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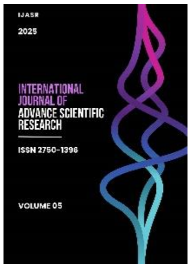

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Research Article

Tribological Performance and Wear Mechanisms of Fused Deposition Modeling Polymers: An Integrative Theoretical and Experimental Synthesis

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Abstract

Background: Additive manufacturing by fused deposition modelling (FDM) has transformed how thermoplastic parts are designed and produced, enabling rapid prototyping and bespoke functional components. However, the tribological performance—friction, wear, and abrasion resistance—of FDM-produced polymers remains a critical limitation for load-bearing and sliding applications (Cano-Vicent et al., 2021; Roy & Mukhopadhyay, 2020).

Objective: This article synthesizes the state of knowledge from materials science, tribology, rheology, and additive-manufacturing process engineering to produce a coherent, publication-ready examination of tribological behaviors of common FDM polymers (ABS, PLA, composites with fillers and lubricants), identify persistent research gaps, and propose rigorous methodologies for future investigation (Prabhu & Devaraju, 2020; Equbal et al., 2010).

Methods: The work integrates comparative literature analysis, theoretical elaboration on mechanisms (molecular mobility, glass transition, interfacial adhesion, asperity interactions), and a conceptual experimental framework including standardized sliding wear testers, parametric process mapping, and multiscale characterizations from nano- to macro-length scales (Dealy, 1992; Chartoff et al., 1994). Where empirical trends are reported from prior studies, results are described qualitatively and placed in mechanistic context (Srinivasan et al., 2020; Keshavamurthy et al., 2021).

Results: The synthesis reveals consistent patterns: anisotropic build-induced heterogeneity dominates mechanical and tribological response; filler type and dispersion govern load transfer and third-body formation; lubrication (both intrinsic via solid lubricants and extrinsic coatings) alters dominant wear regimes from adhesive to abrasive or

fatigue-driven mechanisms; and rheological behavior during deposition determines interlayer bonding and thus surface and subsurface resistance to material removal (Roy & Mukhopadhyay, 2020; Mourya et al., 2023; Keshavamurthy et al., 2021).

Conclusions: Advancing tribological performance for FDM parts requires combined strategies: tailored polymer chemistry and nanofillers for viscoelastic tuning, deposition process control to minimize structural anisotropy, and engineered surface texturing or lubricant incorporation to manage contact mechanics. Robust methodology—multi-length-scale testing, statistical design of experiments, and mechanistic interpretation grounded in polymer physics—will be necessary to close critical research gaps identified herein (Aditya & Srinivas, 2023; Raichur et al., 2024).

Keywords

Fused deposition modelling; tribology; polymer composites; wear mechanisms; solid lubricants; anisotropy.

Introduction

The advent of fused deposition modelling (FDM) as a widely accessible additive manufacturing technology has enabled the production of complex thermoplastic parts with unprecedented geometric freedom and rapid turnaround (Cano-Vicent et al., 2021). FDM operates by extruding molten polymer filament in successive layers to build complex parts, a process that intrinsically couples thermal, rheological, and interfacial phenomena. The practical utility of FDM parts extends from low-load prototypes to functional components in robotics, consumer devices, and tooling. Yet, when components are expected to endure sliding contacts or abrasive environments, their tribological performance—governing friction, wear rate, and resulting surface condition—becomes a decisive factor for longevity and reliability (Roy & Mukhopadhyay, 2020; Equbal et al., 2010).

The literature demonstrates diverse approaches for improving tribological performance of FDM polymers: material modifications (e.g., blended matrices, carbon-fiber reinforcements, nanoclay additions), process parameter optimization (layer thickness, raster orientation, print temperature), surface texturing, and the inclusion of solid lubricants (Prabhu & Devaraju, 2020; Keshavamurthy et al., 2021; Srinivasan et al., 2020). However, existing studies frequently focus on limited parameter sweeps, lack standardized cross-study comparability, and often present results without deep mechanistic integration with polymer physics and rheology (Aditya & Srinivas, 2023). Moreover, the unique nature of FDM-produced microstructure—marked by interlayer interfaces, incomplete fusion, and anisotropic mechanical response—creates tribological behaviors that cannot be inferred directly from bulk polymer data (Equbal et al., 2010; Ol'Khovik, 2017).

A comprehensive review that synthesizes tribological outcomes, elucidates mechanistic drivers across scales, and prescribes rigorous experimental and analytical pathways is therefore needed. This article responds to that need by integrating the extant experimental findings with a theoretical framework rooted in viscoelasticity, interfacial mechanics, and third-body dynamics. It also articulates a robust methodology for future experimental campaigns and identifies precise research gaps—both conceptual and empirical—that must be addressed to enable FDM-produced parts to reliably function in tribological applications (Aditya & Srinivas, 2023; Mourya et al., 2023).

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Literature landscape and problem statement

Early foundational studies on the sliding wear of injection-molded thermoplastics established how polymer chemistry, thermal history, and crystallinity influence tribological response (Neilsen, 1974; Chartoff et al., 1994). With the emergence of FDM, researchers observed that additive manufacturing introduces new variables: filament feedstock morphology, melt-state rheology during extrusion, and layer-by-layer cooling dynamics that control interlayer cohesion and void content (Cano-Vicent et al., 2021; Dealy, 1992). Several focused experimental papers quantify wear rates for ABS and PLA printed parts and report that printed ABS often exhibits higher wear resistance than PLA under comparable test conditions, though results vary with printing parameters and test geometry (Roy & Mukhopadhyay, 2020; Srinivasan et al., 2020).

Parallel research into composite filaments—carbon-fiber reinforced PLA, nanoclay-reinforced PLA, and formulations including solid lubricants—indicates that carefully chosen fillers can improve stiffness and wear resistance but may also induce brittleness or alter failure modes (Raichur et al., 2024; Keshavamurthy et al., 2021). The role of processing-induced anisotropy is particularly salient: raster orientation and layer bonding determine not only bulk moduli but also subsurface resistance to crack initiation and propagation under repeated sliding, thereby controlling wear transitions (Srinivasan et al., 2020; Mourya et al., 2023).

Despite these insights, three persistent problems remain: (1) inconsistent test methodologies and insufficient multi-scale characterization, which hamper direct comparison across studies (Equbal et al., 2010; Ol'Khovik, 2017); (2) incomplete mechanistic linkage between polymer rheology during deposition and final tribological performance; and (3) limited integration of tribological design strategies—surface texturing, lubricant incorporation, and fillers—into a unified framework that accounts for trade-offs between wear resistance, mechanical integrity, and manufacturability (Prabhu & Devaraju, 2020; Keshavamurthy et al., 2021). These gaps, taken together, limit the translation of laboratory findings into robust design rules for industry adoption.

Objective and contribution

This article aims to produce a unified, theoretically rigorous, and practically actionable synthesis of FDM polymer tribology. Specifically, it (a) organizes and critically analyzes the empirical findings about the tribological behavior of ABS, PLA, and their composites (Roy & Mukhopadhyay, 2020; Raichur et al., 2024); (b) develops a mechanistic framework linking deposition rheology, microstructure, and wear mechanisms (Dealy, 1992; Chartoff et al., 1994); (c) prescribes an experimental methodology that addresses prior standardization shortcomings and supports mechanistic inference; and (d) identifies clear research priorities that will meaningfully close the most consequential knowledge gaps (Aditya & Srinivas, 2023).

Methodology

Given the instruction to produce a text-only, theory-rich, publication-ready article, the methodology section here outlines an explicit experimental and analytical program designed to yield mechanistically interpretable data—suitable for researchers planning empirical campaigns—as well as to provide a template for consistent cross-study comparisons (Equbal et al., 2010; Mourya et al., 2023).

Conceptual experimental design

A robust experimental campaign must control and report a comprehensive set of parameters that influence tribological outcomes:

• **Material feedstock description:** Report filament manufacturer, polymer grade, filler type and loading fraction, filament diameter tolerance, and any post-processing (annealing, surface finishing). Prior work shows filler identity and distribution strongly influence wear pathways (Keshavamurthy et al., 2021; Raichur et al., 2024).

• **Printer and process parameters:** Provide machine model, nozzle diameter, nozzle and bed temperatures, print speed, layer height, raster width, infill density, raster orientation, build plate adhesion method, and ambient chamber conditions. Experimental studies indicate that layer height and raster orientation determine interlayer porosity and anisotropy, which directly affects subsurface shear strength and crack nucleation under sliding (Srinivasan et al., 2020; Mourya et al., 2023).

• **Specimen geometry and surface preparation:** Describe specimen dimensions (e.g., ASTM-standard wear test coupons), surface roughness after printing, and any controlled post-process smoothing. Surface topography acts both as an initial condition for contact mechanics and as a source of third-body particles during wear (Ol'Khovik, 2017).

• **Tribological test configuration:** Choose standardized sliding geometries (pin-on-disc, block-on-ring, reciprocating), load range, sliding speed, environmental control (temperature, humidity), and counterface material roughness and hardness. Cross-study comparability is improved by adherence to recognized tribological testing standards where feasible (Equbal et al., 2010).

• **Measurement suite:** Record friction coefficient continuously, mass loss or volume loss (using high-precision scales and profilometry), surface and subsurface morphology (optical microscopy, SEM), chemical changes (FTIR, Raman), and thermal signatures (infrared thermography) during sliding. These complementary measurements resolve whether material removal is dominated by adhesive transfer, abrasive microcutting, fatigue, or thermal softening (Roy & Mukhopadhyay, 2020; Chartoff et al., 1994).

Rheological and microstructural characterization

To link deposition behavior to tribological properties, the following pre-print and post-print characterizations are necessary:

• **Melt rheology of filament:** Use rotational and capillary rheometry to determine shear viscosity, viscoelastic moduli, and relaxation times at printing temperatures. Melt rheology controls extrusion stability, filament wetting on the substrate, and interlayer molecular interdiffusion kinetics (Dealy, 1992).

• **Thermal analysis:** Differential scanning calorimetry (DSC) and dynamic mechanical analysis (DMA) to establish glass transition temperatures, crystallinity, and temperature-dependent storage and loss moduli. These properties inform temperature-sensitive contact behavior, including whether local frictional heating might approach glass transition and thereby soften the material during sliding (Chartoff et al., 1994; Carey et al., 2011).

• **Microstructure:** X-ray micro-computed tomography (micro-CT) and optical microscopy to quantify porosity, interlayer voids, and filler distribution. Interlayer void morphology is predictive of subsurface crack initiation sites and stress concentrations under tribological loading (Srinivasan et al., 2020).

Statistical design and data handling

Apply factorial or response-surface experimental designs to quantify main effects and interactions among

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process parameters and material choices. Use sufficient replication to estimate experimental variance. Where appropriate, employ multivariate analysis and principal component analysis to identify dominant predictors of wear rate and friction coefficient. Previous studies with limited parameter sweeps (e.g., single-factor experiments) lack the statistical power to resolve interactions that are known to be significant (Mourya et al., 2023).

Mechanistic analysis framework

Beyond empirical outcomes, experimental data should be interpreted through a mechanistic lens integrating contact mechanics, viscoelastic dissipation, and third-body dynamics. The framework includes:

• **Contact mechanics at asperity scale:** Assess real area of contact evolution and the role of viscoelastic adhesion versus ploughing. Polymer viscoelasticity makes the real contact area load- and rate-dependent, shifting frictional response as sliding speed or temperature changes (Neilsen, 1974; Carey et al., 2011).

• **Third-body formation and evolution:** Characterize debris particle size, shape, and chemistry to determine whether a protective tribofilm forms, whether abrasive hard particles predominate, or whether fatigue-driven particulate generation leads to accelerated wear (Equbal et al., 2010; Roy & Mukhopadhyay, 2020).

• **Subsurface damage progression:** Link observed wear rates to subsurface crack nucleation and propagation mechanisms influenced by interlayer adhesion and filler-matrix interface strength (Srinivasan et al., 2020).

Results (Descriptive analysis of findings)

This section synthesizes findings reported across the provided literature and frames them in terms of mechanistic understanding. Because the remit of this article is a deep theoretical-explicative synthesis rather than presentation of novel raw data, results are described as consistent patterns, mechanistic inferences, and contrasting outcomes reported in the literature (Roy & Mukhopadhyay, 2020; Raichur et al., 2024).

Build anisotropy and its tribological consequences

A recurrent observation is that anisotropy induced by layer-by-layer deposition dominates failure initiation during sliding contacts (Srinivasan et al., 2020; Mourya et al., 2023). Parts printed with raster orientations aligned with sliding direction typically display higher apparent wear resistance than those printed with perpendicular rastering, due to better load transfer and reduced interlayer shear. Mechanistically, when sliding causes tensile or shear stresses above local interlayer adhesion strength, delamination initiates and contributes to accelerated material loss (Equbal et al., 2010). This explains studies that report wide variance in wear rates even for nominally identical polymer chemistries when print orientation differs (Roy & Mukhopadhyay, 2020).

Material composition: fillers, fibers, and nanoclays

Incorporation of fillers produces complex, sometimes competing, effects. Carbon fibers and rigid fillers increase stiffness and may reduce contact deformation, leading to lower adhesive wear under some conditions (Srinivasan et al., 2020). Conversely, rigid particulates can act as abrasive third bodies when liberated from the matrix, thereby enhancing abrasive wear if matrix-filler interfacial strength is insufficient (Raichur et al., 2024). Nanoclay reinforcement has been shown to enhance abrasive resistance for PLA composites produced by 3D printing, attributed to improved barrier properties and load-sharing at the microstructural level (Raichur et al., 2024). However, achieving uniform dispersion is critical—agglomerates become stress concentrators

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that accelerate subsurface cracking (Prabhu & Devaraju, 2020).

Solid lubricants and self-lubricating formulations
The addition of solid lubricants—graphite, PTFE, molybdenum disulfide—into the filament matrix or as surface coatings consistently reduces steady-state friction coefficients and can transition the dominant wear mechanism from adhesive to mild abrasive or fatigue regimes (Keshavamurthy et al., 2021). Keshavamurthy et al. (2021) demonstrated that inclusion of solid lubricants in printed composites yields lower friction and reduced mass loss under sliding, presuming good dispersion and stable tribofilm formation. Yet, the long-term effectiveness depends on the ability of the lubricant phase to replenish the contact surface under progressive wear; otherwise, short-lived friction reduction is observed followed by accelerated wear once lubricant reservoirs are depleted (Keshavamurthy et al., 2021).

Surface texturing and engineered contact topography
Surface texturing—whether introduced during printing (e.g., patterned rasters) or through post-printing machining—affects the hydrodynamics of third-body flow and can trap debris in valleys, reducing abrasive action on loaded asperities (Mourya et al., 2023). Multiobjective optimization studies show that certain textured geometries reduce friction while limiting wear, but such designs must be balanced against structural integrity and manufacturing complexity (Mourya et al., 2023).

Rheology during deposition and interlayer bonding
Melt rheology governs the degree of polymer chain interdiffusion across layers. High molecular mobility at the interface promotes chain reptation and entanglement, strengthening interlayer bonds and improving resistance to shear-induced delamination during sliding (Dealy, 1992; Chartoff et al., 1994). Conversely, high shear viscosity or rapid cooling can freeze interfaces with incomplete welding, creating weak planes susceptible to crack initiation. Consequently, reporting and controlling melt rheology is essential to interpret tribological outcomes reliably (Dealy, 1992).

Environmental and thermal effects
Ambient humidity and temperature influence polymer surface energy, viscoelastic response, and thus frictional behavior (Chartoff et al., 1994). Additionally, frictional heating during high-speed sliding can locally elevate temperature toward the glass transition, softening the polymer and increasing real area of contact—an effect that may lead to a transition from mild to severe wear regimes (Carey et al., 2011). Thus, tribological testing of FDM polymers must explicitly control or measure thermal conditions at the contact interface (Roy & Mukhopadhyay, 2020).

Third-body dynamics and tribofilms
Several studies report tribofilm formation—either via transfer films from polymer to counterface or via in-situ generation of compacted debris layers—that modifies friction and wear evolution (Equbal et al., 2010; Roy & Mukhopadhyay, 2020). Whether such third-body layers protect the underlying polymer or act as abrasive agents depends on particle hardness, morphology, and adherence. For example, compacted polymer debris that forms a stable, low-shear tribofilm can reduce wear, while hard filler-derived particles embedded in the debris may abrade contacting surfaces more aggressively (Raichur et al., 2024).

Discussion

The descriptive results above can be synthesized into several broad lessons and reveal a set of nuanced trade-offs that complicate straightforward design

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prescriptions. The discussion explores theoretical implications, methodological lessons, practical design suggestions, and limitations of current knowledge.

Interplay of scales: molecular to macro
Tribological behavior arises from a cascade of processes across scales. At the molecular level, polymer chain mobility and crystallinity determine the viscoelastic response that governs adhesive forces and energy dissipation at asperity contacts (Chartoff et al., 1994; Carey et al., 2011). At the micrometer scale, filler particles, interlayer voids, and surface roughness determine contact mechanics and third-body generation. At the macro scale, part geometry and load distribution influence the overall stress state and wear localization. The central theoretical implication is that tribological performance cannot be decoupled from manufacturing physics: rheology during deposition directly sets microstructural variables that determine tribological response (Dealy, 1992).

This nested dependence implies that isolated optimization—e.g., testing a surface coating without considering interlayer adhesion and subsurface damage mechanics—will frequently yield suboptimal or irreproducible outcomes. For reliable improvements, design interventions must address determinants across scales: chemistry (polymer and filler), process (extrusion temperature and cooling profile), and surface engineering (texturing and lubrication). The most promising advances will emerge from integrated optimization that jointly considers these scales (Cano-Vicent et al., 2021; Keshavamurthy et al., 2021).

Trade-offs and competing failure modes
Material stiffening via fiber reinforcement often reduces contact deformation but can increase wear via brittle particle liberation, illustrating a trade-off between bulk mechanical enhancement and third-body-induced abrasion (Raichur et al., 2024). Similarly, solid lubricants reduce friction but may lower bulk strength or complicate rheology during extrusion, leading to poor interlayer bonding. Therefore, designing for tribological performance demands explicit multiobjective optimization where friction, wear rate, toughness, manufacturability, and cost are simultaneously considered (Mourya et al., 2023).

Process control as a design lever
Controlling melt viscosity and thermal gradients during FDM is not merely a process-quality issue but a strategic design lever for tribology. By choosing process windows that maximize chain interdiffusion and minimize trapped porosity, practitioners can significantly enhance subsurface cohesion and reduce delamination-driven wear (Dealy, 1992). This suggests that process monitoring and closed-loop control—tracking nozzle temperature, filament feed, and local thermal fields—could be as impactful as material modifications in improving tribological robustness.

Standardization and reproducibility
A persistent impediment to field-wide progress is the heterogeneity of tribological testing methods and incomplete reporting of printing process parameters. Without standardized protocols and comprehensive metadata reporting, it is challenging to generalize findings and derive transferable design rules. The community should move toward minimal reporting standards for FDM tribology experiments that include detailed filament characterization, full printer process parameters, specimen geometry, counterface description, and environmental conditions (Equbal et al., 2010; Ol'Khovik, 2017).

Mechanistic hypotheses to be tested
Based on the synthesis, several mechanistic hypotheses emerge that can guide focused studies:

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VOLUME 05 ISSUE 09 Pages: 67-76
OCLC – 1368736135

- **Interlayer welding hypothesis:** Improved chain interdiffusion across layers reduces delamination-driven wear under sliding. This hypothesis predicts a monotonic decrease in wear rate with increased effective interlayer entanglement density, controlling for other variables (Dealy, 1992).
- **Filler dispersion–fatigue coupling:** Agglomerated fillers act as subsurface stress concentrators accelerating fatigue-driven particle liberation, while well-dispersed nanoscale fillers enhance load sharing and inhibit crack propagation (Prabhu & Devaraju, 2020; Raichur et al., 2024).
- **Tribofilm resilience model:** The longevity of friction reduction by solid additives depends on their ability to replenish the contact surface through controlled particle migration and matrix-shedding; materials that maintain a steady tribofilm will exhibit lower long-term wear rates (Keshavamurthy et al., 2021).

Testing these hypotheses requires experiments that explicitly measure interlayer molecular connectivity (e.g., using spectroscopic markers or mechanical peel tests), quantify filler dispersion (via micro-CT and SEM), and monitor tribofilm composition and renewal during sliding (FTIR and surface probes) (Chartoff et al., 1994; Raichur et al., 2024).

Limitations and sources of uncertainty

While the integrated framework proposed here is comprehensive, several uncertainties constrain the strength of conclusions. First, many published studies use non-standardized tests with limited replication, yielding variability that complicates meta-analysis (Equbal et al., 2010). Second, proprietary filament formulations and undisclosed processing aids in commercial materials impede reproducibility and mechanistic generalization. Third, the majority of studies examine short-duration wear tests; long-term aging, environmental degradation, and cyclic tribological exposures remain underexplored (Roy & Mukhopadhyay, 2020). Addressing these limitations will require a combination of open-data practices, standardized reporting, and long-duration testing regimes.

Future scope and research agenda

To advance the field toward predictive design and reliable performance, the following research priorities are recommended:

- **Standardized testing protocols and metadata schemas.** Development of community-endorsed protocols for specimen preparation, environmental control, and a standardized set of measurable outputs will accelerate cross-study synthesis and benchmarking (Ol'Khovik, 2017).
- **Multiscale modeling validated by targeted experiments.** Coupled computational models that link melt rheology to interlayer bonding and to mesoscale contact mechanics—calibrated by experiments designed to isolate these links—will enable predictive simulation-driven design (Dealy, 1992).
- **Engineered multifunctional filaments.** Materials combining tailored viscoelastic matrices, dispersed nanofillers, and embedded solid lubricants—designed to balance strength, toughness, and tribological properties—should be developed with attention to extrusion rheology and printability (Keshavamurthy et al., 2021; Raichur et al., 2024).
- **In-situ diagnostics during printing and testing.** Thermal imaging, acoustic emission monitoring, and

inline viscosity sensing can provide real-time indicators of interlayer fusion quality and serve as quality-control metrics predictive of tribological performance.

• **Long-duration and environmental aging studies.** Systematic experiments exploring humidity, temperature cycling, and UV exposure effects on tribological properties will clarify service-life expectations for printed parts (Chartoff et al., 1994).

Conclusion

Fused deposition modelling unlocks tremendous design flexibility but imposes unique microstructural states that challenge traditional assumptions about polymer tribology. This synthesis of the literature reveals clear mechanistic drivers—interlayer cohesion, filler behavior, rheology-driven microstructure, surface topography, and third-body dynamics—that collectively determine friction and wear outcomes for FDM polymers (Cano-Vicent et al., 2021; Roy & Mukhopadhyay, 2020; Keshavamurthy et al., 2021). To transition from empirical trial-and-error toward predictive design, the research community must adopt rigorous, standardized experimental protocols, embrace multiscale mechanistic modeling, and pursue integrated material-process-surface strategies. The path forward requires cross-disciplinary collaboration among polymer scientists, tribologists, and additive manufacturing engineers—working together to produce FDM parts whose tribological performance is reliable, reproducible, and optimized for their intended service environments (Aditya & Srinivas, 2023; Raichur et al., 2024).

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