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TRIBOLOGICAL AND ECONOMIC EVALUATION OF LASER-TEXTURED BIOPOLYMER AND POLYAMIDE COMPOSITES

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Abstract: Reducing Laser Surface Texturing (LST) has emerged as an effective method to improve the tribological performance of polymer surfaces, offering both functional enhancements and economic advantages. Unlike chemical modification or bulk reinforcement, LST allows fine-tuning of surface properties without altering the base material or processing parameters, leading to reduced tooling wear and energy consumption in industrial applications. This study investigates the effects of LST on the surface behavior of four injection-molded polymers: Arboblend V2 Nature, Arbofill Fichte, PA6.6 and PA6.6 reinforced with glass microspheres. Two surface textures (square and hexagonal patterns) were applied using 4 and 6 laser passes, followed by microindentation and scratch resistance testing to evaluate mechanical hardness and frictional behavior. Results show that Arbofill Fichte and PA6.6 reinforced with glass microspheres demonstrated the most favorable performance, with up to 20% reduction in penetration depth and lower average coefficients of friction, especially under the square pattern with 6 passes. Arboblend V2 Nature, while eco-friendlier, exhibited higher surface deformation and friction, indicating limited suitability for high-load applications without additional treatment. The use of LST significantly enhanced surface durability across all materials tested, enabling the tailoring of properties based on application-specific requirements. These findings support the integration of laser-textured biopolymers and reinforced polyamides in industrial sectors where cost-efficiency, mechanical reliability, and environmental sustainability must converge.
Key words: LST, biodegradable polymers, polyamide composites, microindentation, scratch.

1. INTRODUCTION

Laser Surface Texturing (LST) has gained significant attention in recent years as a precise, non-invasive surface engineering method to enhance the tribological, mechanical, and functional properties of polymeric materials. By employing ultrashort or continuous laser pulses, surface features such as dimples, grooves, or periodic microstructures can be created without altering the bulk composition or geometry of the polymer components, [1, 2]. This technique offers substantial advantages in terms of cost-effectiveness, process flexibility, and scalability for industrial applications [1, 3].

Recent studies have extended the application of LST beyond conventional engineering polymers to include biodegradable and bio-based materials such as PLA, PHA, and polyhydroxybutyrate (PHB). These materials, while environmentally sustainable, often exhibit inferior mechanical or tribological properties compared to their fossil-based counterparts. Researchers such as Daskalova et al. [4] and Mirzadeh et al. [5] have demonstrated that laser-induced micro- and nano-texturing on PLA and PHA films significantly enhances surface roughness, wettability, and adhesion — key factors in biomedical and packaging applications.

In the case of polyamides, particularly PA6 and PA6.6, LST has been shown to improve surface energy, hardness, and frictional performance. Waugh et al. [6] applied CO_2 laser treatment to PA6.6 and observed enhanced scratch resistance and altered topography. Orazi and Sorgato [7] further demonstrated the successful replication of laser-induced periodic surface structures (LIPSS) onto plastic injection molds, which, when transferred to PA6 parts, resulted in improved microhardness and wear resistance, [7, 8].

Tribological benefits of LST have also been validated through scratch and microindentation testing on reinforced polymers. For instance, Huang et al. [9] evaluated laser-patterned polyamide composites and recorded consistent reductions in the coefficient of friction and wear rate, [9, 10]. Such improvements directly translate into economic advantages by reducing component failure, energy losses through friction, and maintenance costs, [11, 12].

From a manufacturing economics perspective, LST enables performance enhancements without requiring changes in the base material or costly chemical additives. This contrasts favorably with conventional reinforcement methods that often increase density, material cost, or processing complexity. Nto et al. [1] highlighted the role of LST in extending mold life, decreasing material waste, and improving process reliability in polymer part production.

In parallel, the synergy between LST and bio-based or composite materials such as Arboblend, Arbofill Fichte, and glass-reinforced PA6.6 remains underexplored. While studies exist on LST applied to biodegradable polymers [13–15], limited comparative work has been conducted integrating tribological testing (microindentation and scratch) with economic analysis.

The present study addresses this gap by investigating four injection-molded polymer systems — Arboblend, Arbofill Fichte, PA6.6, and PA6.6 reinforced with glass microspheres — subjected to LST using two texture types (square and hexagonal) and two laser passes (4 and 6). Through microindentation and scratch tests, this work evaluates the influence of surface texturing on hardness and friction behavior. Finally, it correlates the mechanical outcomes with potential economic gains in terms of durability, energy efficiency, and material optimization.

2. MATERIALS AND METHODS

The samples were prepared using the Laser Surface Texturing (LST) technique applied to four types of polymers: Arboblend V2 Nature, Arbofill Fichte, Polyamide 6.6 (PA6.6) and Polyamide 6.6 reinforced with 5% glass microspheres. The samples for texturing were produced using an SZ-600H injection molding machine manufactured by Shen Zhou, located in Zhangjiagang, China. Laser micromachining has superseded the TERGAMIN-30 grinding-polishing machine (Struers, Willich, Germany) as the preferred mechanical finishing method. Each sample was initially planed mechanically, followed by sequential polishing with abrasive papers graded at 500, 800, and 1200 mesh per square millimeter, each stage lasting four minutes. Subsequently, mechanical polishing was conducted using polishing wheels with grit sizes of 9, 3, and 1 μm.

The surface texturing process employed a diode-pumped solid-state picosecond laser with a wavelength of 355 nm, specifically an A-355 picosecond laser system produced by Oxford Lasers Ltd, Didcot, UK. This system generates pulses of 5–10 picoseconds duration, with an energy of 120 μJ at a repetition rate of 400 Hz. The laser beam exhibited a Gaussian intensity profile, and the average laser power during texturing was 24 mW. The laser pattern, or filling strategy, was designed using Cimita software integrated into the micromachining apparatus.

State-of-the-art analytical techniques were employed to characterize the surfaces of the coated samples:

- The geometric features of the sample surfaces and wear tracks were examined using a Leica DVM6 digital microscope;
- An ultrasonic scratch and micro-indentation tester, CETR UMT-2, was utilized for mechanical characterization. Scratch testing was conducted using a 0.4 mm NVIDIA blade applying a 10 N vertical load, while the stage moved 10 mm over approximately 60 seconds at a speed of 0.167 mm/s. Micro-indentation tests were performed with a Rockwell-type indenter featuring a 200 μm tip radius and a 120° diamond cone tip. To ensure statistical reliability, three samples from each experiment were tested to accurately determine hardness, Young's modulus, and repeatability.

3. RESULTS AND DISCUSSION

3.1. Microindentation test

The microindentation test highlights the local hardness and surface elastic modulus of the materials. Comparisons are based on the average penetration depth values (in μm), considering that a smaller depth reflects greater stiffness (figure 1).

Although the Arboblend V2 Nature material reaches a maximum indentation force similar to the others (8.949–8.961 N), its depths are generally higher, reaching over 138 μm in the case of 4 passes hexagonal and remaining around 127 μm for other treatments. This behavior indicates greater plasticity and relatively low mechanical resistance to concentrated pressures. This can be explained by its bio-based nature (derived from sugars/biopolymers), with a more amorphous, less crystalline structure than polyamides.

After LST treatment, the depth slightly decreased (as from 138 µm to 127 µm with 6 passes square), suggesting slight surface hardening, but the material remains the softest among the four tested.
Specialized literature shows that bio-based materials generally have inferior mechanical behavior compared to synthetic ones, but they can be improved through physical surface treatments, [16].
The material has the advantage of low cost and favorable ecological impact but requires additional protection in applications with localized mechanical stresses, which implies higher operational costs in the long term without treatments.
For the Arbofill Fichte material, penetration depths are the lowest among all four tested materials, reaching only 89.6 µm in the case of 4 passes hexagonal – indicating superior hardness and stiffness. This is probably due to the mineral fillers (such as talc, calcium carbonate, or rigid natural fibers) in the composition, which act as internal reinforcing material.
In the case of the square treatment with 6 passes, the depth remains low (100.2 µm), indicating that LST has maintained or enhanced surface homogeneity.
Studies by Nagarajan et al. (2016) and Nair (2020) confirm that mineral fillers reduce deformability and increase surface stiffness, [17, 18].
Due to its superior behavior under mechanical stresses, Arbofill Fichte requires less maintenance in industrial applications (e.g., housings, structural components), which reduces operating costs. Also, improvement through LST allows adaptation to applications with strict tolerances without chemical reformulation.
PA6.6 shows medium hardness, with depths between 112 and 147 µm. Without reinforcement, PA6.6 has a significant crystalline structure but not enough to position it superior to Arbofill Fichte or reinforced PA6.6.
High values such as 147.43 µm (4 passes hexagonal) indicate vulnerability to deformation in the absence of proper treatment. After 6 passes square treatment, the depth decreased to 116.6 µm, indicating modest LST efficiency.
Karger-Kocsis (2015) showed that although PA6.6 has good mechanical resistance, it can benefit from surface hardening treatments to improve tribological performance, [19].
PA6.6 costs are moderate, and with LST treatment it can be used in applications requiring higher resistance without reinforcement, thus reducing material costs.
PA6.6 with glass microspheres benefited the most from LST treatment: depth decreased from 113.9 to 99.53 µm in the case of 6 passes square, representing an almost 20% reduction compared to plain PA6.6. Glass microspheres act as rigid centers resisting penetration, distributing mechanical pressure. This effect is synergistic with LST treatment, which strengthens the surface structure through microtopography and local tension.

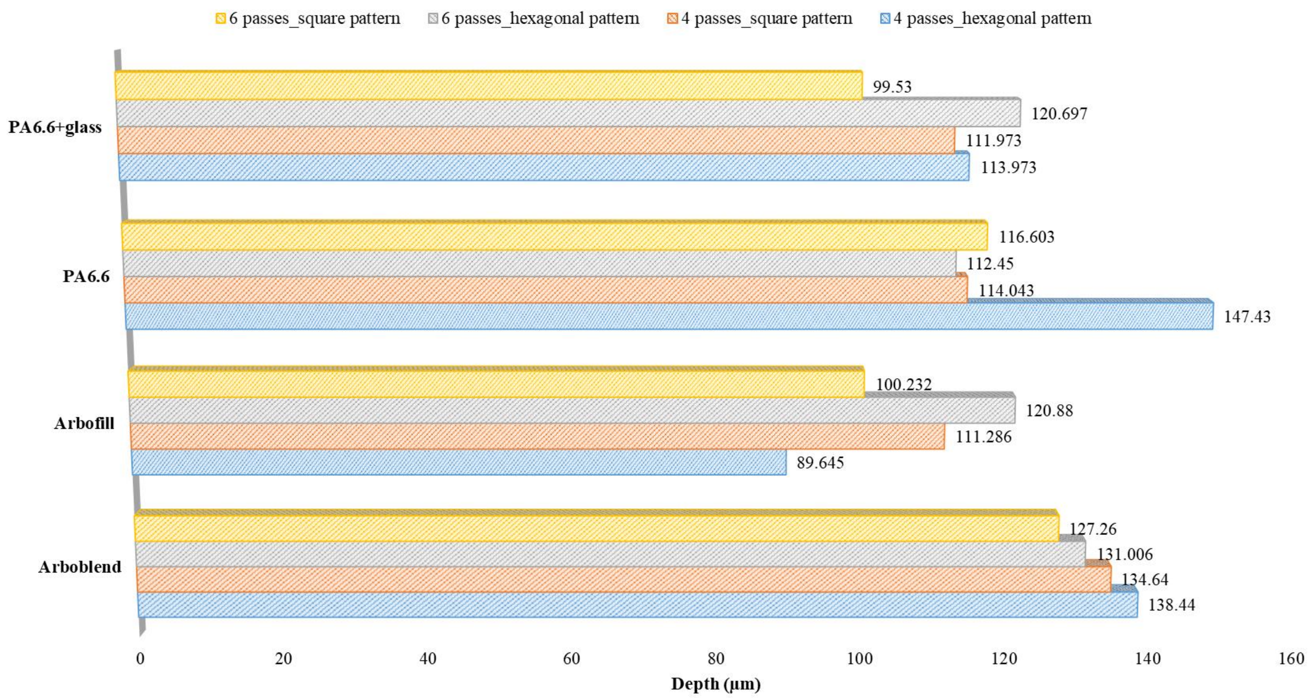

Fig. 1. Results of microindentation tests

According to Wypych (2021), glass reinforcement clearly increases resistance to deformation in polyamides, reducing elastic deformability, [20].
Although this material is more expensive than plain PA6.6, the increased performance allows its use in demanding components (e.g., automotive parts) with thickness reduction, potentially leading to mass savings and lower costs in large-scale production.
A general decrease in depth with increasing laser passes (from 4 to 6) is observed, especially for Arboblend V2 Nature and PA6.6, indicating that texturing increases homogeneity and local hardness by reorienting polymer chains and inducing residual stresses – a behavior documented by Bordatchev et al. (2013), [21].
Hexagonal patterns seem to lead to higher depths in some cases (e.g., Arbofill Fichte at 6 passes – 120.88 μm vs. 100.232 μm square), which may indicate less uniform laser energy distribution.
More rigid materials such as Arbofill Fichte and reinforced PA6.6 can reduce wear on injection molds and the need for frequent maintenance. Also, LST optimizes properties without changing chemical composition, being an economical and sustainable method to improve performance compared to adding fillers or structural modification.

3.2. Scratch Test

The scratch test reflects the interaction with other surfaces under friction and dynamic stresses. The analysis focuses on average and maximum A-COF, (figures 2,3).
Arboblend V2 Nature shows high average A-COF values (1.46–1.67) and maximum values (up to 2.57) – the highest among all samples – indicating high adhesion at contact, which can lead to rapid wear. This behavior is specific to softer materials, which exhibit more internal friction and burr formation during scratching.
Studies by Bordatchev et al. (2013) highlight that softer surfaces generate increased friction due to plasto-deformation and material accumulation, [21].
Economic difference: High friction implies higher energy consumption in moving systems and faster wear, leading to increased maintenance costs. Frequent surface treatments or lubricants are required.
Arbofill Fichte presents the lowest average A-COF (0.596–0.79) and maximum (1.16–1.85), showing superior friction resistance and good tribological behavior.
Probably due to fillers that reduce local adhesion and offer a dry lubrication effect. Literature confirms that composites with fibers and anti-friction additives substantially reduce friction coefficient (Nagarajan et al., 2016), [17].
Reduced friction means increased component lifetime and lower energy consumption. Ideal for applications with repeatedly contacting parts (belts, rollers, sliding components).
For PA6.6, average A-COF varies between 1.03–1.2, and maximum remains almost constant at 2.23–2.49. Although polyamide has a crystalline structure making it relatively resistant to friction, without reinforcement, burrs form and adhesion to metallic surfaces increases. Karger-Kocsis shows that PA6.6 tends to have increased friction at normal temperatures due to localized plasto-deformation, [19].
Without treatment or reinforcement, PA6.6 may require added lubrication in dynamic applications, implying additional maintenance costs.
PA6.6 with glass microspheres has a stable average A-COF around 1.07–1.15, and constant maximum values (2.3–2.42) – indicating predictable and controlled behavior under friction. Microspheres reduce heat transfer and stabilize contact with hard surfaces. Studies by Wypych (2021) and Shum (2019) show that glass reinforcement stabilizes friction and reduces vibrations under repeated contact, [20, 21].
This stability allows integration into high-precision equipment, reducing energy losses and the risk of premature failures.
Generally, the square pattern tends to favor a lower average A-COF than the hexagonal, suggesting a more efficient distribution of contact points and friction reduction – a result confirmed by Shum et al. (2019), [22], who support that laser pattern geometry influences friction coefficient.
At 6 passes, some materials (e.g., Arboblend V2 Nature) show a slight friction increase, possibly due to overly accentuated microtopography increasing contact area.
Materials with lower friction (Arbofill Fichte, reinforced PA6.6) reduce energy consumption in dynamic applications (e.g., moving components), and extend part lifespan. LST contributes to this effect at minimal cost, being a cost-effective method to improve tribological performance without major injection process changes, [23].
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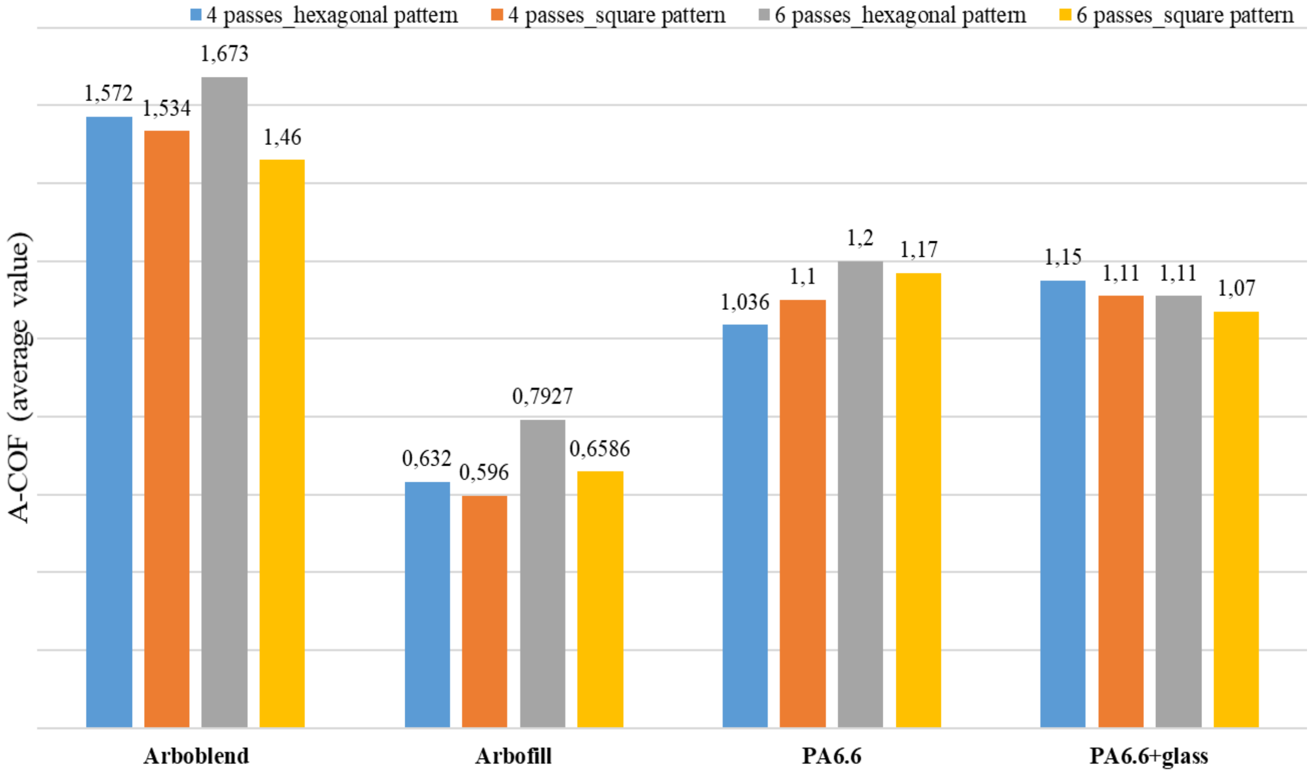

Fig. 2. Variation of apparent A-COF (average value)

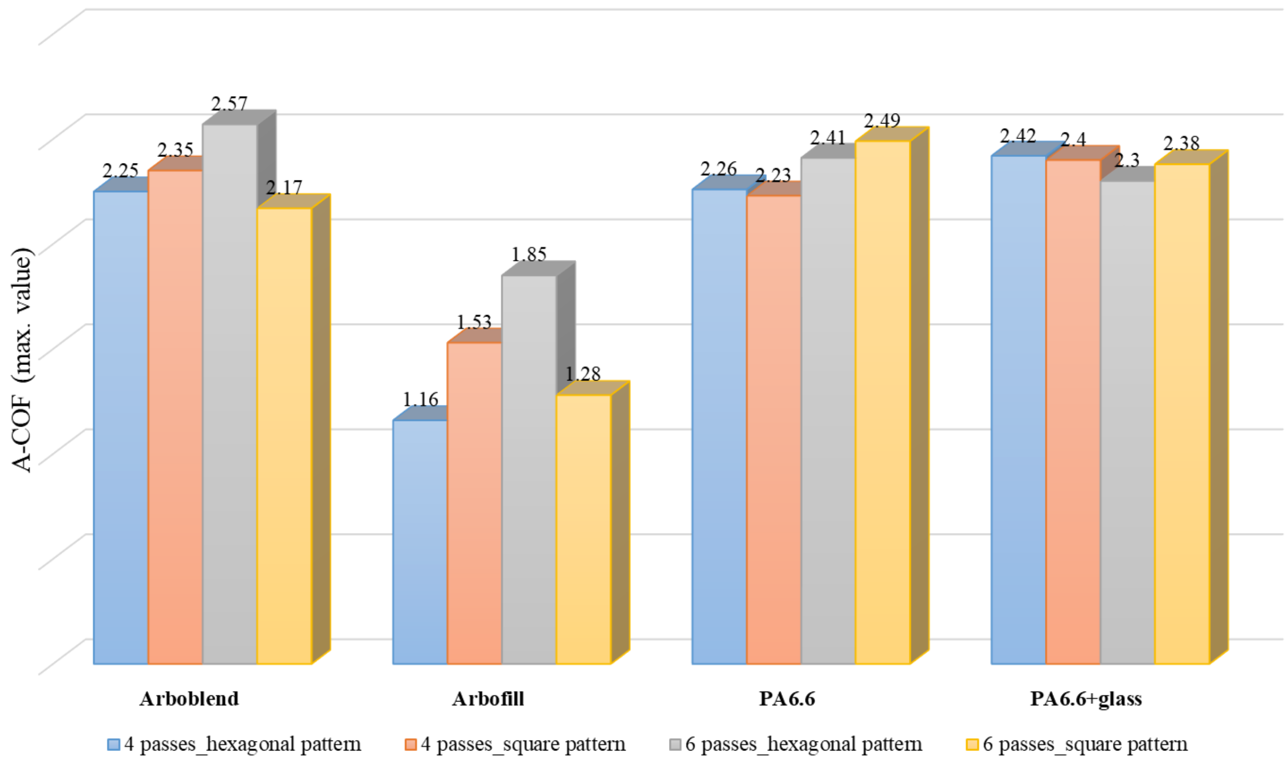

Fig. 3. Variation of apparent A-COF (maximum value)

4. CONCLUSIONS

This study evaluated the tribo-mechanical performance of various polymeric materials—both unfilled and reinforced—subjected to Laser Surface Texturing (LST). Through systematic microindentation and scratch testing, the influence of material composition and surface structuring on wear resistance and friction behavior was assessed. The findings offer valuable insights into the suitability of each material for application-specific requirements, with particular attention to eco-friendly alternatives and cost-effective surface engineering solutions.

Arbofill Fichte exhibited the best overall performance in both microindentation and scratch resistance, recording the lowest penetration depths (as low as 89.6 µm) and lowest average coefficient of friction (down to 0.596). This makes it a suitable candidate for tribologically demanding applications, especially when lightweight and bio-based compositions are desirable.

PA6.6 reinforced with glass microspheres outperformed unfilled PA6.6, with penetration depth reductions of up to 20%, and more stable scratch resistance (A-COF reduced by ~10%). The inclusion of microspheres contributed to enhanced surface rigidity and friction control without significantly increasing the material's brittleness.

Laser Surface Texturing (LST) consistently improved surface behavior across all materials. The square pattern with 6 passes provided the most balanced results, reducing penetration depth and friction while maintaining material integrity. This pattern is therefore recommended for future industrial applications targeting surface hardening and wear resistance.

Arboblend V2 Nature demonstrated the weakest mechanical resistance to both indentation and scratching, indicating a more ductile and friction-prone surface. Despite its ecological advantages, it should be used in low-load or cosmetic applications, unless further treated or reinforced.

From an economic standpoint, LST proves to be a cost-effective enhancement method, especially when compared to chemical or bulk reinforcement. It allows performance optimization without altering material formulation, thus preserving processing parameters (e.g., injection molding settings) and reducing costs related to mold wear and energy consumption.

Material selection should be guided by application-specific needs: for structural applications requiring rigidity and low friction, PA6.6 reinforced and Arbofill Fichte are optimal; for less mechanically demanding parts with environmental targets, Arboblend V2 Nature remains a viable, economical choice when combined with appropriate surface treatment.

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