machine

2.3 Methodology

Tribological qualities, mechanical features and microstructural examinations are the three areas in which the samples have been examined. To determine the compression strength, a specimen was subjected to a force through the lower hydraulic jaw of a Universal Testing Machine (Fig. 1) until it broke (Reddy *et al.* 2020; Taha *et al.* 2022). All three readings were averaged to get the data presented in this research. Using a Vickers micro-hardness tester, the micro-hardness was assessed. The micro-hardness test used a 100 gmf delivered with a 10-second dwell duration. The specimens were analyzed using a high-resolution X-ray diffractometer to identify the different phases present. Tribological properties were assessed using a wear and friction monitor at various loads (40, 45 and 50N) and speeds (550, 600 and 650 rpm). The track material worn was made of EN-31. The wear rate is determined using the following equation (Magnus *et al.* 2020; Jose *et al.* 2022):

$$\begin{aligned} \textit{The wear rate } (W_r) &= \textit{wear volume } (mm^3) \\ &\div \{\textit{time of rotation } (\textit{min}) \\ &\times \textit{sliding speed } (m/min) \\ &\times \textit{applied load } (N)\} \end{aligned}$$

$$\textit{Sliding speed} = \pi DN / 1000 \; (\textit{in } m/min);$$

where,

D - Track diameter in mm(fixed in all calculations at 60 mm)

N - Speed in rpm

$$Sliding\ distance = time\ of\ rotation\ (in\ minute) \times sliding\ speed\ (in\ m/min) \times surface\ area\ (in\ mm^2)\ and\ wear\ volume = \{wear\ reading \times surface\ area\ (in\ mm^2)\}/1000\ (in\ mm^3)$$

3. RESULTS AND DISCUSSION

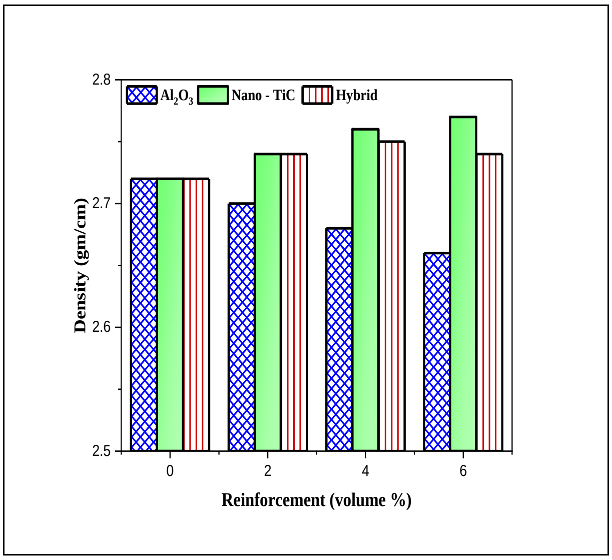

Fig. 2: Comparison of Sintering density of nano-TiC, Al_2O_3 and hybridized nanocomposites

Because of its lightweight reinforcement, alumina-based (Al_2O_3) nanocomposites have a slightly lower density. On the other hand, when the nano-Titanium carbide (nano-TiC) concentration in the aluminum (~ 2.8 gm/cc) increases, the density of the nanocomposite has grown. Fig. 2 shows a density comparison of the two reinforcements, with a hybrid nanocomposite sandwiched between them to show how their respective properties are combined. Experiments on nanocomposite specimens reveal that their sintered density is somewhat greater than their green density, and this is independent of the reinforcements chosen. This is due to the particles of the powder coming into contact and forming a neck as a result of their semi-melting nature. The neck would gradually thicken, resulting in a more compact structure that enhances the density of the resulting nanocomposite material (Sadoun *et al.* 2021; Hao *et al.* 2022).

An improvement in hardness has been seen in nano-TiC due to the strengthening of the TiC particle between the metal particles, which inhibits dislocation (Zayed *et al.* 2019). The increased reinforcing in the matrix material has increased the composite material's hardness. The resistance to plastic deformation brought about by the hard reinforcement within the soft matrix is also responsible for the increase in hardness (Umunakwe *et al.* 2020; Sytchenko *et al.* 2020). The nanocomposite reinforced with 5 vol. % Al_2O_3 exhibits the maximum hardness value of 62 HV due to the reinforcing effect of the Al_2O_3 particles(Kong *et al.* 2020). The homogeneous distribution of reinforcements is another defining feature of the strengthening process. Fig.3 shows the dramatic increase in hardness of hybrid nanocomposites.

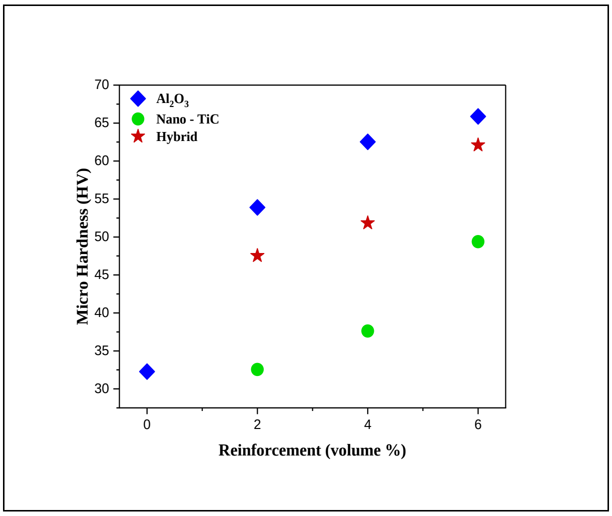

Fig. 3: Comparison of Microhardness for different and hybridized reinforcement nanocomposites

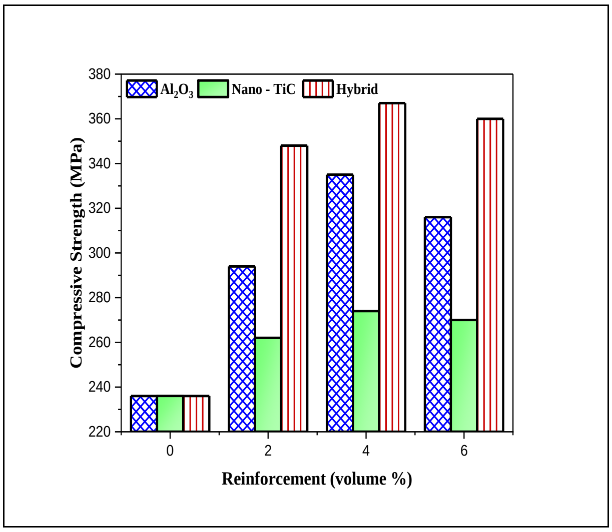

Fig. 4: Evaluation of Compressive strength for various reinforcement of nanocomposites

Reinforcing enhances compressive strength up to a certain degree beyond which the compressive strength decreases. The compressive property is reduced as a result of less internal adhesion among the aluminum particles, even while increasing the nano-TiC increases strength through nano-strengthening (Sadhukhan and Subbarao 2021). Increasing the concentration of nano-

TiC reinforcement from 4 to 6 vol. % results in a drop in compressive strength from 276 to 265 MPa. Compressive strength is improved when the matrix Al_2O_3 content is increased via strengthening and transfer of load mechanisms among the aluminum and its reinforcement. The maximum compressive strength value of 370 MPa was found in the hybrid nanocomposites with 2 vol. %, representing a 58% increase, compared to other samples, as depicted in Fig. 3. The load-bearing capacity of TiC particles is strong, and the grain boundary strength is enhanced because Al_2O_3 encapsulates TiC and provides resistance at the border.

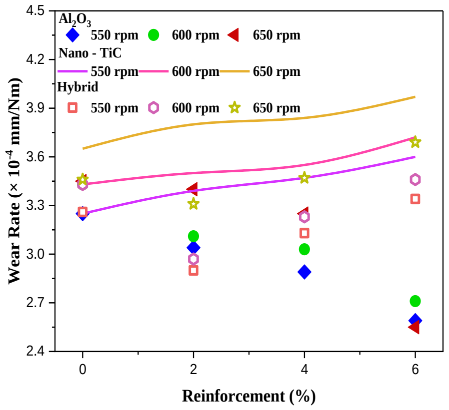

Fig. 5: Impact on Wear rate at 550, 600 and 650 rpm for different reinforcement at45 N constant load

Fig. 5 shows the results of the wear testing that was conducted on the specimens under 550, 600 and 650 rpm speeds with a persistent load of 45 N. For hybrid reinforced nanocomposite and nano-TiC, the wear rate increases with increasing speed. Delamination occurs in aluminum due to its softer matrix, and oxides are produced in air-conditioned conditions by friction between the disk and pin. Because nanoparticles do not offer better resistance to TiC, the wear rate increases and abrasive wear is induced. Fig. 5 shows that the nano-TiC nanocomposite had the maximum wear rate. The wear rate decreases with increasing rpm due to Al_2O_3's self-lubricating characteristics. A wear test was conducted at a constant speed of 550 rpm, with the load varied at 40, 45 and 50 N. The results indicates that the nanocomposite with 6 vol.% Al_2O_3 has the lowest wear, whereas the nanocomposite with 6 vol.% nano-TiC has the highest wear rate, as shown in Fig. 6.

Pores form when air becomes trapped in the dense sample during the green compaction process. Air trapped inside is released as voids during the sintering process. The absence of pores in the specimen suggests effective compaction. There is no intermediate state among Al_2O_3, TiC and aluminum that indicates nanoparticles can affect grain crystallization during sintering. A material's hardness affects how it wears and how much friction it experiences. Furthermore, mechanical qualities are enhanced and wear rate is decreased in materials with finer grain sizes; the reverse is also true.

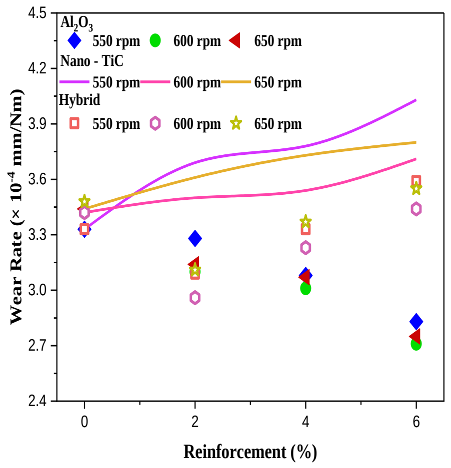

Fig. 6: Impact on Wear rate at 40, 45and 50N for different reinforcement at 600rpm

From the XRD report's (hlk) planes, it is confirmed that the composites contain nano-reinforcement. According to the XRD spectra, as shown in Fig. 7, no intermetallic phase is generated during the sintering process. The results show that the majority of aluminum is found in its crystalline form, with the plane appearing most prominently in all of the spectra, suggesting that it is present as a matrix phase.

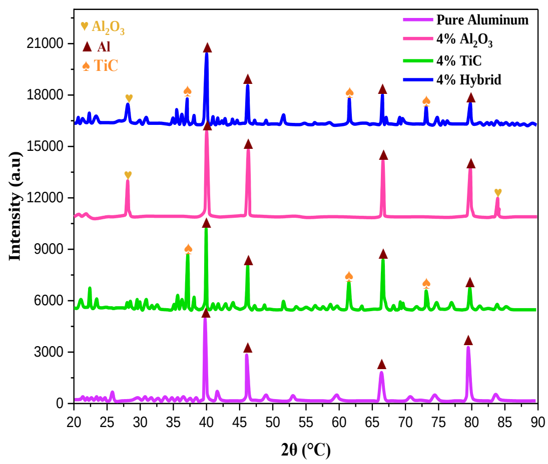

Fig. 7: XRD form of neat aluminum and 4% reinforcement of nanocomposites

The intensity of the planes is greater in the Al_2O_3-reinforced nanocomposite than in the hybrid nanocomposite. The TiC-reinforced nanocomposite exhibits a comparable feature to the hybrid material. The reinforcements are evenly dispersed throughout the nanocomposite.

The nanoparticles have firmly attached to the aluminum particles, elucidating the load transfer mechanism and resulting in increased compressive strength. The wear mechanism of aluminum matrix nanocomposites was analyzed using Energy-Dispersive X-ray Spectroscopy (EDS). Several wear mechanisms such as abrasion, scuffing, adhesion and delamination, were discovered by the researchers in their study of the nanoparticle-lubricated steel matrix. Sharp, deep grooves are the outcome of abrasion, which is brought about by abrasive particles that land on the worn surface. Scuffing is characterized by sticky connections. The worn surface that shows plastic deformation is the most common place for delamination to happen. When dirt sticks to one surface and sticks to another, it is called adhesive wear. The wear surface of nanocomposite samples shows less groove depth and number when reinforced with nanoparticles in a soft aluminum matrix compared to the pure matrix material. The microscopic results show that the wear surface's smoothness in the TiC- and/or Al_2O_3-reinforced nanocomposite is due to TiC nanoparticles bearing the main load during wear, while Al_2O_3 acts as a solid lubricating agent.

Table 1. Mechanical characteristics of the composites

Matrix	Reinforcement with conc.	Fabrication techniques	Properties		Reference
			Hardness (HV)	Compressive Strength (MPa)	
Al	4 vol. % NanoTiC and Al_2O_3	PM	51.84	367	This paper

4. CONCLUSION

Powder metallurgy has been successfully used to create hybrid metal matrix nanocomposites based on aluminum. The aluminum matrix included nano-reinforcements made of alumina and TiC. The hardness of the nanocomposite specimens was found to increase as the volume concentration of the reinforcing increased. The hardest specimens were those reinforced with Al_2O_3 at 62.53 HV with 4 vol. %, the next were the hybrid nanocomposites at 52.4 HV with 4 vol. %, and finally TiC-reinforced nanocomposites at 38.1 HV with 4 vol. %. With a compressive strength of 348MPa at 2 vol. %, the hybrid nanocomposite outperformed pure aluminum by 51%. Nanoparticle agglomeration may be responsible for the declining compressive strength as reinforcement levels increase. Titanium carbide-based reinforcement increased wear rates while carbon-based reinforcement decreased them. The wear resistance parameters of the hybrid nanocomposite were favorable.

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