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Comparative Study on the Tribological Performance of Conventional and Metal Matrix Composite Brake Pads in Automotive Applications

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Abstract: This study investigates the wear and mechanical properties of aluminum alloy composites reinforced with titanium dioxide (TiO2) nanoparticles. Aluminum-based composites are increasingly favored in engineering due to their excellent properties, and incorporating TiO2 nanoparticles presents a promising method for further enhancement. The composites were produced using a powder metallurgy technique, and their mechanical performance—including tensile strength, hardness, and impact resistance—was thoroughly assessed. Additionally, wear tests under various conditions were conducted to evaluate the composites' wear resistance. The findings indicate that incorporating TiO2 nanoparticles significantly enhances both the mechanical properties and wear resistance of the aluminum alloy.
Keywords: Wear rate analysis, COF, Metal matrix composites, Tribometer, Mechanical properties.

I. INTRODUCTION

Tribology is a multidisciplinary field focused on the study of interactions between moving surfaces, encompassing friction, wear, adhesion, and lubrication phenomena. Optimizing tribological behavior is particularly challenging due to the hidden nature of subsurface contacts. A comprehensive understanding of these interactions requires expertise across several scientific domains, including physical chemistry, mechanics, thermal science, materials science, and biological interfaces. Biological systems, such as knee joints and eyelids, illustrate the deep connections between tribology and biology, as well as biomedicine. Tribological phenomena often involve complex interactions, such as mechano-chemical reactions during wear and the physico-chemical-thermal effects of lubricant additives that create sliding-induced tribo-films. This complexity highlights the need for a holistic approach that integrates various scientific disciplines to advance our understanding and enhance the performance of tribological systems in a wide range of applications.

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.

Somayaji et al. (2023)[2] produced composites reinforced with graphite fillers composed of Al6082 in order to analyze its morphology using XRD. They discovered that in every filler combination, there was a significant aggregation of graphite particles or non-uniform dispersion.

M. Anthony Xavior & S. Venkatesan (2019)[9], noted Aluminum-based metal matrix composites were created for lightweight applications, mainly in the automotive and aerospace industries. The creation and characterisation of aluminum alloy 7050 matrix composites enhanced with graphene nanoparticles are the main subjects of this study paper.

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In order to create the composites, liquid metallurgical methods including squeeze and stir casting were used. For the fabrication trials, certain parameters such as the three-level graphene content, the stirring speed, and the melting temperature were taken into account. The yield strength, tensile strength, and hardness of AA7050-graphene composites made by stir and squeeze casting are assessed using Taguchi's L27 Orthogonal array. Analysis of variance (ANOVA) was done based on the experimental findings to ascertain the degree of influence/

According to B.M. Muthamizh Selvan et al. (2018)[10], By using an in-situ stir casting technique, composite materials with an aluminum alloy 8011 matrix and 0, 4, and 8 weight percentages of ZrB2 reinforcements were created. X-ray diffraction and scanning electron microscopy examination were used to look for the reinforcements and make sure they were distributed uniformly. Using a pin-on-disc wear tester in accordance with Taguchi's orthogonal array design, experiments were carried out to examine the impact of dry sliding wear parameters, such as sliding distance, percentage reinforcement, load, sliding velocity, and temperature, on wear rate and coefficient of friction. Statistical methods were also employed to examine the tribological behavior of synthetic composites. Analysis of variances was used to establish significance and the parameters' impact on the response, and gray relational analysis.

III. OBJECTIVES

1) To develop Aluminum alloy 6061 composites reinforced with TiO2 nanoparticles using the powder metallurgy method.
2) To compare the friction and wear characteristics of current brake pad materials, including Al, Mg, Zn, and Cu.
3) To model real-world conditions for automobile brakes, such as sliding velocity, contact pressure, and temperature.
4) To assess the tribo-mechanical properties of both traditional brake pad materials and newly developed composites.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Sliding Wear Response

The results indicate that aluminum alloys consistently exhibit a reduction in wear rate over multiple test runs. Based on these findings, the Al6061 alloy matrix is recommended as a superior option for the intended applications. This recommendation is supported by the test results, which show that Al6061 outperforms other materials—such as Al, Mg, Zn, and Cu—in terms of wear rate and coefficient of friction.

Fig 4.1: Wear rate of different materials

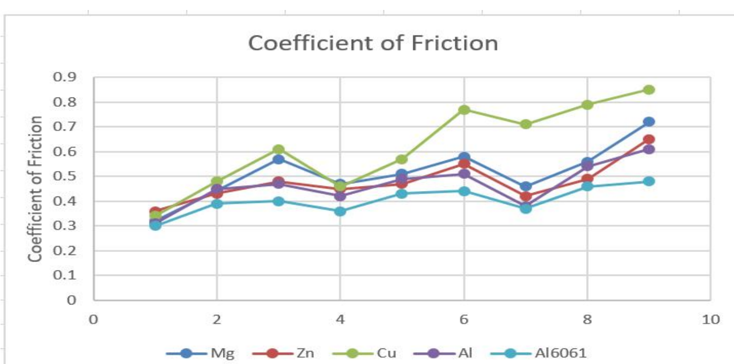

Fig 4.2: COF of different materials

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1) Tensile Strength

The tensile strength and elongation percentages of the Al6061+TiO2 composites are shown in table 5.5, respectively. In contrast to pure Al6061, which claims a strength of 309 MPa, AL6061+3% TiO2, AL6061+6% TiO2, and Al6061+9% TiO2 report strengths of 315, 333, and 351 MPa, respectively

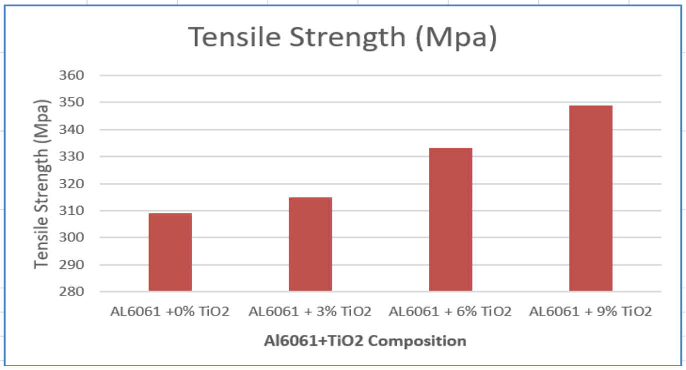

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Fig 4.3: Tensile Strength of TiO2 Composition

2) Compressive Strength

The compressive strength of AL6061 is 103 MPa, while that of AL6061+3% TiO2, AL6061+6% TiO2, and AL6061+9% TiO2 configurations report compressive strengths of 113, 164, and 193 MPa, respectively

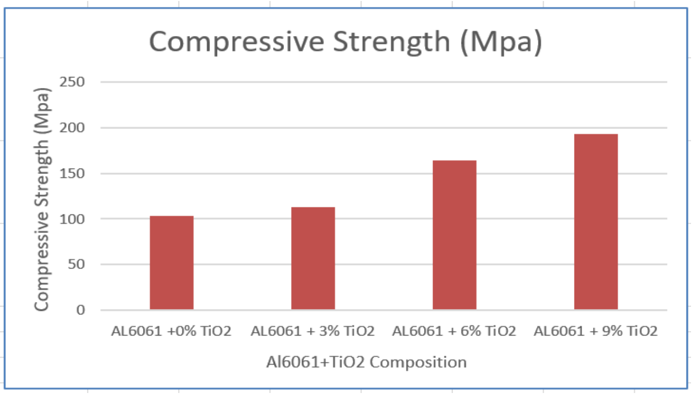

Fig 4.4: Compressive Strength of TiO2 Composition

3) Hardness (BHN)

It was interestingly found from the testing findings that the composites' hardness steadily increased as the amount of TiO2 increased. AL6061 displays a hardness of 80 BHN. AL6061+3% TiO2, AL6061+6% TiO2, and AL6061+9% TiO2 configurations, respectively, report BHN values of 109, 111, and 125.

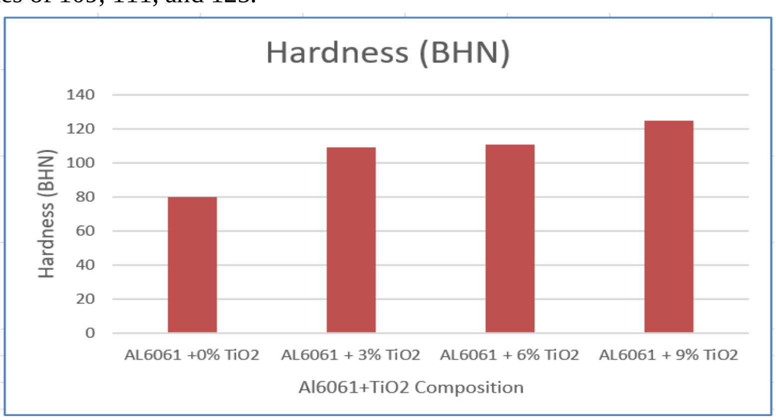

Fig 4.5: Hardness (BHN) of TiO2 Composition

V. FINITE ELEMENT ANALYSIS

It is observed from the results that, Maximum stresses are developed in the Composite Specimen bar and exactly matches with the field failure. A comparison of equivalent stress values for Composite Specimen bar design and subsequent modified designs of the Composite Specimen bar are calculated. Following table shows comparison between different designs of Composite Specimen bar through FEA.

Table 5.1: FEA Results

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

VI. CONCLUSION

1) Different tribological and mechanical tests on Al+TiO2 metal matrix composites and other brake pad materials led to the following conclusions.
2) The Powder metallurgy process was used to manufacture the aluminium alloy (AL6061) reinforced with 6% TiO2 particulate, which has excellent mechanical and tribological properties.
3) Experimental results (sliding wear and COF) of proposed material (Al+TiO2 composite) are quite better than existing brake pad materials.
4) The addition of TiO2 from 0% to 9% to the AL6061 alloy increases its tensile strength (21%), compressive strength (27%), and hardness (38%).Further addition of TiO2 above 9% resulted in a significant decrease in mechanical properties.
5) The composite with 9% TiO2 has the best level of resistance to wear, high coefficient of friction (COF), tensile strength, hardness, and compressive strength.
6) If we compare the von-Mises stress values for applied load, the design of specimen bar is more feasible and safe. The percentage variation between FEA and Experimental method for specimen bar is 1%. It is observed from above table that, there is less than 10% variation observed between FEA and Experimental methods. This variation is acceptable. Therefore, it is concluded that, the composite specimen bar is safe for the current 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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