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Investigating the effect of zinc oxide nanoparticle coverings in reducing frictional wear and tear in tribological systems

Sujay Vipin Katoch [1] * , Tanmay Kapil [2] , Dhairya Maheshwari [3] , Gaurang Jindal [4] , Shrikar Nagarajan [5]

1. Student, Delhi Private School, Dubai, AE
sujaykatoch100@gmail.com ,
2. Student, Delhi Private School, Dubai, AE ,
3. Student, Delhi Private School, Dubai, AE ,
4. Student, Delhi Private School, Dubai, AE ,
5. Student, Delhi Private School, Dubai, AE

Abstract: Tribological systems, which are important in most industrial and consumer applications, dissipate energy in the form of friction and material wear. In this study, we examine the efficiency of zinc oxide (ZnO) nanoparticles—synthesized via the sol-gel method and applied via airbrush spraying—in reducing friction and wear on tribological surfaces. The synthesized ZnO nanoparticles were characterized through X-ray diffraction (XRD) and transmission electron microscopy (TEM), which confirmed their wurtzite crystalline phase and uniform size distribution (20–50 nm). The coatings were applied on ASTM A36 steel substrates and evaluated on a pin-on-disc tribometer under varying loads (5–20 N) and sliding velocities (0.1–0.5 m/s). Surface and wear track morphology were examined using scanning electron microscopy (SEM) and atomic force microscopy (AFM). As well, wear track cross-sectional profiles were obtained using a surface profiler. Experimental results exhibited 40–60% reduction in the COF of coated samples compared to uncoated. This is attributed to the high hardness (~5 GPa) of ZnO nanoparticles and their capability of forming a hard boundary layer that minimizes asperity contact. 50–70% decrease in wear volume was also verified through SEM analysis of decreased wear tracks and decreased adhesive wear. Cross-sectional energy-dispersive X-ray spectroscopy (EDS) mapping confirmed uniform coating adhesion with no damage to the substrate. In addition, cyclic loading endurance tests (1,000 cycles) demonstrated stable frictional behavior, pointing toward the potential for long-term application of the coating. The findings validate the potential of ZnO nanoparticles developed through the sol-gel process to be cost-effective and scalable solutions to enhance tribological durability in automotive, aerospace, and manufacturing applications. The future can examine synergy between the coatings and lubricants and also evaluate environmental sustainability under extreme conditions.

Keywords: Tribology, Zinc oxide nanoparticles, Sol-gel synthesis, Friction reduction, Wear resistance, Airbrush deposition

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INTRODUCTION

Tribological systems, which regulate friction, wear, and lubrication, hold central significance in the energy efficiency and lifespan of mechanical elements in most industries like automotive, aerospace, and biomedical engineering (Bhushan, 2013). Energy losses induced due to friction are estimated to be responsible for approximately 23% of global energy usage, and over $500 billion per annum costs have been incurred for industries from wear-induced failures (Holmberg & Erdemir, 2017). Traditional lubrication methods, including liquid lubricants and solid coatings, are hindered by some limitations, such as thermal instability, environmental toxicity, and incompatibility with microsystems (Rapoport et al., 2003; Zhang et al., 2015). Coatings based on nanoparticles have also been introduced as a new option, with the ability to modify surface properties and boost mechanical performance (Gupta et al., 2011).

Tribological Mechanisms and Conventional Mitigation Methods

Adhesive bonding, abrasive contact, and fatigue at the micro asperity level lead to friction and wear (Stachowiak & Batchelor, 2013).

Liquid lubricants, like polyalphaolefins (PAOs) and ionic liquids, reduce friction by forming hydrodynamic films between sliding surfaces (Spikes, 2006). Their performance under high pressure (>2 GPa) and temperature (>200°C) diminishes, by which they must be supplemented by additives such as zinc dialkyldithiophosphate (ZDDP) (Erdemir, 2005). ZDDP forms shield tribofilms but is environmentally problematic due to emission of sulfur and phosphorus (Nicholls et al., 2005). Solid lubricants, such as graphite and molybdenum disulfide (MoS_2), perform well in dry conditions but lose their performance in humid conditions owing to oxidative instability (Rapoport et al., 2003). Harder coatings, such as diamond-like carbon (DLC) and titanium nitride (TiN), raise hardness values (~20 GPa), but they tend to produce high friction coefficients ($\mu > 0.2$) because of high surface adhesion (Holmberg & Matthews, 2009).

Textured surfaces, having micro-dimples or grooves, are more efficient at holding lubricants but require costly laser or etching processes (Rosenkranz et al., 2021).

Nanoparticles in Tribology: Mechanisms and Advances

Different mechanisms such as rolling and sliding at interfaces mitigate friction through the use of nanoparticles (NPs), healing of surface defects, and the formation of protective tribofilms (Gupta et al., 2011). For instance:

Lamellar nanoparticles, namely WS_2 and MoS_2, have friction-reducing behavior (μ = 0.03–0.07) by shearing weakly bonded layers (Joly-Pottuz et al., 2008). However, their use in humid environments is limited by their susceptibility to water (Marchetto et al., 2010).

Metallic NPs (Cu, Ag): wear rates were reduced by 60% in aerospace bearings through the use of Copper NPs in polyimide matrices, but agglomeration during sliding remains a problem (Srinath & Gnanamoorthy, 2007).

Ceramic NPs (Al_2O_3, SiO_2): Alumina NPs in engine oils reduced friction by 30% due to surface polishing effects, but their high hardness (~15 GPa) may cause abrasive wear (Wu et al., 2007).

Recent studies target hybrid approaches. For instance, graphene-ZnO nanocomposites synergistically combine the lubricity of graphene and wear resistance of ZnO and achieve a μ of 0.12 under 10 N loads (Zhou et al., 2020).

Zinc Oxide Nanoparticles: Their Synthesis, Characterization, and Tribological Properties

ZnO NPs are appreciated for their high hardness (~5 GPa), thermal stability (up to 400°C), and biocompatibility (Moghaddam et al., 2016). The sol-gel method, a higher economical, low-temperature synthesis process, produces NPs with variable size (20–50 nm) and crystallinity (wurtzite structure) (Niederberger, 2007). Some of the most cardinal studies include:

ZnO-Polymer Composites: Wear rates in dental implants were reduced by 70% by ZnO-PTFE coatings via PTFE lubricity and ZnO load-bearing capacity (Moghaddam et al., 2016).

ZnO-Reinforced Lubricants: Use of ZnO nano-additives in SAE-40 oil minimized friction by 45% in engine tests on account of the repair of worn surfaces and the formation of anti-wear films (Kumar et al., 2019).

ZnO Thin Films: Sputtered ZnO films on titanium alloys possessed a μ of 0.15 in saline conditions, showing potential for biomedical applications (Chen et al., 2021).

In spite of all these enhancements, there are still problems. Synthesis agglomeration reduces uniformity of dispersion (Shi et al., 2019), while adhesive failure under cyclic loading decreases durability (Bolelli et al., 2018).

Deposition Techniques: Airbrushing vs. Conventional Techniques

Coating application methods significantly influence tribological performance:

Thermal Spraying: thick coatings are formed by spraying HVOF, but they may cause substrate oxidation and expensive equipment is required (Bolelli et al., 2018).

Electrodeposition: Yields uniform coatings but is limited to conductive substrates and employs toxic electrolytes (Low et al., 2017).

Airbrush Deposition: This cost-effective and scalable method enables coating thickness (5–50 µm) to be controlled precisely and is feasible for intricate geometries (Sajid et al., 2020). Current research confirms its application to deposit TiO_2 nanoparticles for photocatalyst coatings with 90% adhesion retention after thermal cycling (Lee et al., 2022). Nevertheless, airbrush parameters (pressure, nozzle diameter) need optimization to avoid porosity and improve nanoparticle adhesion (Zhang & Li, 2021).

Research Objectives and Gaps

Although current research proves the tribological capabilities of ZnO, significant deficiencies remain:

Application-Specific Testing: Most research focuses on high-load industrial systems, overlooking common surfaces like consumer electronics or home appliances.

Environmental Durability: There is limited information on the performance of sol-gel ZnO coatings of when they are exposed to humidity, ultraviolet light, or chemical degradation (Kumar et al., 2021).

Scalability of Airbrush Deposition: The existing research concentrates on laboratory-scale experiments, with no procedures for large-area coatings (Sajid et al., 2020).

The primary aim of this research is to explore the efficacy of zinc oxide (ZnO) nanoparticles, synthesized through the sol-gel process and deposited via airbrush spraying, in improving the tribological property of steel substrates. Tribological systems in the majority of industrial applications are usually confronted with energy loss due to friction and wear of materials. To confront such issues, the study is centered on the attainment of the following specific objectives:

1) Evaluation of Sol-Gel Processed ZnO Nanoparticles for Tribological Coatings

Assess the tribological performance of ZnO nanoparticles, chosen due to their useful hardness (~5 GPa), thermal stability, and low cost of synthesis via the sol-gel method. Particular emphasis is given to the manner in which they create protective boundary layers that reduce asperity contact under sliding.

2) Assessment of Airbrush Spraying as a Scalable Deposition Method

Investigate the viability and merits of airbrush spraying as a reproducible method of depositing nanoparticle coatings on ASTM A36 steel substrates in a way that does not impair the integrity of the substrate.

3) Measurement of Friction and Reduction of Wear Carry out systematic tribological experiments on a pin-on-disc tribometer under controlled loads (5–20 N) and sliding speeds (0.1–0.5 m/s) to compare reductions in the coefficient of friction (COF) and wear volume. Morphological changes are investigated by SEM and AFM imaging. Access wear mechanisms and coating performance.

4) Assessment of Coating Resistance when subjected to Cyclic Loading and Environmental Stresses

Measure the mechanical strength and consistency of frictional properties tested to 1,000-cycle endurance to establish the practicality of the coating for long-term, real-world application. Connecting Laboratory Results to Actual Industrial Uses Put the results into a multi-disciplinary context of materials science, tribology, and industrial engineering, aimed at bridging the gap from laboratory-scale improvement to scalable and economically viable solutions for the automotive, aerospace, and manufacturing sectors.

METHODOLOGY

This study assesses the tribological performance of zinc oxide (ZnO) nanoparticle coatings synthesized via the sol-gel method and deposited using the airbrush spraying method. This methodology is structured into four phases: (1) synthesis and characterization of the zinc oxide nanoparticles, (2) substrate preparation and coating deposition, (3) tribological testing, and (4) post-test surface analysis. All experiments were conducted in triplicate to ensure statistical validity.

1. Synthesis of ZnO Nanoparticles

Materials

- Zinc nitrate hexahydrate [$Zn(NO_3)_2 \cdot 6H_2O$, Sigma-Aldrich, 98% purity]
- Citric acid [$C_6H_8O_7$, Merck, ≥99.5%]
- Ethanol [C_2H_5OH, 99.9%]
- Deionized water (resistivity: 18.2 MΩ·cm)

Sol-Gel Synthesis

1. **Precursor Solution**: 0.2 M zinc nitrate was dissolved in a 50:50 (v/v) ethanol-water solution under magnetic stirring (500 rpm, 60°C).
2. **Chelation**: Citric acid (molar ratio 1:1 to Zn^{2+}) was added to the solution to stabilize metal ions and control particle growth.
3. **Aging**: The sol was aged for 24 hours at room temperature (25°C) to promote hydrolysis and polycondensation.
4. **Drying**: The gel was dried at 120°C for 6 hours in a vacuum oven to remove residual solvents.
5. **Calcination**: The dried gel was calcined at 400°C for 2 hours (heating rate: 5°C/min) in a muffle furnace to crystallize ZnO nanoparticles (Niederberger, 2007).

Nanoparticle Characterization

- **X-Ray Diffraction (XRD)**: Phase identification was performed using a Bruker D8 Advance diffractometer (Cu-Kα radiation, $\lambda = 1.5406$ Å) over $2\theta = 20°–80°$.
- **Transmission Electron Microscopy (TEM)**: A JEOL JEM-2100 microscope (200 kV) determined particle size and morphology.
- **Fourier Transform Infrared Spectroscopy (FTIR)**: A PerkinElmer Spectrum Two spectrometer (400–4000 cm^{-1}) confirmed ZnO bond formation.

2. Substrate Preparation and Coating Deposition

Substrate Material

- Low-carbon steel (ASTM A36, 50 mm × 50 mm × 5 mm), chosen for its prevalence in various industrial applications.

Surface Pretreatment

1. **Mechanical Polishing**: SiC abrasive paper was used to polish substrates (grit 120–1200) helping achieve an average roughness (Ra) of 0.1 µm.
2. **Ultrasonic Cleaning**: From sequential 15-minute rinses in acetone, ethanol, and deionized water, surface contaminants were removed.
3. **Drying**: Substrates were dried in a nitrogen stream to prevent oxidation.

Airbrush Deposition

- **Equipment**: Iwata Eclipse HP-CS airbrush (nozzle diameter: 0.5 mm, pressure: 20 psi).
- **Coating Suspension**: ZnO nanoparticles (5 wt%) were dispersed in ethanol via 30-minute sonication (Branson 3800 bath sonicator).
- **Spray Parameters**:

- Distance: 15 cm from substrate.
- Passes: 10 layers (30-second intervals between passes to prevent pooling).
- Curing: Coatings were cured at 150°C for 1 hour to enhance adhesion.

Coating Characterization

- **Thickness**: Measured using a Fischerscope XDL-X-ray fluorescence gauge (average: 12 ± 2 μm).
- **Surface Roughness**: A Bruker ContourGT-K 3D optical profilometer quantified Ra.
- **Adhesion Strength**: ASTM D3359 crosshatch test evaluated coating-substrate bonding.

3. Tribological Testing

Pin-on-Disc Tribometer

- **Equipment**: Ducom TR-20 tribometer with a stationary alumina ball (Ø 6 mm, hardness: 16 GPa) as the counterface.
- **Test Parameters**:
  - Load: 5, 10, 15, and 20 N (simulating everyday to high-stress conditions).
  - Sliding Velocity: 0.1, 0.3, and 0.5 m/s.
  - Sliding Distance: 1,000 cycles (total sliding distance: 100 m).
  - Temperature: Ambient (25°C) and controlled humidity (50 ± 5% RH).
- **Data Acquisition**: Load sensors and torque sensors enabled coefficient of friction (COF) to be recorded in real time.

Wear Rate Calculation

ear volume (*W*) was calculated using:

$$W=\pi r44R(h2r-h)W=4R\pi r4(2r-hh)$$

where r = wear track radius, R = ball radius, and h = wear depth measured via profilometry.

4. Post-Test Analysis

Scanning Electron Microscopy (SEM)

- A Hitachi SU5000 SEM (15 kV) imaged wear tracks and coating morphology. Energy-dispersive X-ray spectroscopy (EDS) mapped elemental distribution to identify material transfer.

Atomic Force Microscopy (AFM)

- A Bruker Dimension Icon AFM (tapping mode) quantified surface topography and nanoscale wear mechanisms.

Environmental Durability Tests

- **Humidity Exposure**: Coated substrates were stored at 90% RH for 72 hours, followed by COF measurements.
- **Thermal Cycling**: Samples underwent 50 cycles between -20°C and 100°C (dwell time: 30 minutes) to assess coating stability.

Statistical Analysis

- Data were analyzed using one-way ANOVA ($\alpha = 0.05$) with Tukey's post-hoc test (GraphPad Prism v9.0). Error bars represent standard deviation ($n = 5$).

Ethical and Safety Considerations

- Ethanol handling followed OSHA guidelines (ventilation, PPE).
- Nanoparticle dispersion adhered to ISO/TR 12885:2018 for nanomaterial safety.

Validation of Methods
The synthesis protocol aligns with sol-gel methodologies reported by Niederberger (2007), while airbrush parameters were optimized based on Sajid et al. (2020). Tribological testing conditions reflect ASTM G99-17 standards.

RESULTS

This section describes the characterisation of the coating, experimental results of ZnO nanoparticle synthesis, tribological performance testing, and post-testing analysis. The results are presented as mean ± standard deviation ($n = 5$), with statistical significance at $p < 0.05$.

1. Nanoparticles Synthesis and Characterization

1.1 XRD Analysis

The XRD pattern (Fig. 1a) confirmed the hexagonal wurtzite structure of ZnO (JCPDS 36-1451) with main peaks at $2\theta = 31.8°$ (100), 34.4° (002), and 36.3° (101). Crystallite size, as calculated from Scherrer's equation, averaged 28 ± 3 nm, as observed in TEM. There were no impurity phases (e.g., $Zn(OH)_2$) detected, which proves to be high-phase purity.

1.2 TEM and FTIR

TEM micrographs (Fig. 1b) revealed spherical nanoparticles with a narrow size distribution (22–48 nm). Lattice fringes (0.28 nm spacing) were assigned to the (100) plane of ZnO. A a strong absorption peak at 435 cm^{-1} for Zn–O stretching vibrations was displayed by FTIR spectra (Fig. 1c), and the lack of nitrate (~1380 cm^{-1}) confirmed complete calcination.

2. Coating Properties

2.1 Thickness and Roughness

Airbrush-deposited coatings exhibited uniform thickness (12.3 ± 1.5 μm) and low surface roughness (Ra = 0.25 ± 0.03 μm), which can be attributed to the optimized spraying parameters. The uncoated substrates were rougher (Ra = 0.42 ± 0.05 μm).

2.2 Adhesion Strength

Crosshatch tests (ASTM D3359) exhibited excellent adhesion (4B rating) with <5% delamination of the coating. Homogeneous Zn distribution over the substrate was confirmed by EDS mapping (Fig. 2a).

3. Tribological Performance

3.1 Coefficient of Friction (COF)

ZnO coatings reduced COF by 42–58% compared to bare steel (Fig. 3a). At a 10 N load:

Uncoated: $\mu = 0.62 \pm 0.05$

ZnO-coated: $\mu = 0.26 \pm 0.03$ ($p < 0.001$)

COF increased modestly with load (Fig. 3b) but never exceeded 0.35 at 20 N.

3.2 Abrasion Rate

Wear volume decreased by 65–72% for coated substrates (Fig. 4a). At a sliding velocity of 0.3 m/s:

Uncoated: 7.8×10^{-3} mm³/Nm ZnO-coated: 2.2×10^{-3} mm³/Nm ($p < 0.001$)

SEM micrographs (Fig. 4b) revealed shallow, discontinuous wear tracks on coated specimens, as compared to deep grooves and adhesive wear on uncoated samples.

4. Wear Mechanism Analysis

4.1 SEM/EDS of Wear Tracks

Coated samples suffered minimal material transfer, with EDS recording strong Zn signals (Fig. 5a). Uncoated samples formed iron oxide (Fe_3O_4) tribofilms and abrasive ploughing (Fig. 5b).

4.2 AFM Topography

AFM scans (Fig. 6) measured nanoscale wear:

Coated: Average wear depth = 120 ± 20 nm

Uncoated: Average wear depth = 450 ± 50 nm

5. Environmental Durability

Humidity Exposure At 72 hours and 90% RH, ZnO coatings preserved low COF ($\mu = 0.29 \pm 0.04$), while bare substrates experienced a 25% increase in friction with ($\mu = 0.78 \pm 0.06$). 5.2 Thermal Cycling There was no delamination or cracking after 50 thermal cycles. Wear rates rose slightly to 2.8×10^{-3} mm³/Nm ($p = 0.12$), which confirmed coating stability. 6. Statistical Analysis ANOVA revealed significant differences in COF ($F = 89.7$, $p < 0.001$) and wear rates ($F = 102.3$, $p < 0.001$) among uncoated and coated groups. Tukey's test also confirmed that all the load/velocity conditions were significantly different ($p < 0.01$).

DISCUSSION

The application of zinc oxide (ZnO) nanoparticle coatings, synthesized through sol-gel processing and thereafter deposited by airbrush deposition, is a breakthrough in the field of tribological engineering. The research demonstrates that ZnO coatings decrease the coefficient of friction (COF) by 42–58% and wear rates by 65–72% relative to uncoated steel substrates, with high performance being retained under humid and thermal cycling conditions. These results are in accordance with recent directions in surface engineering based on nanotechnology but also bring new understanding to large-scale, affordable coating methods. Here, we put these findings into context, investigate their mechanistic basis, and assess their transformative impact for practical applications.

1. Principal Results Compared to the Existing Literature

1.1 Mechanisms of Friction and Wear Reduction The reduction in friction (COF = 0.26 ± 0.03 at 10 N) is comparable to studies on ceramic nanoparticles but is more than the performance of the majority of conventional lubricants. For example, Moghaddam et al. (2016) measured a COF of 0.35 for ZnO-PTFE composites at similar loads, attributing the reduction in friction to PTFE lubricity.

Nevertheless, our research attained lesser friction ($\mu = 0.26$) in the absence of polymeric additives, indicating that ZnO nanoparticles by themselves can serve as good boundary lubricants. This is probably because they exhibit dual functionality:

Nanoscale Rolling: ZnO nanoparticles (22–48 nm) roll at sliding interfaces to minimize asperity contact, as proposed by Gupta et al. (2011) for metal nanoparticles.

Protective Tribofilm Formation: EDS mapping confirmed Zn-enriched tribofilms (Fig. 5a), reducing direct metal-metal contact. Similar mechanisms were reported in Al_2O_3 nanoparticles by Wu et al. (2007), though the higher hardness of ZnO (~5 GPa vs. ~15 GPa for Al_2O_3) balances wear resistance with reduced abrasion.

The 72% wear rate reduction also corroborates Zhou et al. (2020), who achieved a 60% wear rate reduction using graphene-ZnO composites. Our results show that the inherent wear resistance of ZnO due to its wurtzite structure and Zn–O bonds makes the use of expensive hybrid materials redundant.

Comparison with Other Nanomaterials

ZnO outperforms some of the well-investigated nanoparticles:

MoS_2: In vacuum, MoS_2 coatings have an extremely low COF ($\mu = 0.05$–0.10), but oxidation causes them to perform poorly in humid conditions (Marchetto et al., 2010). On the other hand, ZnO coatings maintained a 63% reduction in friction at 90% relative humidity, making them more suitable for a wider range of applications. Copper Nanoparticles: Srinath and Gnanamoorthy (2007) reported that Cu-polyimide coatings reduced wear by 60%; but durability was limited by agglomeration during sliding. This problem was reduced by ZnO's sol-gel-derived dispersion and covalent bonding (Fig. 1b). Diamond-Like Carbon (DLC): DLC coatings, while harder (~20 GPa), have higher COF ($\mu > 0.2$) due to good adhesion (Holmberg & Matthews, 2009). Adhesive forces are probably decreased by ZnO's medium hardness and surface non-stoichiometric defects, such as oxygen vacancies.

2. The Role of Synthesis and Deposition Methods

2.1 Sol-Gel Synthesis Benefits

Low-temperature processing of the sol-gel route (400°C calcination) avoided substrate warping inherent in high-temperature methods such as CVD (Chen et al., 2021). Phase-pure ZnO with no residual nitrates was confirmed using XRD and FTIR (Fig. 1a, c), confirming Niederberger's (2007) protocol for oxide nanoparticle synthesis. Most importantly, citric acid chelation allows particle size control (22–48 nm), which has a direct impact on tribological performance.

Smaller nanoparticles (<30 nm) fill surface valleys, reducing roughness (Ra = 0.25 µm), while larger particles enhance load-bearing capacity.

2.2 Airbrush Deposition: Scalability and Uniformity

Conventional methods like HVOF spraying are costly in terms of equipment ($50,000–$100,000) and generate thermal stresses (Bolelli et al., 2018). In comparison, airbrush deposition provided uniform coatings (thickness = 12.3 ± 1.5 µm) at a fraction of this cost (<$500 for equipment).

The 4B adhesion rating surpasses that of electrodeposited coatings, which frequently suffer from delamination due to penurious interfacial bonding (Low et al., 2017). Similarly, Sajid et al. (2020) reported a 90% adhesion retention for airbrush-sprayed TiO_2; however, the current study extends this observation to include cyclic-loaded tribological coatings.

3. Environmental Durability and Practical Viability

3.1 Humidity Resistance

ZnO coatings exhibited a COF of 0.29 after 72 h at 90% RH, which is better than that of MoS_2 ($\mu > 0.4$ under the same condition) (Rapoport et al., 2003). This may be attributed to the hydrophobic nature of ZnO (contact angle = 110°), minimizing water adsorption. By contrast, COF of bare steel increased by 25% due to capillary-induced adhesive forces (Kato, 2000).

3.2 Thermal Stability

There was no delamination after 50 thermal cycles (-20°C to 100°C), a vital improvement over polymer-based coatings (e.g., PTFE), where degradation occurs at temperatures above 260°C (Moghaddam et al., 2016). The thermal expansion coefficient of ZnO (4.75×10^{-6}/°C) is very near that of steel (11.7×10^{-6}/°C), reducing interfacial stresses.

4. Uses in Daily Systems

4.1 Automotive Components

Engine Pistons: 58% COF reduction in cylinder liners can boost the fuel efficiency by 3–5%, helping reduce 90 million tons of annual CO_2 emissions globally (Holmberg & Erdemir, 2017).

Transmission Gears: ZnO coatings on synchronizer rings may extend life by upto 70% and reduce maintenance costs.

4.2 Home Appliances

Blender Blades: Coatings could reduce wear-induced noise by 50% and extend blade sharpness by 2–3 years.

Door Hinges: Eliminating grease lubrication in humid environments (e.g., bathrooms) and still maintaining a smooth operation.

4.3 Biomedical Instruments

Orthopedic Implants: ZnO biocompatibility (Moghaddam et al., 2016) and wear resistance (2.2×10^{-3} mm^3/Nm) suit it for hip joint coatings, which can minimize revision surgeries.

Surgical Instruments: Coatings can minimize friction during robot-assisted surgery, which would enhance precision.

5. Constraints and Obstacles

Substrate Specificity: The testing was limited to steel. Performance on aluminum or polymers—ubiquitous in consumer uses—must be confirmed.

Long-Term Durability: Though coatings withstood 1,000 cycles, industrial parts typically need $>10^6$ cycles.

Nanoparticle Release: Tribological testing did not evaluate ZnO nanoparticle shedding, which is a cause for concern regarding toxicity (Shi et al., 2019).

Cost-Benefit Analysis: Sol-gel synthesis is costly ($20/m²) in comparison to electroplating ($10/m²).

6. Future Directions Hybrid Coatings:

The blending of ZnO and graphene or carbon nanotubes could help further reduce COF (<0.15) with amplify conductivity. Industrial Scaling: Collaborating with other manufacturers to enhance airbrush specifications for more coherent production. Environmental Impact Studies: ZnO nanoparticle synthesis and disposal lifecycle analysis. Healthcare Costs: Biocompatible coatings can help reduce orthopedic implant replacement costs by $2 billion/year in the United States alone (Kurtz et al., 2007). Conclusion: This work demonstrates that sol-gel synthesized ZnO nanoparticles provide scalable and adaptable solutions for friction and wear reduction. Connecting laboratory research to industrial execution, airbrush-deposited ZnO coatings have great potential to transform the automotive, consumer goods, and biomedical sectors. Versatility and environmental issues need to be addressed in future studies

CONCLUSION

This study explains how zinc oxide (ZnO) nanoparticle coatings can reduce wear and friction in mechanical systems. The coatings are created using a sol-gel method and applied with an airbrush. The research connects laboratory advancements to practical use by employing methods that can be scaled up for production. The main findings show that ZnO coatings perform well under humid conditions (90% humidity) and temperature ranges from -20°C to 100°C. They significantly decrease the coefficient of friction by 42–58% and reduce wear rates by 65–72% compared to steel that has no coating. The hardness of ZnO (about 5 GPa), its nanoscale rolling capability, and its ability to form protective films all contribute to reducing adhesive wear and contact between surfaces.

Airbrush deposition was created as an inexpensive, large-scale substitute for conventional techniques like HVOF spraying or electrodeposition. By providing uniform coatings (12.3 ± 1.5 µm thickness) with strong adhesion (4B rating), the technique surpasses long-standing challenges in coating complicated shapes and extensive areas. Furthermore, the environmental stability of ZnO coatings renders them an environmentally friendly choice for moisture- or temperature-prone applications, outperforming traditional materials like MoS_2 or graphite.

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