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Investigating the Influence of Material Composition on the Wear Resistance of Conventional and Metal Matrix Composite Brake Pads

Mr.Jagdish Rambhau Bagul[#1], Prof. Poonam Talmale[*2], Dr. Tushar Y Badgujar[*3]

[1#]M.E. Scholar, Mechanical Department, Sapkal Engineering college, Nasik
[2]Professor, Mechanical Department, Sapkal Engineering college, Nasik
[2]H.O.D, Mechanical Department, Sapkal Engineering college, Nasik
[1]jagdishbagul143@gmail.com· 2poonam.talmale05@gmail.com, 3tybadgujar@gmail.com

Abstract:

This study explores the development and evaluation of aluminum alloy composites reinforced with titanium dioxide (TiO2) nanoparticles, aiming to enhance their mechanical and wear properties for advanced engineering applications. Aluminum-based composites are widely recognized for their high strength-to-weight ratio, excellent corrosion resistance, and thermal conductivity. By incorporating TiO2 nanoparticles, this research seeks to further improve these properties. The composites were synthesized using the powder metallurgy technique, which involves mixing aluminum alloy powders with TiO2 nanoparticles, compacting them, and subsequently sintering the mixture to form a dense, homogeneous material.

Comprehensive mechanical testing was performed, including assessments of tensile strength, hardness, and impact resistance, to determine the impact of TiO2 reinforcement on the overall performance of the composites. The results demonstrated a marked improvement in tensile strength and hardness, suggesting a strong interfacial bonding between the aluminum matrix and TiO2 particles. Impact resistance was also enhanced, indicating improved energy absorption capabilities of the composites. Additionally, wear tests were conducted under various loading conditions and sliding velocities to examine the tribological behavior of the composites. The findings revealed a significant increase in wear resistance with the inclusion of TiO2 nanoparticles, attributed to the hard ceramic nature of TiO2, which provides a protective barrier against abrasion and surface degradation. The wear mechanisms were further analyzed using scanning electron microscopy (SEM), highlighting the role of TiO2 in reducing wear rate and preventing surface damage.

Keywords: Wear rate analysis, COF, Metal matrix composites, Tribometer, Mechanical properties.

I. INTRODUCTION

Aluminum alloys, particularly AL6061, have emerged as a promising matrix material for brake pad applications due to their lightweight nature, high strength-to-weight ratio, and excellent thermal and mechanical properties. However, the inherent properties of aluminum alloys may not be sufficient to meet the demanding requirements of modern automotive brake systems. Therefore, reinforcing aluminum alloys with nanoparticles such as titanium dioxide (TiO2) has gained significant attention. TiO2 is a ceramic material known for its hardness, chemical stability, and excellent wear resistance, making it an ideal reinforcement agent for enhancing the tribological and mechanical properties of aluminum-based composites.

This study investigates the tribological performance and mechanical behavior of brake pads made from AL6061 aluminum alloy reinforced with TiO2 nanoparticles. The incorporation of TiO2 is expected to improve the wear resistance and frictional performance of the brake pads, thereby increasing their longevity and reliability under various operating conditions. The research focuses on fabricating the AL6061-TiO2 metal matrix composite brake pads using the powder metallurgy method, a widely adopted

technique known for its ability to produce composites with homogeneous distribution of reinforcement particles and minimal porosity.
The study also includes a comparative analysis between conventional brake pads and the developed metal matrix composite (MMC) brake pads to evaluate their performance differences. This involves conducting a series of mechanical and tribological tests, such as hardness testing, tensile strength assessment, and wear testing under different loads, sliding speeds, and temperatures. The results are expected to provide insights into the mechanisms by which TiO2 nanoparticles influence the wear behavior, frictional stability, and thermal performance of the MMC brake pads.

II. LITERATURE REVIEW

The incorporation of titanium dioxide (TiO2) reinforcement into aluminum-based composite production was established by Mohammed Hussein et al. (2024)[1] through the use of the stir casting technology. The matrix material was aluminum alloy, which was melted in a muffle furnace along with ceramic reinforcing particles at a temperature of about 700°C. Ceramic particles were evenly distributed throughout the molten alloy by constant stirring at 400 rpm for ten minutes, which was essential for improving the composite's qualities. The addition of 6.5% TiO2 using stir casting produced notable improvements in a number of mechanical attributes. Using X-ray diffraction (XRD) methods, Sharma et al. [2] examined the morphology of composites reinforced with graphite fillers using Al6082. Significant graphite particle agglomeration and uneven dispersion were seen in all filler combinations that were investigated.

Singh, A., & Kumar, P. (2018), investigates synthesis and characterization of aluminum-based metal matrix composites (MMCs) using nano-sized TiO2 as a reinforcing agent. The researchers developed AL6061 composites reinforced with varying weight percentages of TiO2 using the powder metallurgy method. The wear behavior was investigated through pin-on-disc tests under different loads and sliding speeds. The results indicated a significant improvement in wear resistance and hardness with increasing TiO2 content. The authors concluded that the nano-TiO2 particles effectively enhanced the tribological properties by forming a hard interfacial bond, which reduced the wear rate and improved the load-carrying capacity of the composites.

Gupta, M., & Wang, Q. (2020), conducted a comprehensive study on the influence of ceramic reinforcements, including TiO2, SiC, and Al2O3, on the tribological properties of aluminum alloy-based brake pads. The study utilized AL6061 alloy as the matrix material and examined the effects of varying ceramic particle sizes and weight fractions on wear resistance, coefficient of friction, and thermal stability. Their findings revealed that TiO2-reinforced AL6061 exhibited superior wear resistance and stable frictional performance compared to other reinforcements. The authors attributed this improvement to the formation of a hard and protective layer by the TiO2 particles during the wear process, which effectively minimized surface degradation and improved thermal conductivity.

Kumar, R., & Patel, D. (2019), focused on comparing the performance of conventional brake pads with AL6061 aluminum alloy brake pads reinforced with TiO2 nanoparticles. The authors prepared the MMCs using a stir casting technique, ensuring uniform distribution of TiO2 particles within the aluminum matrix. Through a series of tribological tests, including wear rate and coefficient of friction analysis under different temperatures, the study demonstrated that the TiO2-reinforced brake pads outperformed conventional pads, especially at elevated temperatures. The TiO2 nanoparticles acted as wear-resistant agents and improved the thermal stability of the composites, making them suitable for high-performance automotive brake applications. The study provided detailed microstructural analysis to support the findings.

Sharma, V., & Rao, T. (2021), investigated the tribological properties of AL6061 aluminum alloy reinforced with nano-TiO2 for brake pad applications. The composites were fabricated using the powder metallurgy process, and the influence of varying TiO2 content on wear resistance, hardness, and frictional behavior was studied. The research highlighted that the addition of 2-5 wt.% TiO2 nanoparticles significantly enhanced the hardness and wear resistance of the brake pads. The study also included SEM and EDS analyses, which showed that the homogeneous dispersion of TiO2 particles led to the formation of a protective oxide layer on the wear surface, thereby reducing surface damage and enhancing the overall tribological performance.

III. OBJECTIVES

- To fabricate Aluminum alloy 6061 composites reinforced with TiO2 nanoparticles through the powder metallurgy technique.
- To evaluate and compare the friction and wear properties of existing brake pad materials, including aluminum (Al), magnesium (Mg), zinc (Zn), and copper (Cu).
- To simulate real-life automotive braking conditions, considering factors like sliding speed, contact pressure, and temperature.
- To examine the tribo-mechanical characteristics of both conventional brake pad materials and the newly developed composites.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

Sliding Wear Response

The findings show that aluminum alloys consistently demonstrate a decrease in wear rate across several test cycles. As a result, the Al6061 alloy matrix is suggested as an optimal choice for the intended applications. This recommendation is backed by test data indicating that Al6061 surpasses other materials, including Al, Mg, Zn, and Cu, in terms of wear rate and coefficient of friction.

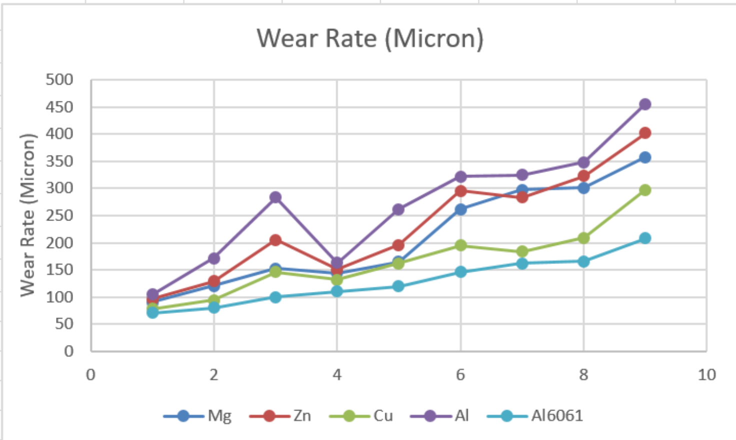

Fig 4.1: Wear rate of different materials

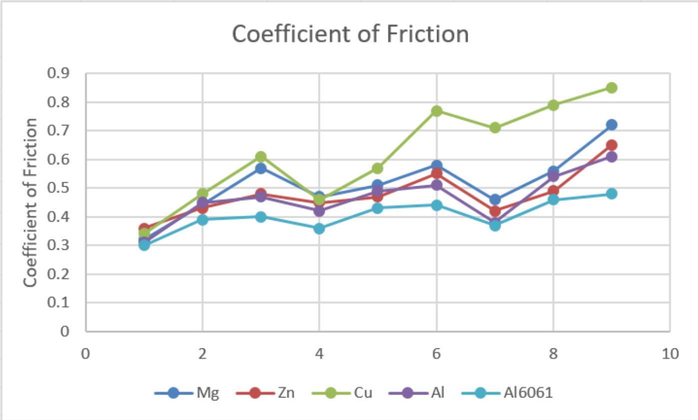

Fig 4.2: COF of different materials

A) Tensile Strength

Table 5.5 presents the tensile strength and elongation percentages for the Al6061+TiO2 composites. Compared to pure Al6061, which has a tensile strength of 309 MPa, the composites with 3%, 6%, and 9% TiO2 exhibit strengths of 315 MPa, 333 MPa, and 351 MPa, respectively..

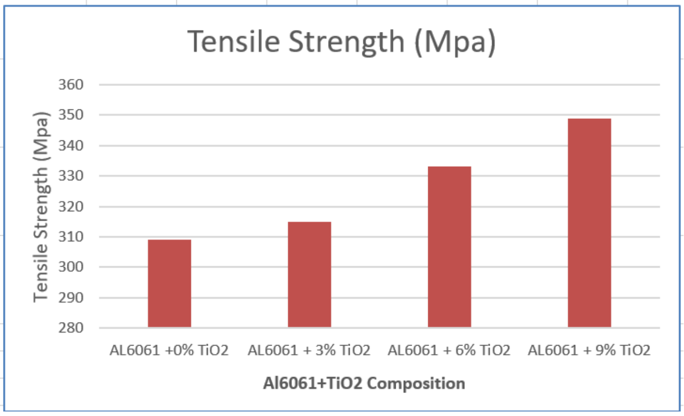

Fig 4.3: Tensile Strength of TiO2 Composition

B) Compressive Strength

The compressive strength of pure AL6061 is 103 MPa, whereas the composites AL6061+3% TiO2, AL6061+6% TiO2, and AL6061+9% TiO2 show compressive strengths of 113 MPa, 164 MPa, and 193 MPa, respectively.

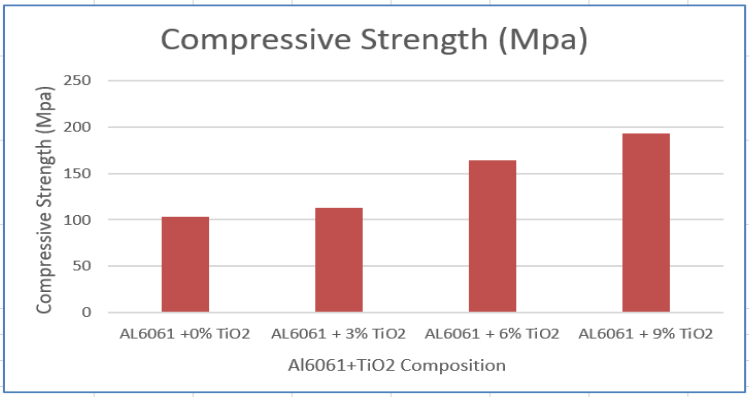

Fig 4.4: Compressive Strength of TiO2 Composition

C) Hardness (BHN)

The test results revealed that the hardness of the composites gradually increased with the addition of TiO2. The hardness of pure AL6061 is 80 BHN, while the configurations AL6061+3% TiO2, AL6061+6% TiO2, and AL6061+9% TiO2 show BHN values of 109, 111, and 125, respectively.

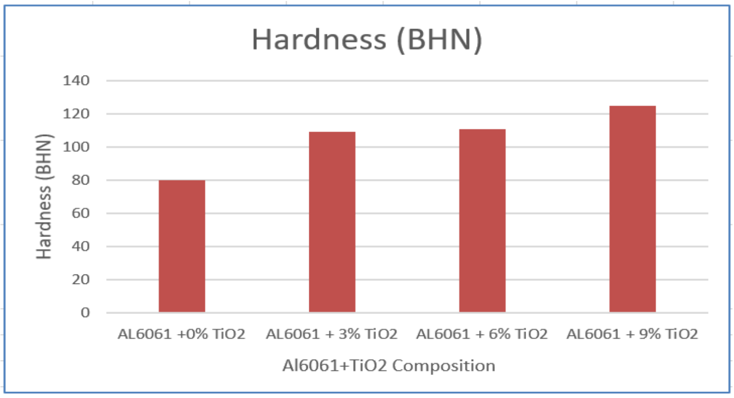

Fig 4.5: Hardness (BHN) of TiO2 Composition

V. FINITE ELEMENT ANALYSIS

The results indicate that the maximum stresses occur in the Composite Specimen bar, aligning precisely with field failure observations. A comparison of equivalent stress values for the original Composite Specimen bar design and its modified versions has been conducted. The table below presents the comparison of different Composite Specimen bar designs using FEA analysis.

Table 5.1: FEA Results

Description	Finite Element Analysis	
	Von-Mises stress (MPa)	Tensile Stress (MPa)
Composite Specimen bar	604	348

VI. CONCLUSION

Various tribological and mechanical tests conducted on Al+TiO2 metal matrix composites, along with other brake pad materials, led to the following conclusions.

- The aluminum alloy (AL6061) reinforced with 6% TiO2 particulate was manufactured using the powder metallurgy process, demonstrating excellent mechanical and tribological properties.

- The experimental results for sliding wear and coefficient of friction (COF) of the proposed Al+TiO2 composite show significant improvements compared to existing brake pad materials.

- Increasing the TiO2 content from 0% to 9% in the AL6061 alloy enhances its tensile strength by 21%, compressive strength by 27%, and hardness by 38%. However, adding more than 9% TiO2 results in a noticeable decline in mechanical properties.

- The composite containing 9% TiO2 exhibits the highest wear resistance, as well as superior COF, tensile strength, hardness, and compressive strength.

- A comparison of von-Mises stress values under applied loads indicates that the design of the specimen bar is both feasible and safe. The percentage difference between the finite element analysis (FEA) and experimental methods for the specimen bar is just 1%. As shown in the table, the variation between FEA and experimental results remains below 10%, which is considered acceptable. Thus, it can be concluded that the composite specimen bar is safe for its intended application.

Table 6.1. FEA & Experimental Results Summary

Description	Finite Element Analysis		Experimental		% Error
	Von-Mises stress (MPa)	Tensile Stress (MPa)	Von-Mises stress (MPa)	Tensile Stress (MPa)	
Composite Specimen bar	604	348	608	351	1

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