

Experimental Studies on Mechanical and Tribological Properties of Hybrid Nanocomposites

Kalapala Prasad¹, Kimudu Kusuma Sai Sri²

¹ *Department of Mechanical Engineering, University College of Engineering, Jawaharlal Nehru Technological University Kakinada, Kakinada Dist. – 533003, Andhra Pradesh, India.*

² *Student from Mechanical Engineering, Department of Mechanical Engineering University College of Engineering, Jawaharlal Nehru Technological University Kakinada, Kakinada Dist. – 533003, Andhra Pradesh, India.*

Abstract—This study investigates the effect of hybrid Al₂O₃–CNT reinforcement on the mechanical and tribological properties of AA7075 aluminium alloy. AA7075 hybrid nanocomposites containing a constant 5 wt. % Al₂O₃ and varying CNT contents of 0.1–0.5 wt. % were fabricated using powder metallurgy. The developed composites were evaluated through microhardness, tensile, compression and wear tests. The maximum microhardness of 101.36 HV was obtained for A3 (0.1 wt. % CNT), representing a 25.86% improvement over A1. A4 (0.2 wt.% CNT) exhibited the highest tensile strength 306.66 MPa and compressive strength 251 MPa, along with the minimum wear rate of 31.6×10^{-4} mm³/m and coefficient of friction of 0.296. Further CNT addition resulted in fluctuating properties, which may be attributed to non-uniform dispersion, agglomeration and porosity. Overall, A4 demonstrated the most favourable combination of mechanical and tribological performance, indicating the potential of controlled Al₂O₃–CNT reinforcement for improving AA7075-based hybrid nanocomposites.

Index Terms—AA7075, Al₂O₃, carbon nanotubes, hybrid nanocomposites, powder metallurgy. mechanical properties, wear behaviour.

I. INTRODUCTION

The increasing demand for lightweight materials with high strength, improved wear resistance and adequate corrosion resistance has encouraged the development of advanced materials for aerospace, automotive, defence and other structural applications. Aluminium alloys are widely used in such applications because of their low density, high specific strength and good machinability. Among them, AA7075 is a

precipitation hardenable aluminium alloy containing zinc, magnesium and copper, is well known for its high strength-to-weight ratio. However, its relatively limited wear resistance, surface hardness and susceptibility to localized and stress-corrosion degradation can restrict its performance under severe service conditions. Therefore, improving the mechanical, tribological and corrosion performance of AA7075 while retaining its lightweight characteristics is an important research objective.

Metal matrix composites (MMCs) have been developed to overcome some of these limitations through the incorporation of hard reinforcement phases into the metallic matrix. In particular, metal matrix nanocomposites (MMNCs) containing nanoscale reinforcements offer enhanced strengthening efficiency because of their high specific surface area and large matrix–reinforcement interface. Nanoparticles can contribute to strengthening through mechanisms such as grain refinement, Orowan strengthening, dislocation strengthening and efficient load transfer. However, the performance of MMNCs strongly depends on reinforcement dispersion, particle size, interfacial bonding and reinforcement content. Agglomeration of nanoparticles at higher concentrations can adversely affect the mechanical and tribological properties of the composite.

Hybrid metal matrix nanocomposites provide an additional approach by incorporating two different reinforcement phases into a single metallic matrix. The use of complementary reinforcements can

provide a synergistic effect and enable the properties of the composite to be tailored according to specific application requirements. Aluminium oxide (Al_2O_3) is an attractive ceramic reinforcement for aluminium alloys because of its high hardness, stiffness, wear resistance and chemical stability. Its incorporation into AA7075 can improve resistance to plastic deformation and abrasive wear and can contribute to microstructural refinement. However, ceramic nanoparticles have a tendency to agglomerate because of their high surface energy, which may lead to non-uniform reinforcement distribution and deterioration of mechanical properties.

Carbon nanotubes (CNTs) are one-dimensional carbon nanomaterials possessing high specific strength, high elastic modulus and excellent structural stability. Their high aspect ratio provides the potential for efficient load transfer and crack-bridging effects when they are properly dispersed within the metal matrix. The combination of Al_2O_3 nanoparticles and CNTs can therefore provide complementary reinforcement effects, where Al_2O_3 primarily contributes to hardness and wear resistance, while CNTs can contribute to load transfer and resistance to crack initiation and propagation. The effectiveness of this hybrid system is strongly dependent on the amount and distribution of CNTs within the AA7075 matrix.

Powder metallurgy (PM) is an effective solid-state processing technique for fabricating aluminium-based nanocomposites because it enables controlled reinforcement addition and facilitates relatively uniform dispersion of nanoscale particles. The process generally involves powder blending or high-energy ball milling, cold compaction and sintering. High-energy ball milling promotes intimate mixing and refinement of the powder constituents, while compaction and subsequent sintering facilitate particle bonding and densification without complete melting of the matrix. Consequently, PM is particularly suitable for the fabrication of hybrid

nanocomposites containing ceramic nanoparticles and carbon-based nanomaterials.

Although considerable research has been conducted on reinforced AA7075 composites, the combined effect of Al_2O_3 and low concentrations of CNTs on the microstructure and mechanical, wear and corrosion behaviour of AA7075 fabricated through powder metallurgy requires further investigation. In particular, identifying an appropriate CNT content is important because insufficient reinforcement may provide limited strengthening, whereas excessive CNT addition can promote agglomeration and adversely affect the properties of the composite.

Therefore, the present study investigates AA7075 hybrid nanocomposites containing a constant 5 wt. % Al_2O_3 and varying CNT contents from 0 to 0.5 wt. %. The composites were fabricated using high-energy ball milling followed by cold compaction and pressureless sintering. The effect of CNT addition on the mechanical, tribological and corrosion behaviour was evaluated through microhardness, tensile, compression, wear and corrosion tests. The objective of the study is to determine the influence of hybrid Al_2O_3 -CNT reinforcement on the performance of AA7075 and to identify the composition providing favourable overall properties for potential lightweight engineering applications. The improved combination of mechanical strength, wear resistance and corrosion performance can contribute to reduced component weight, enhanced durability and extended service life.

II. MATERIALS AND METHODS

2.1 Fabrication of Hybrid Nanocomposites: AA7075 powder was reinforced with a constant 5 wt. % Al_2O_3 nanoparticles and varying CNT contents of 0–0.5 wt. %. Seven compositions, designated A1–A7 was prepared. A1 represents unreinforced AA7075, while A2 contains 5 wt. % Al_2O_3 without CNT. A3–A7 contain 5 wt. % Al_2O_3 with 0.1–0.5 wt. % CNT respectively.

Table 1.1: Chemical composition of AA7075 alloy

Elements	Zinc	Magnesium	Copper	Iron	Silicon	Aluminium
%	5.22	2.40	1.40	1.97	0.3	88.71

2.2 Specimens preparation

2.2.1 High-Energy Ball Milling: The weighed AA7075, Al₂O₃ and CNT powders were mechanically blended using a planetary high-energy ball mill. Milling was carried out at 300 rpm for 6 h with a ball-to-powder ratio of 10:1. Tungsten carbide vials and balls were used as the milling media. The milling process promoted intimate mixing and dispersion of the reinforcement particles within the AA7075 powder.

2.2.2 Cold Compaction: The milled powders were compacted using a cylindrical die of 10 mm diameter at a pressure of 750 MPa to produce green compacts. Zinc stearate was applied to the die wall as a lubricant to facilitate removal of the compact.

2.2.3 Pressureless Sintering: The green compacts were subsequently sintered at 450°C for 1.5 h under an argon atmosphere using a pressureless vacuum sintering furnace. The sintering process promoted diffusion and bonding between the powder particles and improved the densification of the composites.

2.3 Mechanical Properties

2.3.1 Microhardness: Microhardness measurements were performed according to ASTM E384-2017 using an FSA Micro Vickers hardness tester. A diamond indenter was applied with a load of 100 gf (0.1 kgf) and a dwell time of 10 s five indentations were made at different locations on each specimen, and the average value was reported as the microhardness.

2.3.2 Tensile Strength: Tensile specimens were prepared according to ASTM E8. The specimens had a width of 10 mm and a gauge length of 25 mm. The tensile test was conducted at a crosshead speed of 2 mm/min. Three specimens were tested for each composition, and the average ultimate tensile strength was reported.

2.3.3 Compression Strength: Compression tests were conducted according to ASTM E9 using cylindrical specimens with a diameter of 10 mm and a height of 15 mm. Three specimens were tested for each composition, and the average ultimate compressive strength was reported.

2.4 Tribological Properties

2.4.1 Wear Test: Dry sliding wear tests were performed using a pin-on-disc tribometer in accordance with ASTM G99 to evaluate the tribological behaviour of the AA7075-based hybrid nanocomposites. The tests were conducted under a normal load of 20 N, sliding velocity of 1.5 m/s, and total sliding distance of 1004 m against an EN31 steel counter disc.

Cylindrical specimens of 10 mm diameter and 30 mm length were used as wear pins. The contacting surfaces were polished using 1200-grit abrasive paper and cleaned with acetone before testing to remove surface contaminants. The initial mass of each specimen was measured using a precision weighing balance. After the wear test, the specimens were cleaned and weighed again to determine the mass loss. The wear volume loss was obtained from the measured wear-track geometry, and the wear rate was calculated from the ratio of wear volume loss to the corresponding sliding distance.

The coefficient of friction (COF) was continuously recorded during the sliding test. The average COF obtained from the stable portion of the wear curve was used for comparison among the different compositions. The wear behaviour of the base AA7075 alloy and AA7075–5 wt. % Al₂O₃–0–0.5 wt. % CNT hybrid nanocomposites was evaluated based on wear rate and coefficient of friction.

III. RESULTS

AA7075 aluminium alloy was used as the matrix, with 5 wt. % Al₂O₃ nanoparticles as the primary reinforcement and 0.1–0.5 wt. % carbon nanotubes (CNTs) as the secondary reinforcement. The AA7075–Al₂O₃–CNT hybrid nanocomposites were fabricated using the powder metallurgy technique. The processing involved high-energy ball milling for 6 h, followed by cold compaction and pressureless sintering under an argon atmosphere. The fabricated composites were evaluated their mechanical and wear. The influence of varying CNT content on the overall performance of the AA7075-based hybrid nanocomposites was investigated.

3.1 Mechanical Properties

The mechanical behaviour of the AA7075 hybrid nanocomposites was evaluated in terms of

microhardness, tensile strength and compressive strength. The tests were performed on specimens prepared according to the relevant ASTM standards.

3.1.1 Microhardness: The microhardness of A1–A7 was 80.54, 91.12, 101.36, 89.82, 71.10, 63.01 and 60.54 HV, respectively. The maximum hardness of 101.36 HV was obtained for A3, showing a 25.86%

improvement over A1. The increase is attributed to the strengthening effect of Al_2O_3 and CNTs, which restrict dislocation movement and improve load transfer. Further CNT addition resulted in a decrease in hardness, possibly due to non-uniform dispersion and agglomeration.

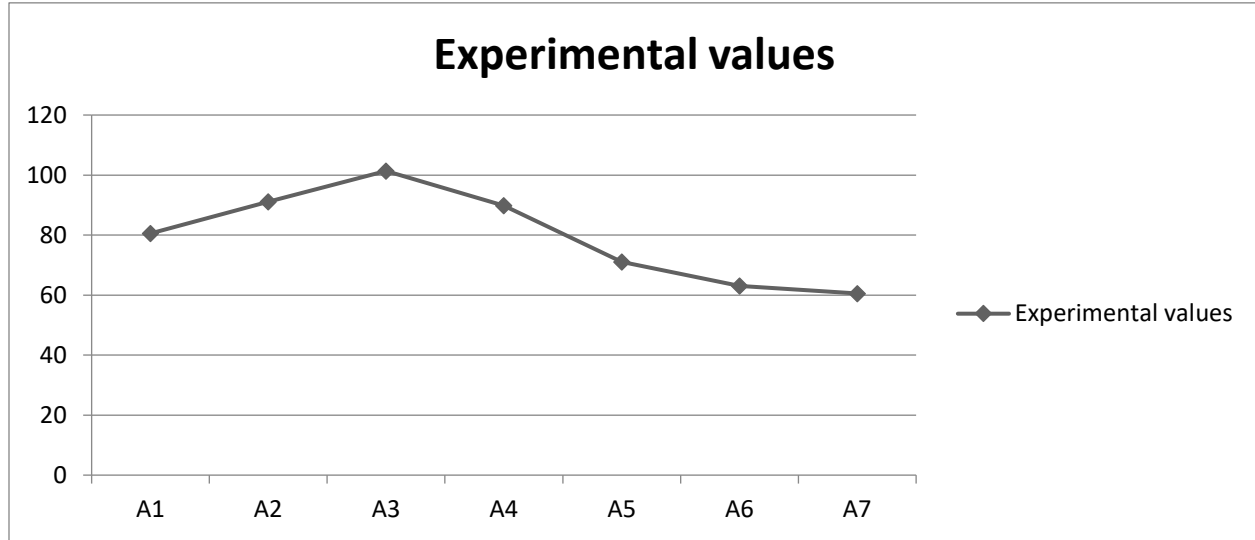


Figure 1.1: Microhardness of AA7075 hybrid nanocomposites

3.1.2 Tensile Strength: The tensile strength values of A1–A7 were 225.86, 262.16, 281.00, 306.66, 294.66, 248.72 and 204.33 MPa, respectively. The maximum tensile strength of 306.66 MPa was achieved by A4, representing a 35.78% improvement over A1. This

enhancement can be attributed to effective load transfer, dislocation restriction and reinforcement strengthening. Further CNT addition reduced the tensile strength, possibly due to agglomeration and increased porosity.

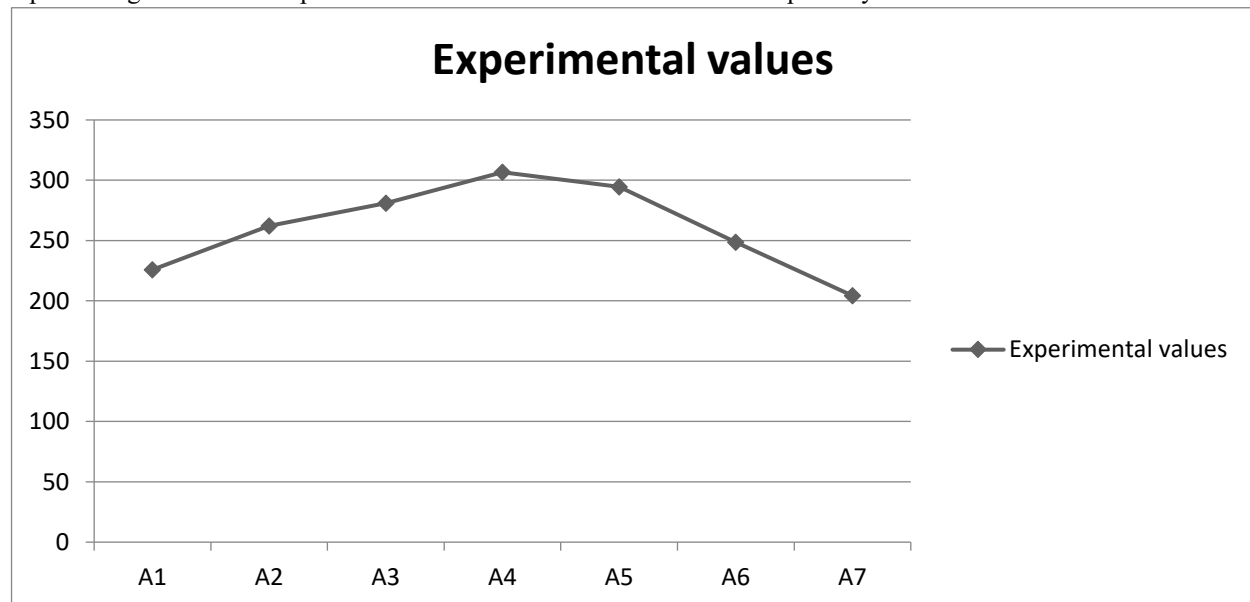


Figure 1.2: Tensile Strength of AA7075 hybrid nanocomposites

3.1.3 Compressive Strength: The compressive strength values of A1–A7 were 156, 166, 230, 251, 195, 175 and 150 MPa, respectively. The maximum compressive strength of 251 MPa was obtained for A4. The improvement up to A4 is associated with

restricted plastic deformation, hindered dislocation movement and enhanced load transfer. Beyond A4, the reduction in compressive strength may be attributed to non-uniform CNT distribution, agglomeration and porosity.

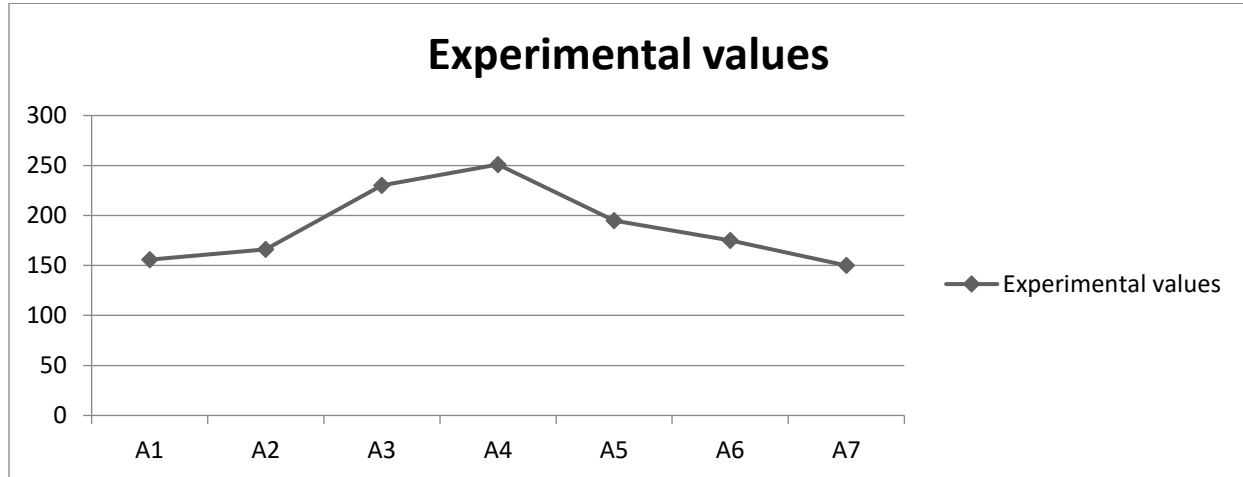


Figure 1.3: Compressive Strength of AA7075 hybrid nanocomposites

3.2 Tribological Properties

The tribological properties of the developed AA7075 hybrid nanocomposites were evaluated through wear rate and coefficient of friction measurements under dry sliding conditions. The wear tests were conducted in accordance with ASTM standards using a pin-on-disc tribometer.

3.2.1 Wear Rate: The wear rate values of A1–A7 were 152.0, 102.5, 63.5, 31.6, 48.2, 72.5 and $95.2 \times 10^{-4} \text{ mm}^3/\text{m}$, respectively. The minimum wear rate of $31.6 \times 10^{-4} \text{ mm}^3/\text{m}$ was obtained for A4, indicating the highest wear resistance among the developed

composites. The reduction in wear rate up to A4 can be attributed to the combined strengthening effect of Al_2O_3 and CNT reinforcements, increased hardness, and improved load-bearing capacity of the composite. The presence of well-dispersed hard Al_2O_3 particles and CNTs can restrict plastic deformation and reduce material removal during sliding, thereby improving the wear resistance. Beyond A4, the increase in wear rate may be attributed to non-uniform CNT distribution, CNT agglomeration and increased porosity, which can reduce the effectiveness of the reinforcement and promote localized material removal during sliding.

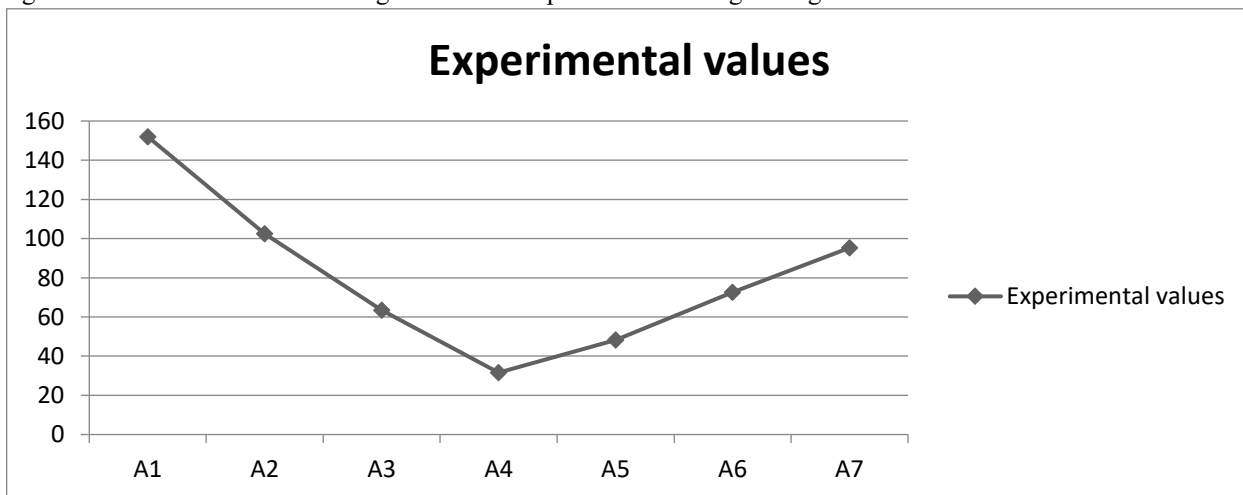


Figure 1.4: Wear Rate of AA7075 hybrid nanocomposites

3.2.2 Coefficient of Friction: The coefficient of friction values of A1–A7 were 0.402, 0.394, 0.356, 0.296, 0.312, 0.315 and 0.314, respectively. The minimum coefficient of friction of 0.296 was obtained for A4, indicating improved frictional behaviour and reduced resistance to sliding. The reduction in coefficient of friction up to A4 can be attributed to the combined effect of Al₂O₃ and CNT reinforcements. The CNTs can provide a solid-lubricating effect, while

the hard Al₂O₃ particles can improve load-bearing capacity and reduce direct metal-to-metal contact during sliding. The increase in coefficient of friction beyond A4 may be attributed to changes in reinforcement distribution, possible CNT agglomeration, surface characteristics and variations in the formation and stability of the tribolayer.

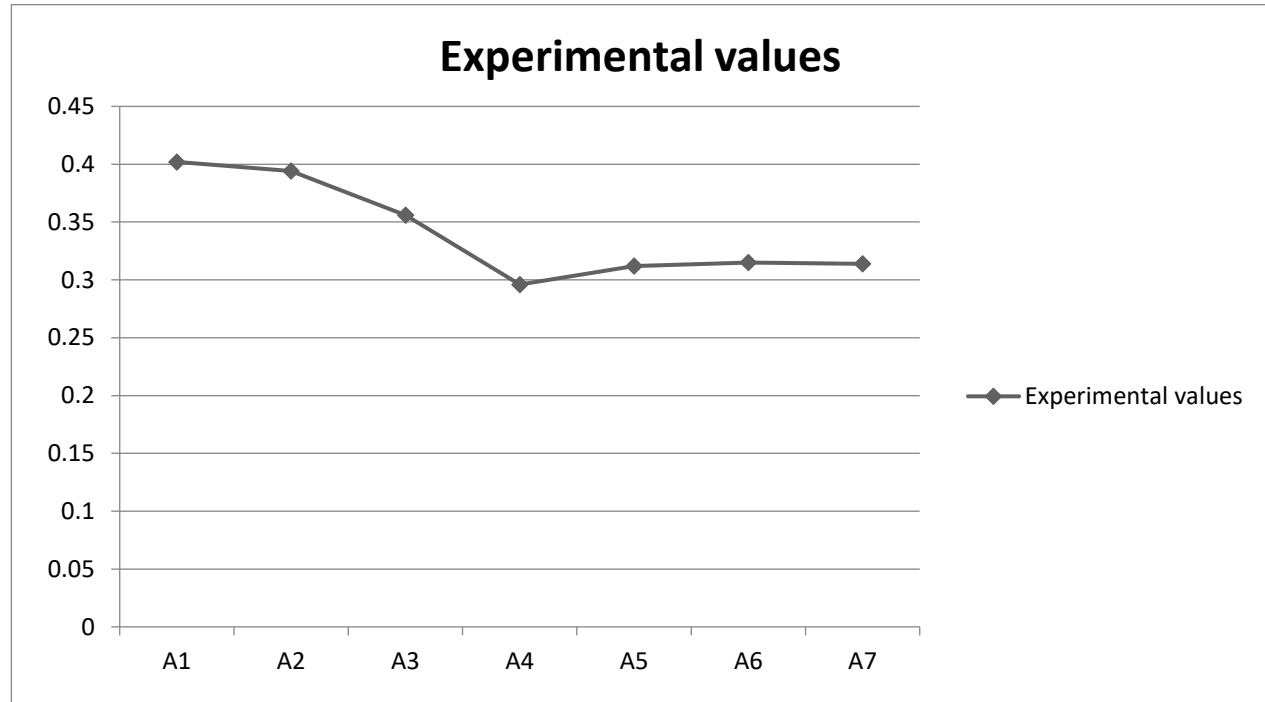


Figure 1.5: Coefficient of Friction of AA7075 hybrid nanocomposites

IV. CONCLUSION

AA7075 hybrid nanocomposites reinforced with 5 wt. % Al₂O₃ and 0.1–0.5 wt.% CNTs were successfully fabricated by powder metallurgy. XRD and SEM confirmed microstructural refinement and effective incorporation of the reinforcements. The maximum microhardness of 101.36 HV was obtained for A3 (0.1 wt. % CNT), while A4 (0.2 wt. % CNT) exhibited the highest tensile strength 306.66 MPa and compressive strength 251 MPa. A4 also showed the minimum wear rate 31.6×10^{-4} mm³/m and coefficient of friction 0.296. The improvements are attributed to grain refinement, reinforcement strengthening, improved load transfer, and the solid-lubricating effect of CNTs. Further CNT addition resulted in fluctuating properties, possibly due to

agglomeration, non-uniform dispersion, and porosity. Overall, A4 demonstrated the most favourable combination of mechanical and tribological performance.

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