Chapter 2

Mechanical and Thermal Evaluation of Nanocomposite Coatings for Wheelchair Components

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Abstract

This chapter explores the development and evaluation of nanocomposite coatings applied to wheelchair components to enhance their mechanical strength, wear resistance, and thermal stability. Nanocomposites containing aluminum oxide (Al_2O_3), silicon carbide (SiC), and titanium dioxide (TiO_2) nanoparticles were synthesized using an epoxy matrix through the sol–gel technique. Experimental tests including tensile, hardness, and thermal conductivity analyses were conducted to determine performance improvements. Quantitative data reveal that the incorporation of 3 wt.% Al_2O_3 nanoparticles improved surface hardness by 28%, tensile strength by 22%, and reduced surface wear by 35% compared

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with uncoated substrates. Furthermore, thermal conductivity increased by 18%, indicating superior heat dissipation capacity essential for user comfort and durability.

Keywords: Nanocomposite coatings, Wheelchair components, Thermal conductivity, Mechanical properties, Surface modification.

1. Introduction

Wheelchairs are among the most essential assistive devices that provide mobility, independence, and quality of life for individuals with disabilities or limited motor function. The structural components of wheelchairs—such as frames, rims, handles, and connectors—are often exposed to cyclic loading, frictional contact, environmental humidity, and temperature fluctuations. These conditions gradually deteriorate the surface integrity of the materials, leading to corrosion, surface wear, and loss of mechanical strength. The degradation not only affects performance and user comfort but can also compromise safety by causing premature component failure (Rao et al., 2021).

Traditionally, wheelchair components are manufactured using metals such as aluminum alloys and mild steel because of their favorable combination of mechanical strength, lightweight characteristics, and cost-effectiveness. However, bare metal surfaces are vulnerable to oxidation, mechanical abrasion, and heat accumulation during prolonged usage, particularly in tropical environments. For instance, repeated manual propulsion of a wheelchair can raise the surface temperature of hand rims by 10–15 °C, causing user discomfort and thermal fatigue in the long term. Therefore, the enhancement of surface performance through advanced coatings has become a key area of materials engineering research for mobility devices (Singh & Kumar, 2022).

1.1 Evolution of Surface Coatings in Mobility Systems

Conventional protective coatings—such as paints, anodized films, and polymer overlays—offer partial protection against corrosion but lack the mechanical robustness required for frequent dynamic loading. In recent decades, nanocomposite coatings have emerged as an effective alternative. These materials incorporate nanoscale ceramic or metallic fillers into a polymeric or metallic matrix, generating a multi-phase system with tailored physical and chemical properties. The presence of nanoparticles such as Al_2O_3, SiC, and TiO_2 dramatically improves hardness, wear resistance, and thermal conductivity by enhancing interfacial bonding and load transfer efficiency (Patel et al., 2020). The innovation of nanocomposite coatings aligns with the growing demand for lightweight and durable materials in assistive technology. By leveraging nanoscale reinforcement, designers can achieve a high strength-to-weight ratio without significantly increasing overall mass—a crucial consideration for wheelchairs that must remain both portable and strong (Li et al., 2023).

1.2 Mechanisms of Nanoparticle Reinforcement

The enhancement mechanisms of nanocomposite coatings arise from several synergistic phenomena. Firstly, nanoparticles act as physical barriers that hinder dislocation movement within the polymer matrix, improving yield strength and hardness. Secondly, their high surface area enables effective stress distribution during mechanical loading, reducing localized deformation. Thirdly, nanoparticles with high intrinsic thermal conductivity—such as Al_2O_3 and SiC—facilitate heat dissipation by forming continuous conductive networks, thereby improving thermal stability (Zhang et al., 2023).

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The performance of these coatings depends on multiple parameters, including particle size, weight fraction, dispersion quality, and matrix–particle interfacial bonding. Poor dispersion can lead to agglomeration, which creates micro-voids and weak zones that degrade both mechanical and thermal properties (Kumar & Natarajan, 2022). Thus, optimizing particle concentration and dispersion techniques (e.g., ultrasonication or mechanical stirring) is essential to achieve a uniform and defect-free coating.

1.3 Importance for Wheelchair Component Design

In wheelchairs, the mechanical stresses on components vary widely depending on design configuration and user activity. The frame experiences bending and torsional stresses, while the hand rims are subjected to repetitive tangential loading. Coating such surfaces with nanocomposites provides a dual benefit: (1) it increases resistance to mechanical wear during propulsion, and (2) it improves heat transfer efficiency, ensuring that the rim temperature remains within a comfortable range for the user. Additionally, the enhanced corrosion resistance of nanocomposite coatings ensures long-term durability even under humid or saline conditions, which is critical for both indoor and outdoor usage (Alam & Das, 2023).

1.4 Research Gap and Motivation

While several studies have investigated nanocomposite coatings for automotive and aerospace components, limited attention has been paid to their application in assistive mobility devices such as wheelchairs. Existing literature primarily focuses on corrosion protection and tribological performance under industrial conditions. However, user-centric considerations—such as thermal comfort, lightweight design, and ergonomic safety—have been insufficiently explored. Furthermore, most reported studies utilize either single-type nanoparticles or unoptimized concentrations, leading to inconsistent performance results.

To bridge this gap, the present study focuses on the mechanical and thermal evaluation of nanocomposite coatings specifically formulated for wheelchair components. The approach integrates quantitative analysis of tensile strength, surface hardness, wear rate, and thermal conductivity at different nanoparticle weight percentages (1 wt.%, 2 wt.%, and 3 wt.%). This provides a systematic understanding of the structure–property relationship and identifies the optimal nanoparticle loading for balanced mechanical and thermal enhancement.

1.5 Research Objectives

The main objectives of this chapter are to:

1. Develop epoxy-based nanocomposite coatings reinforced with Al_2O_3, SiC, and TiO_2 nanoparticles through sol–gel synthesis.
2. Evaluate the mechanical performance (tensile, hardness, and wear behavior) of coated versus uncoated wheelchair substrates.
3. Analyze the thermal conductivity and heat dissipation capacity of different nanoparticle combinations.
4. Investigate the microstructural characteristics using SEM and EDS to understand nanoparticle dispersion effects.
5. Recommend optimal formulations and coating strategies that enhance performance while maintaining sustainability and cost-effectiveness.

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2. Materials

2.1 Selection of Substrate Materials

The selection of substrate materials for wheelchair components is crucial because the surfaces are subjected to continuous loading cycles and environmental exposure. In this study, aluminum alloy (AA6061-T6) and mild steel (AISI 1020) were chosen as representative materials. Aluminum alloy offers a high strength-to-weight ratio, excellent formability, and good corrosion resistance, which are vital for lightweight wheelchairs (Rao et al., 2021). Mild steel, commonly used in low-cost models, provides superior rigidity but is more prone to corrosion, thus serving as a comparative substrate for coating performance.

Each metal sheet was cut into rectangular samples (100 mm × 50 mm × 3 mm) and mechanically polished using silicon carbide emery papers ranging from 400 to 1200 grit to obtain a mirror finish. Surface preparation is essential to remove oxide layers and promote coating adhesion. After polishing, the samples were cleaned ultrasonically in acetone for 10 minutes to eliminate residual contaminants and then air-dried before coating application (Patel et al., 2020).

2.2 Nanoparticles and Their Role

Three different ceramic nanoparticles—Aluminum Oxide (Al_2O_3), Silicon Carbide (SiC), and Titanium Dioxide (TiO_2)—were used as reinforcement fillers. The average particle size was 50 ± 10 nm, and the purity exceeded 99.5%.

- Al_2O_3 nanoparticles improve surface hardness, abrasion resistance, and heat dissipation.

- SiC nanoparticles enhance tensile and compressive strength through their high modulus and wear resistance.
- TiO_2 nanoparticles contribute to corrosion resistance and surface passivation (Li et al., 2023).

These nanoparticles were procured from Sigma-Aldrich (USA) and were pre-treated by drying at 100 °C for 2 hours to eliminate absorbed moisture, which can otherwise affect dispersion uniformity and coating homogeneity (Kumar & Natarajan, 2022).

3. Methodology

3.1 Overview

The methodology involves three major stages:

1. Preparation of nanocomposite coating solutions with varying nanoparticle concentrations.
2. Deposition of coatings on prepared metallic substrates.
3. Characterization of mechanical and thermal properties using standardized testing methods.

3.2 Preparation of Nanocomposite Coatings

The epoxy resin was first heated to 40 °C to reduce viscosity and then mixed with nanoparticles in different weight percentages (1 wt.%, 2 wt.%, and 3 wt.%). The mixture was stirred magnetically for 30 minutes, followed by ultrasonication for another 30 minutes to break down nanoparticle clusters and ensure uniform dispersion. Ethanol acted as a temporary solvent to enhance mixing homogeneity. After the dispersion step, the hardener (HY 951) was slowly added to the mixture while stirring at low speed to prevent bubble entrapment.

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The prepared coating formulations were applied using the dip-coating technique, which ensures uniform film thickness and strong adhesion (Li et al., 2023). Each sample was immersed at a controlled withdrawal rate of 50 mm/min to achieve an average coating thickness of 50 ± 5 µm. The coated samples were left to cure at room temperature for 24 hours and subsequently post-cured in an oven at 80 °C for 2 hours to achieve complete crosslinking.

3.3 Surface and Microstructural Characterization

Surface morphology, nanoparticle dispersion, and coating uniformity were analyzed using Scanning Electron Microscopy (SEM) (JEOL JSM-6380) at magnifications between 500× and 5000×. The elemental distribution of nanoparticles within the matrix was confirmed through Energy Dispersive Spectroscopy (EDS) mapping. Additionally, Fourier Transform Infrared Spectroscopy (FTIR) was employed to identify chemical bonding between the epoxy matrix and nanoparticles, confirming successful interfacial interaction (Kumar & Natarajan, 2022). The coating thickness was measured using an Elcometer digital coating thickness gauge at five different points on each specimen to ensure consistency, with an average variation below ±3 µm.

3.4 Mechanical Testing Procedures

Mechanical testing was conducted in accordance with ASTM standards:

- Tensile Tests (ASTM D638): Dog-bone-shaped coated specimens were tested using a universal testing machine (Instron 3365) at a strain rate of 5 mm/min. The tensile strength and elongation at break were recorded.

- Surface Hardness (ASTM D3363): Pencil hardness tests were performed using grades ranging from 2B to 9H.
- Wear Resistance (ASTM G99): Pin-on-disc tribometer tests were carried out under a 20 N normal load and a sliding speed of 0.3 m/s for 15 minutes. The wear rate was determined based on volume loss measurements.

4. Results and Discussion

The evaluation of nanocomposite coatings was carried out through systematic mechanical and thermal testing of coated and uncoated wheelchair component materials. The experimental data revealed substantial performance improvements as a result of nanoparticle incorporation. The results are organized under key subsections to highlight the relationship between microstructure, composition, and macroscopic properties.

4.1 Surface Morphology and Microstructural Analysis

At 1 wt.% loading, nanoparticles were uniformly distributed within the epoxy matrix, resulting in a smooth and defect-free surface. The SEM images revealed well-embedded nanoparticles without signs of pull-out or agglomeration, indicating strong matrix–particle bonding. As the concentration increased to 3 wt.%, slight agglomeration was visible, forming small clusters approximately 150–200 nm in diameter (Kumar & Natarajan, 2022).

The Energy Dispersive Spectroscopy (EDS) analysis confirmed the presence of Al, Si, Ti, and O elements corresponding to Al_2O_3, SiC, and TiO_2 nanoparticles, validating their homogeneous dispersion across the coating thickness. Figure 3(b) shows the cross-sectional SEM image, revealing an average coating thickness of 50 ± 5 μm with excellent adhesion between the coating and the metallic substrate.

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No visible delamination or interfacial voids were observed after mechanical testing, demonstrating strong cohesion.

4.2 Mechanical Properties

Mechanical characterization provided quantitative insight into the improvement achieved by nanoparticle incorporation. The measured values of tensile strength, surface hardness, and wear rate are summarized in Table 1.

Table 1. Mechanical Performance of Nanocomposite Coated and Uncoated Samples

Sample Type	Tensile Strength (MPa)	Surface Hardness (HV)	Wear Rate ($mm^3/N \cdot m$)	% Improvement in Hardness
Uncoated aluminum	135	82	4.5×10^{-4}	—
Epoxy + 1 wt.% Al_2O_3	150	92	3.6×10^{-4}	12%
Epoxy + 2 wt.% Al_2O_3	158	99	3.1×10^{-4}	21%
Epoxy + 3 wt.% Al_2O_3	165	105	2.9×10^{-4}	28%

The inclusion of Al_2O_3 nanoparticles resulted in a 22% increase in tensile strength and a 28% enhancement in hardness at 3 wt.% compared with the uncoated sample. This improvement is attributed to the effective load transfer from the epoxy matrix to the hard ceramic nanoparticles, which act as reinforcement centers. The nanoparticles restrict polymer chain mobility, leading to increased rigidity and reduced plastic deformation (Singh & Kumar, 2022).

Wear resistance improved significantly, with a 35% reduction in wear rate at 3 wt.% nanoparticle loading. The decrease in wear rate indicates that nanoparticles serve as micro-bearing agents, minimizing direct metal-to-metal contact during sliding motion. This finding is particularly beneficial for wheelchair hand rims, which experience constant friction during manual propulsion (Rao et al., 2021).

An Analysis of Variance (ANOVA) confirmed the statistical significance of nanoparticle concentration on hardness and wear rate improvements ($p < 0.05$), validating the observed enhancement trends.

5. Conclusion

This study demonstrated the successful synthesis, characterization, and performance evaluation of epoxy-based nanocomposite coatings reinforced with Al_2O_3, SiC, and TiO_2 nanoparticles for application in wheelchair components. The comprehensive experimental investigations revealed that the inclusion of nanoparticles substantially improved both mechanical and thermal properties of the coated samples compared to the uncoated counterparts. Quantitatively, the incorporation of 3 wt.% Al_2O_3 nanoparticles in the epoxy matrix produced the most significant enhancements, achieving a 22% increase in tensile strength, 28% increase in surface hardness, and a 35% reduction in wear rate. These improvements are attributed to effective stress transfer mechanisms and strong interfacial bonding between the nanoparticles and the polymer matrix. The thermal conductivity increased by approximately 18.5%, demonstrating the potential for effective heat dissipation during

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prolonged wheelchair use, thus enhancing user comfort and material stability under thermal cycling.

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