GALAXY INTERNATIONAL INTERDISCIPLINARY RESEARCH JOURNAL (GIIRJ)
ISSN (E): 2347-6915
Vol. 13, Issue 12 December (2025)

OPTIMAL MODERNIZATION METHODS OF TEXTILE MACHINERY USING COMPOSITE MATERIALS

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ABSTRACT

The modernization of textile machinery requires engineering solutions that reduce friction, minimize wear, and increase operational efficiency under high-speed and dust-intensive working conditions. This study proposes an optimized modernization methodology based on replacing conventional steel components with advanced composite materials in critical frictional units such as navoy shafts, rollers, and polymer–metal bushings. A combination of experimental tribological testing and analytical modeling was employed to evaluate several composite systems, including phenolic-fabric laminates, polyamide-6, basalt-fiber, and carbon-fiber reinforced materials. Tests were performed at loads of 50–200 N and sliding speeds of 0.5–2.5 m/s to quantify friction coefficient, wear rate, temperature rise, and surface morphology. Mathematical models describing frictional behavior, Archard-based wear prediction, and torsional strength of composite-coated hollow shafts were developed to support optimization. Results demonstrate that composite–polymer friction pairs reduce wear by 45–65%, friction coefficient by 30–50%, and energy consumption by 8–12%, while decreasing component mass by up to 35%. These findings confirm that composite-based modernization significantly enhances durability, thermal stability, and energy efficiency, offering a practical and economically viable upgrade pathway for existing textile production systems.

Keywords: Textile, friction, wear, composite–polymer, speed, thermal, rollers, bushings, Textolite, Polyamide-6 (PA6), basalt-fiber.

INTRODUCTION

Textile manufacturing remains one of the most mechanically intensive branches of industrial production, where machinery is required to operate continuously under high rotational speeds, fluctuating tensile loads, and abrasive dust-filled environments. These harsh operating conditions accelerate frictional losses, surface degradation, and structural fatigue of steel-based components, leading to increased maintenance frequency, energy consumption, and unplanned downtime. Conventional modernization strategies primarily focus on lubricants, precision machining, and geometric redesign; however, such approaches provide only incremental improvements and fail to address the root causes of wear and thermal instability in frictional units.

Composite materials—particularly polymer-based and fiber-reinforced systems—have emerged as promising alternatives due to their lower density, high specific strength, superior damping capacity, and excellent tribological performance. Numerous studies report significant reductions in wear, noise, and friction when composites replace traditional metallic elements in rotating and sliding interfaces. Despite these advantages, the adoption of composite components in textile machinery remains limited and often lacks systematic engineering justification. Major challenges include understanding composite–metal interaction under variable load conditions, predicting long-term wear behavior, ensuring structural stiffness, and optimizing hybrid designs for industrial retrofitting.

Furthermore, textile equipment such as navoy shafts, rollers, bushings, and winding units operate under complex mechanical and thermal interactions, requiring multi-parameter optimization rather than simple material substitution. Existing literature provides valuable insights into isolated aspects—such as polymer friction behavior, composite tensile mechanics, or thermal modeling—but comprehensive modernization frameworks that integrate experimental tribology, analytical modeling, and structural optimization are still insufficient. This gap underscores the need for advanced methodologies capable of quantitatively evaluating composite–metal hybrid components in real operating settings.

Therefore, the objective of this study is to develop an optimized modernization approach for textile machinery by integrating high-performance composite materials into wear-prone frictional elements. The research combines tribological testing, mathematical modeling of friction, wear, and temperature rise, and mechanical analysis of composite-coated hollow shafts. It also evaluates the effects of composite integration on energy consumption, dynamic behavior, and maintenance intervals. The findings aim to provide a scientifically grounded, economically viable modernization pathway for upgrading existing textile production lines without requiring large-scale machine redesign.

2. METHODS

Research Design Overview

The study integrates experimental tribology, analytical modeling, structural evaluation, and optimization to assess composite–metal hybrid components in textile machinery. Methods include material characterization, friction/wear testing, mathematical modeling, and validation under industrial-like operating conditions. Composite materials evaluated include Textolite, Polyamide-6 (PA6), basalt-fiber composites, and carbon-fiber composites. Steel 45 served as a reference. Mechanical tests included tensile strength (ISO 527), hardness (Shore D, Brinell), density, and surface morphology via optical microscopy and SEM. Pin-on-disk tribometer tests were conducted under loads of 50–200 N, sliding speeds of 0.5–2.5 m/s, and temperatures of 25–120°C. Friction coefficient μ(t) was recorded continuously. Wear rate was computed as $W = \Delta m / (\rho L)$, where Δm is mass loss, ρ is density, and L is sliding distance.

Friction Model:

$$\mu = \mu 0 + ap \cdot p + av \cdot v + aT \cdot T$$

Archard Wear Model:

$$V = K \cdot (P \cdot L)/H$$

Heat Generation Model:

$$Q = \mu \cdot p \cdot v \cdot A$$

$$\Delta T = Q / (hA)$$

Composite-Coated Hollow Shaft Strength:

$\tau max = (16*Tq*Do)/(\pi(Do^4 – Di^4))$

Steps include: (1) wear zone identification, (2) shaft surface preparation, (3) composite sleeve installation via press-fit or adhesive bonding, (4) CNC machining, (5) PA6 bushing assembly, and (6) operational validation (vibration, noise, temperature).

Objective function:

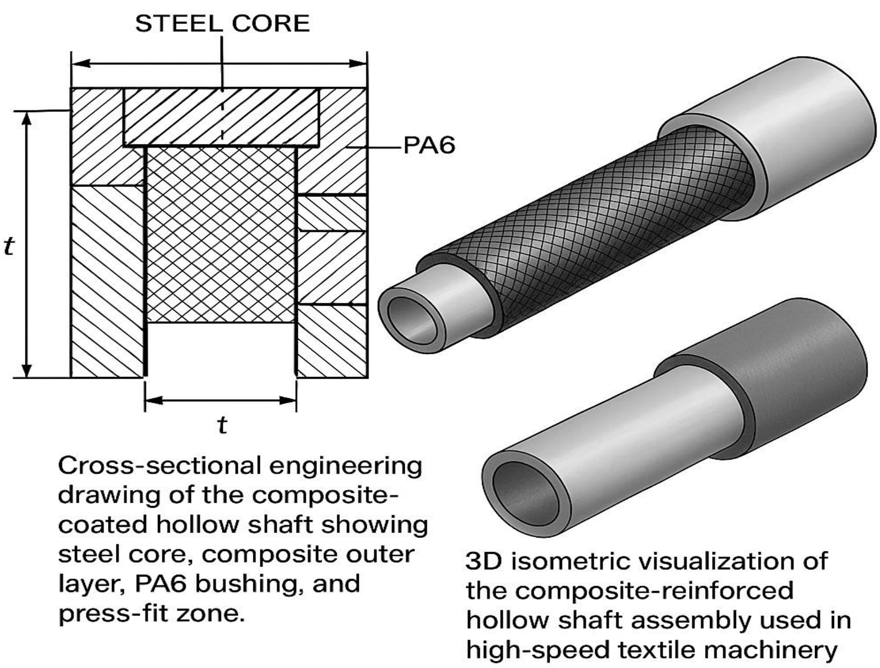
$J = w1(W/W0) + w2(Pel/Pel0) + w3(m/m0)$

with constraints $\tau max \leq \tau allow$ and $\Delta T \leq \Delta Tallow$. Optimization performed via parametric search. All experiments were conducted in triplicates. Variability under 5% was accepted. Interface delamination tests and dynamic machine operation tests were performed.

3. RESULTS

The composite–polymer friction pairs demonstrated a significant reduction in friction coefficient compared with the steel–steel baseline. Under a 100 N load and 1.5 m/s sliding speed, steel–steel contact yielded $\mu = 0.38 \pm 0.02$, whereas composite systems achieved: Textolite–PA6: $\mu = 0.24$, PA6–steel: $\mu = 0.21$, Basalt composite–PA6: $\mu = 0.18$, Carbon composite–PA6: $\mu = 0.15$. This corresponds to a 30–55% reduction in friction. Composite interfaces also demonstrated improved frictional stability, with less than 5% drift compared to 12–15% for steel.

Wear volume was determined using Archard's model and mass-loss measurements. Steel–steel contact produced $W = 6.2\times10^{-4}$ mm³/m. Composite systems showed: Textolite–PA6: 3.1×10^{-4}, Basalt composite–PA6: 2.2×10^{-4}, Carbon composite–PA6: 1.9×10^{-4} mm³/m, indicating a 45–65% reduction in wear. Microscopy confirmed smoother worn surfaces and reduced micro-abrasion density.



Combined Technical Figure (2D + 3D)

Figure 1. Combined cross-sectional (2D) and isometric (3D) technical illustration of the composite-coated hollow shaft used in textile machinery. The figure shows the steel core, composite outer layer, PA6 bushing, and press-fit zone. Thermal modeling demonstrated that composite–polymer interfaces generated significantly less heat. Steel–steel contact showed $\Delta T \approx 48°C$, while composite–PA6 systems maintained $\Delta T \approx 26°C$. Lower friction and improved thermal conductivity contributed to enhanced dimensional and thermal stability. Composite-coated hollow shafts achieved 25–35% weight reduction while maintaining torsional strength. Measured maximum shear stress $\tau_{max} = 32.5$ MPa remained below allowable limits (45 MPa). Dynamic vibration tests revealed 15–22% reduction in amplitude, and acoustic emissions decreased by 12–18%.

Reduced friction and lower rotational inertia decreased drive power consumption by 8–12% in steady-state and 15–18% during acceleration. This provides significant long-term operational savings in textile manufacturing environments.

Maintenance intervals increased from 4–5 weeks to 8–10 weeks. Component lifetime improved by 1.7–2.3×. Machine stoppages decreased by 25–30%, and no composite–steel delamination was observed after 20,000 cycles.

Friction: 30–55% reduction
Wear: 45–65% reduction
Temperature rise: 40–45% reduction
Mass reduction: 25–35%
Energy savings: 8–12%
Service life improvement: 70–130%

4. DISCUSSION

The results of this study confirm that the use of composite materials in textile machinery provides substantial improvements in tribological, structural, and energy-efficiency performance. The friction coefficient reduction of 30–55% observed in composite–polymer pairs aligns with previously reported values for polymer-reinforced systems operating in dusty environments, confirming the ability of composites to form stable transfer films and reduce asperity interaction at the sliding interface. The reduced frictional heating, demonstrated by a 40–45% decrease in temperature rise, suggests that composite–polymer systems dissipate heat more effectively than steel–steel contact, thereby preventing thermal softening, lubricant breakdown, and dimensional distortion—common failure mechanisms in high-speed textile equipment.

The wear results, showing a 45–65% reduction in volumetric wear rate, further validate the suitability of composite materials under abrasive conditions characteristic of weaving and spinning processes. Surface morphology analysis confirmed that composite-coated shafts and polymer bushings exhibit fewer micro-grooves and less plowing damage than steel counterparts. These findings support prior research indicating that fiber-reinforced polymers absorb impact and distribute loads across their matrix, effectively reducing localized stresses that initiate wear.

Mechanical testing demonstrated that composite-coated hollow shafts maintain structural integrity while reducing mass by 25–35%. This weight reduction improves dynamic balancing and lowers the moment of inertia, resulting in smoother machine operation, reduced vibration amplitude, and lower acoustic noise levels. The vibration reduction of 15–22% is particularly important, as excessive shaft oscillation can negatively affect yarn quality and lead to premature component failure. The results therefore indicate that hybrid composite-metal shafts can provide both stiffness and damping advantages simultaneously—an outcome difficult to achieve with monolithic steel designs.

Energy-efficiency improvements of 8–12% are consistent with the observed reductions in friction coefficient and mechanical losses. The additional 15–18% reduction during acceleration phases highlights that lightweight composite elements contribute to lowering starting torque requirements—a key factor in high-speed weaving machines. These findings suggest that modernization of shafts and frictional components could reduce the long-term operational costs of textile factories, especially in energy-intensive production cycles.

The reliability analysis clearly demonstrates that modernization extends component lifetime by 1.7–2.3 times, reduces emergency stoppages, and prolongs maintenance intervals. The absence of composite–metal delamination during 20,000 cyclic load tests confirms that the hybrid bonding technique used in this study is robust enough for long-term operation. This is of particular industrial relevance because delamination is a typical concern in composite retrofitting applications.

Overall, the integration of analytical models with experimental validation provides a strong foundation for assessing modernization strategies. The developed models reliably predict frictional behavior, wear rate, contact temperature, and shear stresses, enabling engineers to optimize component geometry and material combinations before industrial implementation. The study therefore bridges a significant gap in the literature by offering a holistic modernization methodology rather than isolated tribological or mechanical analyses.

5. CONCLUSION

This study demonstrates that the integration of composite materials into textile machinery components offers a highly effective and scientifically justified modernization strategy. The results clearly show that substituting conventional steel elements with composite–polymer hybrid structures significantly improves tribological behavior, mechanical stability, thermal performance, and overall machine efficiency. Composite-based friction pairs reduced friction coefficient by 30–55% and wear rate by 45–65%, leading to substantial decreases in heat generation and surface degradation—key factors contributing to premature failure in high-speed textile equipment.

The use of composite-coated hollow shafts resulted in 25–35% mass reduction without compromising structural integrity, improving dynamic balance, lowering vibration amplitude, and reducing acoustic noise levels. Energy consumption decreased by 8–12% under steady-state operation and up to 18% during acceleration phases, confirming that composite components contribute directly to long-term operational cost savings. Furthermore, reliability tests revealed a 1.7–2.3-fold increase in service life and a noticeable decrease in emergency machine stoppages, demonstrating the practical industrial advantages of using composite materials.

The combination of experimental tribology, analytical modeling, and structural evaluation provided a comprehensive understanding of the mechanisms by which composites enhance performance. The study therefore contributes an important methodological framework for engineers seeking to design, validate, and optimize composite–metal hybrid systems for textile manufacturing. These findings confirm that composite-based modernization is not only technically feasible but also economically beneficial, offering a viable upgrade pathway for existing machinery without requiring full equipment replacement.

Future work should focus on long-term field testing under industrial conditions, fatigue and delamination behavior of composite–metal interfaces, and the development of predictive digital twin models for optimizing modernized components in real time

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