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CHARACTERIZATION OF LASER-TEXTURED SURFACES – A REVIEW

BY

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Abstract. Laser surface texturing (LST) is an advanced and highly versatile technique for tailoring the surface properties of biopolymeric materials, with broad applications in biomedical, automotive, and industrial domains. This review investigates the influence of LST on the mechanical, tribological, thermal, and wettability characteristics of both polymeric and biopolymeric surfaces, with the overarching goal of enhancing their performance and durability. The methodology centers on laser ablation, employed to generate microstructures with various geometries, while optimizing critical processing parameters such as laser fluence, scanning speed, and pulse duration. The review encompasses a wide range of materials, including PLA, PHA, PEEK, HDPE, and PET, examining their responses to laser-induced surface modifications. Experimental investigations include mechanical tests (microhardness, tensile strength), tribological assessments (coefficient of friction, wear resistance), thermal analyses (DSC, TGA), and wettability measurements (contact angle). In addition, the impact of different texturing patterns–such as linear, hexagonal, and circular–is evaluated to determine their specific effects on material behavior.

Keywords: biodegradable polymer; surface texturing, wettability, degradation, friction coefficient, wear resistance.

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1. Introduction

In recent decades, the rapid advancement of material processing technologies has opened new horizons for optimizing the functional performance of surfaces. In this context, surface texturing has emerged as a promising and versatile technique, playing a crucial role in enhancing the physical, mechanical, chemical, and technological properties of materials. Among the many available methods, laser surface texturing (LST) stands out as a cutting-edge solution due to its high precision, energy efficiency, and minimal environmental impact.

Texturing involves modifying the micro- and nano-topography of a surface to achieve specific functionality. It can take various geometric forms–from hemispheres and elliptical cavities to honeycomb patterns and grooves–each tailored to serve distinct purposes such as reducing the coefficient of friction, increasing durability, or improving light absorption. Due to these characteristics, LST is employed in a wide range of industrial and biomedical applications: from automotive components and solar panels to medical implants and microelectronic circuits.

The fundamental principle of laser texturing is based on ablation, a process in which the surface material is melted and evaporated by a focused, high-intensity laser beam. Unlike other methods such as chemical etching or abrasive blasting, laser texturing stands out for its lack of consumables, which leads to reduced operational costs, minimal maintenance, and a safer working environment for operators. This technique allows for precise control over process parameters (such as energy density, depth, and geometry of the micro-cavities), enabling highly tailored surface functionalization for a wide variety of materials including metals, ceramics, and especially biopolymers.

In particular, for biopolymers–biodegradable and biocompatible materials derived from renewable sources–laser texturing holds strategic importance. Biopolymers such as PLA, PHA, and chitosan are widely used in fields such as regenerative medicine, the food and pharmaceutical industries, and eco-friendly applications. Texturing these materials enhances their tribological, mechanical, or wettability properties, which are crucial for integration into biological environments or demanding technical conditions. For instance, in medical implants, textured structures can increase biocompatibility and osteoconductivity, promoting better integration into biological tissues and reducing implant rejection rates.

The applications of LST are supported by extensive experimental research. Recent studies have shown that laser texturing has significantly improved the durability of automotive components, increased the efficiency of electronic devices, and enabled the development of advanced biomedical materials such as textured sutures and customized surgical meshes. In microelectronics, LST contributes to the creation of fine structures on conductive substrates, directly impacting the energy efficiency of devices.

Therefore, laser surface texturing of biopolymer-based materials represents a highly promising research direction, combining material sustainability with high-precision processing efficiency. This technology aligns with both industrial demands for performance and durability, and environmental requirements, opening new perspectives in the design of smart materials and high-tech applications.

2. The Influence of LST on the Properties of Polymers

2.1. The Influence of LST on Mechanical Properties

Laser Surface Texturing (LST) is an advanced method for modifying polymer surfaces, having a significant impact on their mechanical properties. The effect of LST depends on the type of polymer used and the parameters of the laser beam (Silberschmidt *et al.*, 2022).

When evaluating the influence of CO_2 laser irradiation on thin films of poly(L-lactic acid) (PLLA), an increase in microhardness (Table 1) and structural modifications adaptable to cellular requirements were observed. For HDPE and PET, tensile tests revealed a significant decrease in tensile strength: 27% for HDPE and 46% for PET (Fig. 1), (Di Siena *et al.*, 2023).

Table 1

Micromechanical properties presented as mean and standard deviation (X ± SD) determined by indentation testing for reference and irradiated samples (Tomanik et al., 2020)

Type of specimen	EIT (GPa)	HIT (MPa)	HV	hm (µm)	Noi (nJ)	Wp (nJ)
Ref	2.1 ± 0.9	200.5 ± 53.2	18.9 ± 5.0	6.1 ± 0.9	116.0 ± 46.7	145.7 ± 27.3
F1	3.4 ± 0.8	300.2 ± 54.9	28.3 ± 5.2	4.7 ± 0.5	80.6 ± 13.0	113.4 ± 5.6
F2	4.1 ± 1.0	429.6 ± 205.8	40.5 ± 19.4	4.3 ± 0.7	73.6 ± 7.3	117.3 ± 9.3
F3	0.4 ± 0.03	115.9 ± 17.7	10.9 ± 1.7	1.2 ± 0.4	376.6 ± 40.2	166.7 ± 25.0

Legend: E_{IT} - Young's modulus, H_{IT} - instrumented microhardness, HV -Vickers microhardness , hm - maximum indentation depth, We - elastic deformation energy, Wp - plastic deformation energy.

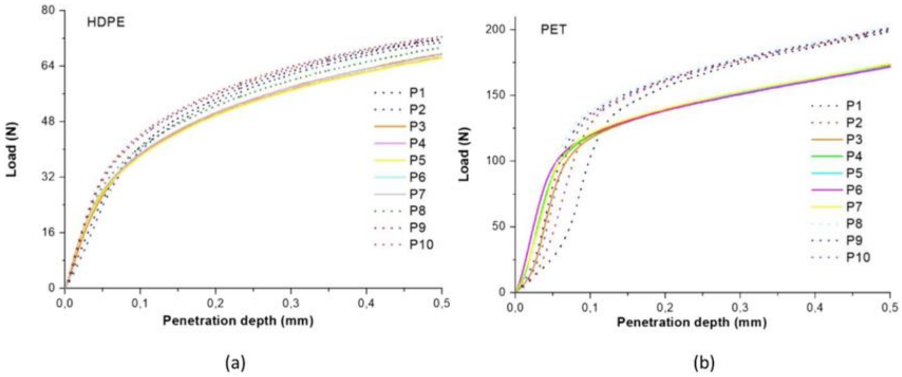


Fig. 1 – Results of FIMEC test on HDPE (a) and PET (b), (Di Siena *et al*., 2023).

The analysis of surface roughness modifications of PEEK and PEKK after laser treatments (Er:YAG, Nd:YAG, diode, femtosecond) was conducted using SEM imaging (Fig. 2), revealing distinct topographies for each type of treatment (Asik *et al*., 2023*)*. Laser texturing of polyethylene (PE) for adhesive bonding confirmed substantial increases in bond strength: 281% for circular textures and 491% for linear ones (Table 2), (Tofil *et al*., 2023).

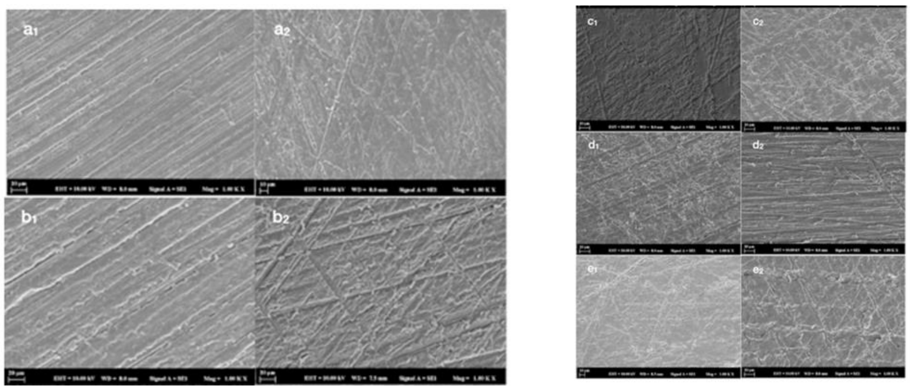


Fig. 2 – Scanning electron micro graphs (original magnification ×1000) of different surface treat ments. a1:PEEK Control, a2: PEKK Control, b1: PEEK Er: YAG Laser, b2: PEKK Er: YAG Laser, c1: PEEK Nd: YAG Laser, c2: PEKK Nd: YAG Laser, d1: PEEK Diode Laser, d2: PEKK Diode Laser, e1: PEEK Femtosecond Laser, e2: PEKK Femtosecond Laser (Asik *et al*., 2023).

Table 2
Average joint breaking strength results (Tofil et al., 2023)

	PE without Micropattern	PE with Circle Micropattern	PE with Perpendicular Lines Micropattern
Measurement 1, N	55	145	252
Measurement 2, N	42	134	235
Measurement 3, N	56	140	241
Measurement 4, N	48	138	249
Measurement 5, N	50	149	255
Average, N	50.2	141.2	246.4
Standard deviation, N	5.67	5.89	8.23
Min, N	42	134	235
Max, N	56	149	255
The average increase in strenght, %		281.27	490.84

For the biopolymer Arboblend V2 Nature, tests revealed variations in Young's modulus and microhardness depending on the applied texture and the number of passes (Figs. 4 and 5), (Mazurchevici *et al*., 2023).

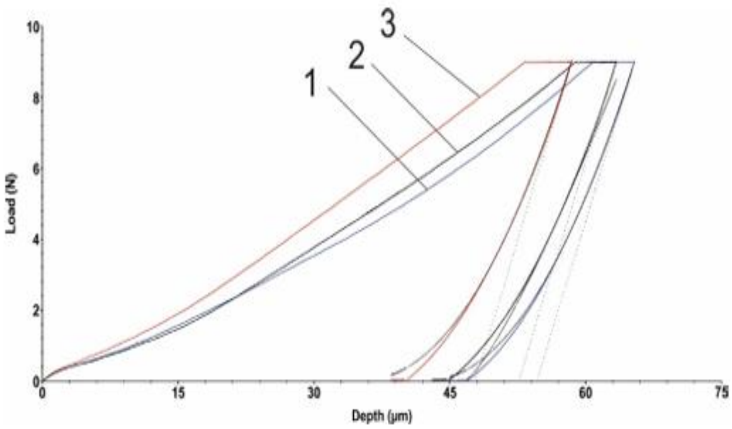


Fig. 3 – Hexagonal texture microindentation test (2 passes): 1, 2, 3–measurement (Mazurchevici *et al*., 2023).

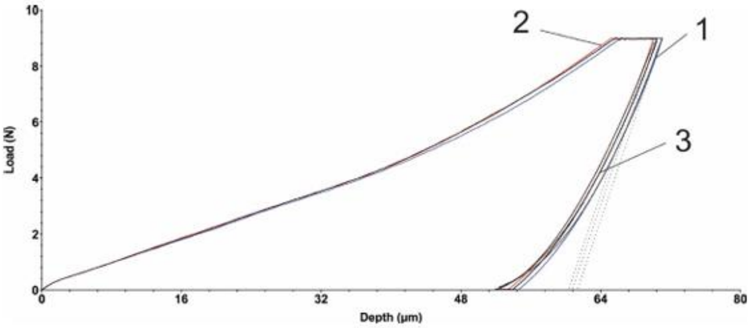


Fig. 4 – Square texture microindentation test (4 passes): 1, 2, 3–measurements (Mazurchevici *et al*., 2023).

The texturing of polyoxymethylene (POM) was optimized using the Grey-Taguchi method, showing that laser power influences texture depth, while scanning speed affects surface roughness. Predictive models exhibited low errors (Fig. 8), (Zhang *et al*., 2023*)*.

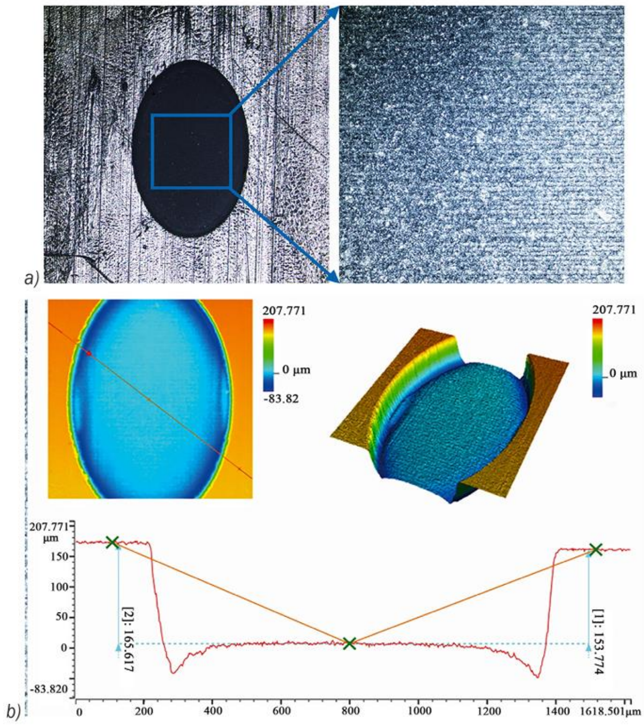


Fig. 5 – Measurement of a) surface roughness and b) depth (Zhang *et al*., 2023).

2.2. Improvement of Surface Tribological Behavior

Improving the tribological behavior of surfaces is a major objective in materials engineering, with implications in industries such as automotive, aerospace, and biomedical. Recent studies show that controlled textures can reduce the coefficient of friction by up to 80% (Table 3) and influence wear mechanisms including adhesion, abrasion, and fatigue (Fig. 6), (Han *et al*., 2010).

The influence of texture geometry parameters on tribological performance is also analyzed, demonstrating that a higher aspect ratio can significantly reduce kinetic friction (Fig. 7), (Yasaka *et al*., 2016). Laser treatment also increases surface microhardness, as shown in Fig. 8 (Sang *et al*., 2023), and its effects are also observed for materials such as PEEK (Fig. 9), (Tomanik *et al*., 2020).

Table 3
Stable values of friction coefficient for different types of PEEK materials(Sang et al., 2023)

Texture types	No texture	Linear texture	Mesh texture
Coefficient of friction	0.2147	0.1736	0.1428

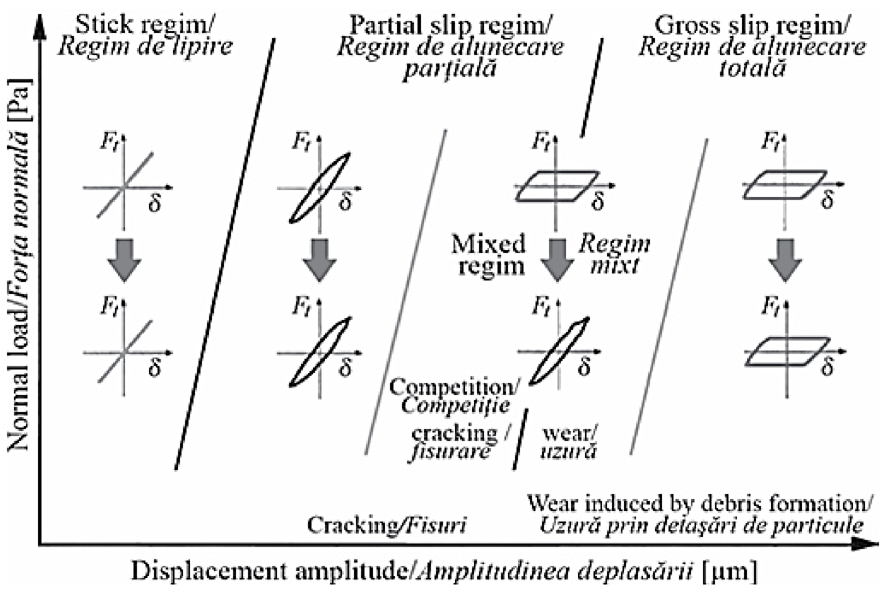


Fig. 6 – Fretting maps (Han *et al.*, 2010).

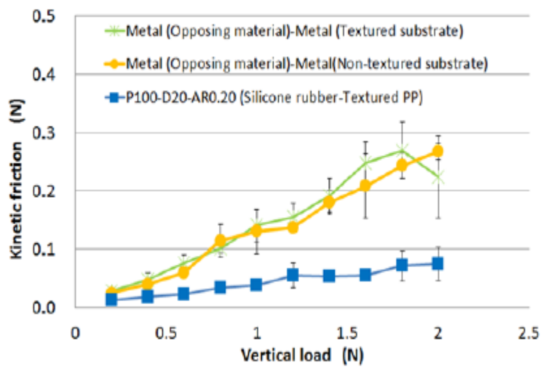


Fig. 7 – Kinetic friction (soft materials vs hard materials),
(Yasaka *et al.*, 2016).

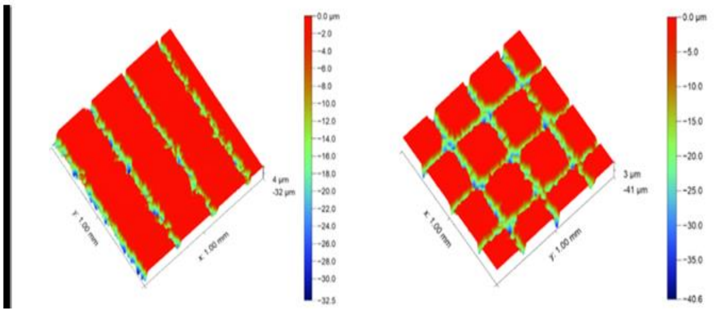


Fig. 8 – 3D morphology of PEEK materials surface with two texture types,
(Sang *et al.*, 2023).

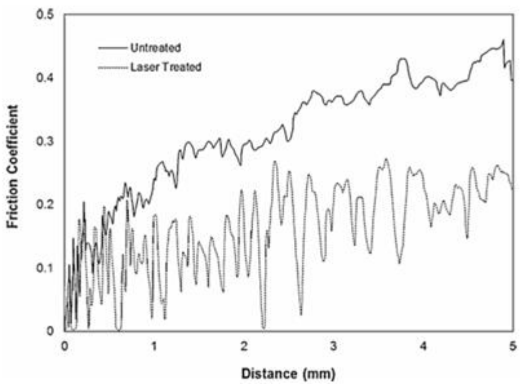


Fig. 9 – Friction coefficient along the laser treated and untreated surfaces,
(Tomanik *et al.*, 2020).

2.3. Analysis of the Thermal Properties of Polymers (DSC- Differential Scanning Calorimetry and TGA - Thermogravimetric Analysis

The knowledge of the thermal properties of polymers is essential for optimizing their processing and performance. Techniques such as DSC and TGA allow the evaluation of thermal stability, glass transition and melting temperatures, as well as behavior under degradation.

Polymers exhibit high thermal stability, with mass loss occurring at temperatures above 350°C. DSC highlights variations in glass transition temperatures depending on chemical composition (Fig. 10), (Yilbas *et al*., 2014). For HDPE and PET, it can be observed that laser irradiation influences crystallinity (Fig. 11), while TGA indicates significant degradation of HDPE at ~482°C, whereas PET shows superior stability (Fig. 12), (Di Siena *et al*., 2023).

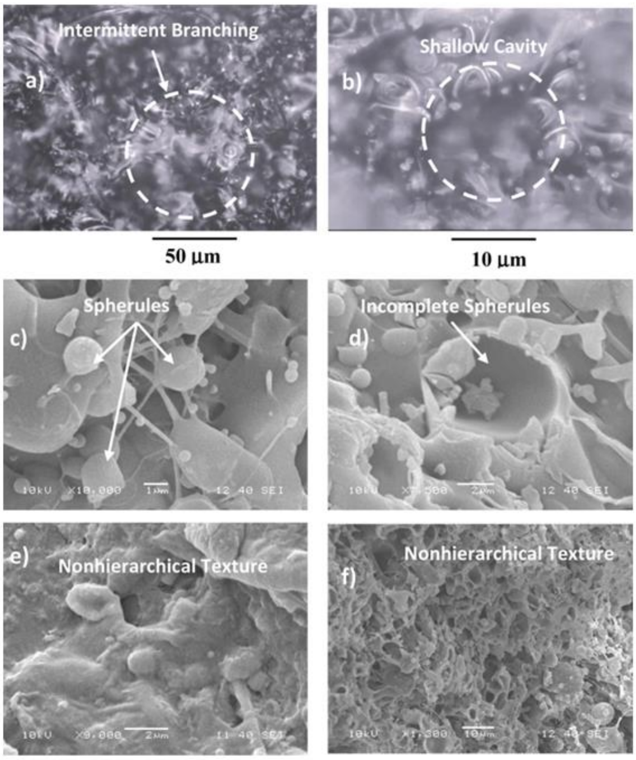


Fig. 10 – Optical images and SEM micrographs of laser treated surface: (a) optical image demonstrating the crystals formed at the surface and radial growth of crystals and intermittent branching, (b) laser produced fine size shallow cavity and spherules, (c) spherules formed at the surface, (d) incomplete spherules, and (e and f) nonhierarchical texture (Yilbas *et al.*, 2014).

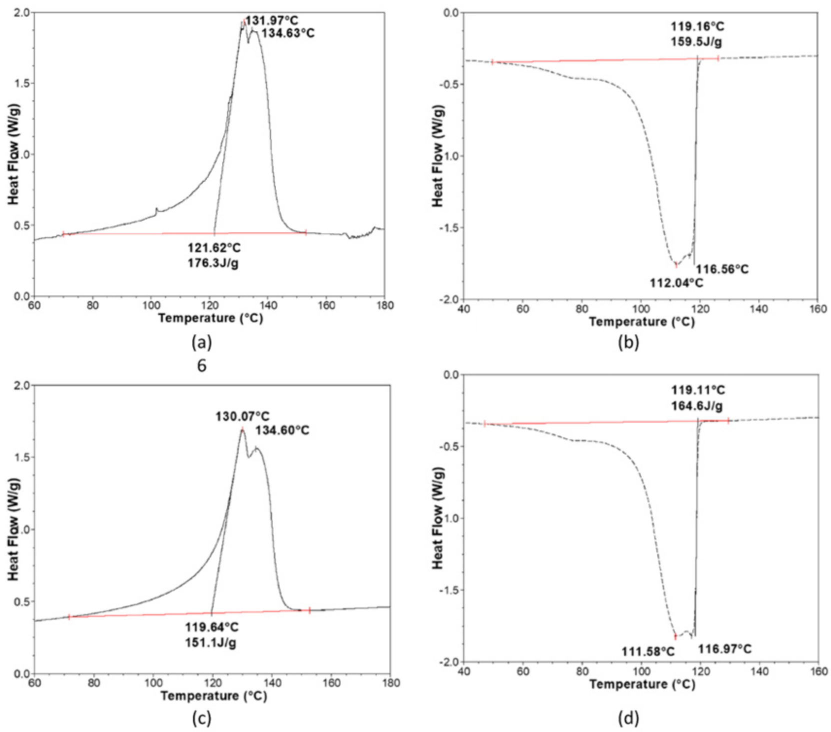


Fig. 11 – DSC curve of irradiated HDPE with both heating/cooling cycles: (a,c) evaluation of the melting temperature and enthalpy respectively during the first and second heating cycles; (b,d) evaluation of the crystallization temperature and enthalpy respectively during the first and second cooling cycles (Di Siena *et al*., 2023).

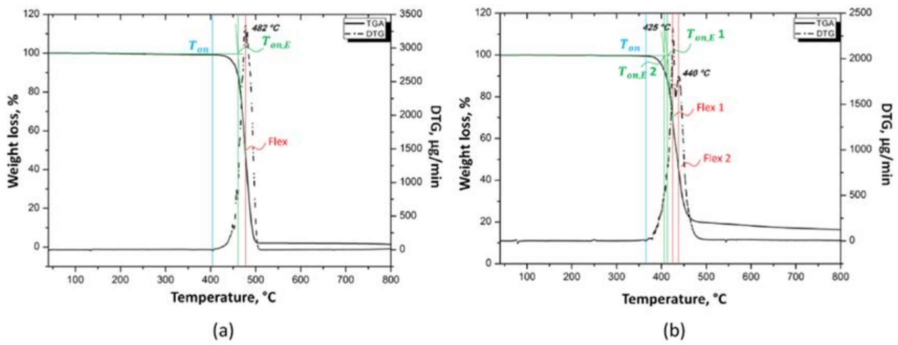


Fig. 12 – TGA curve (solid line) and DTG (dotted line) of HDPE (a) and PET (b), (Di Siena *et al*., 2023).

Laser experiments on PVC, PET, and PP have demonstrated three distinct ablation regimes: non-thermal, thermal, and saturation (Figs. 13 and 14). PVC and PET exhibit glassy-elastic transitions that amplify thermal effects, while PP, with a higher thermal capacity, limits ablation (Bernabeu *et al*., 2023). For PMMA processing with laser, studies on microchannels fabricated by CO_2 laser have shown that laser parameters influence the geometry of the resulting structures (Figs. 15 and 16). The incubation effect reduces the ablation threshold with multiple scans, optimizing processing precision (Li *et al*., 2024).

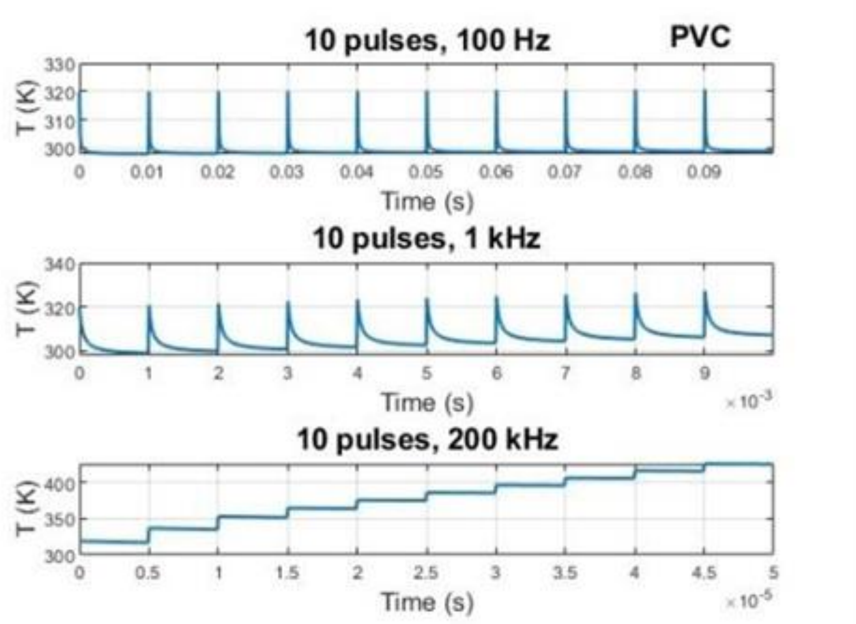
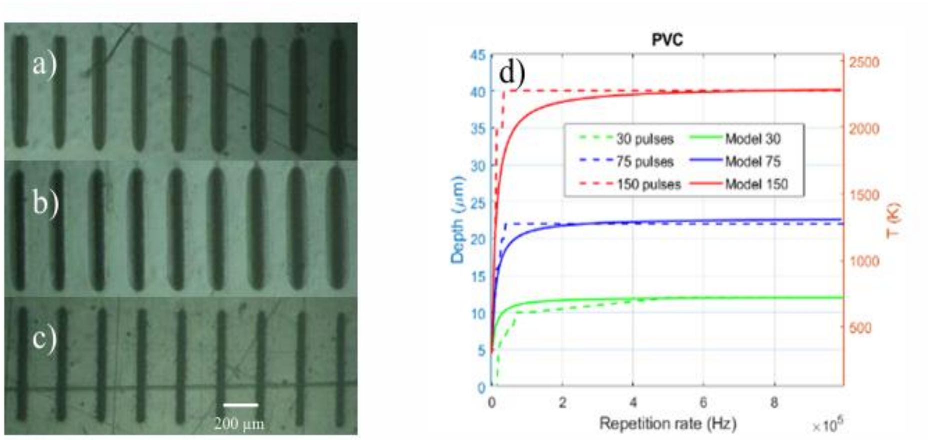


Fig. 13 – Simulations of PVC temperature profile for 10 pulses and 100 Hz, 1 kHz and 200 kHz for λ=515 nm conditions.



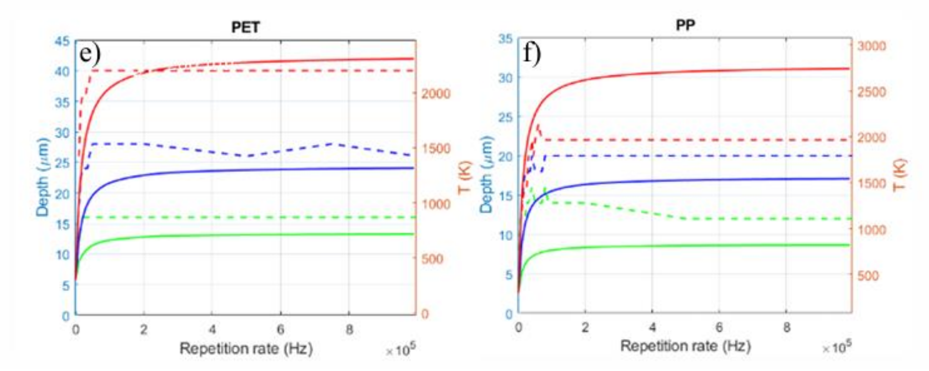


Fig. 14 – PVC (a), PET (b) and PP (c) irradiations at 515 nm with N=150 pulses and frequency increasing from right to left. (d-f) Measured irradiated lines depth (dashed lines, left axis) and temperature simulations at the centre of the spot (continuous lines, right axis) for 30 pulses (green), 75 pulses (blue) and 150 pulses (red)/spot area as functions of repetition rate for PVC (d), PET (e) and PP (f).

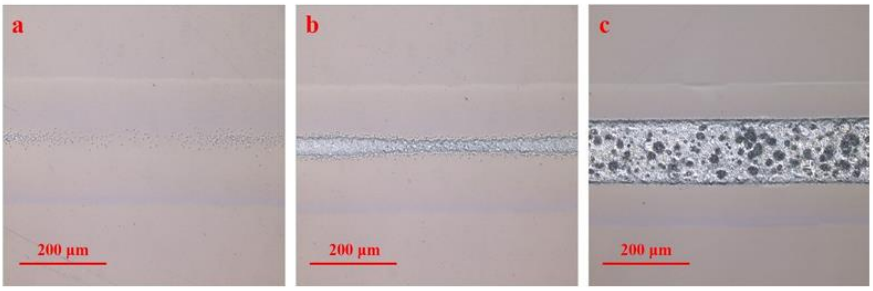
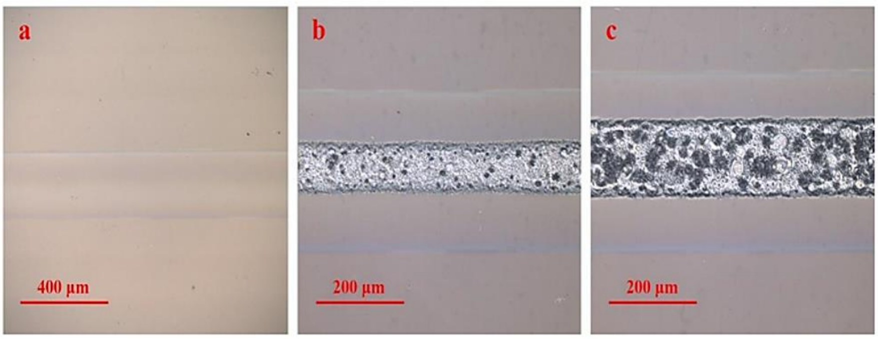


Fig. 15 – Ablation morphology on the surface of PMMA obtained with a single-pass laser scan with the following scanning speeds and laser energy densities: (a) 2700 mm/s, 2.06 J/cm^2; (b) 2600 mm/s, 2.14 J/cm^2; (c) 1800 mm/s, 3.10 J/cm^2.



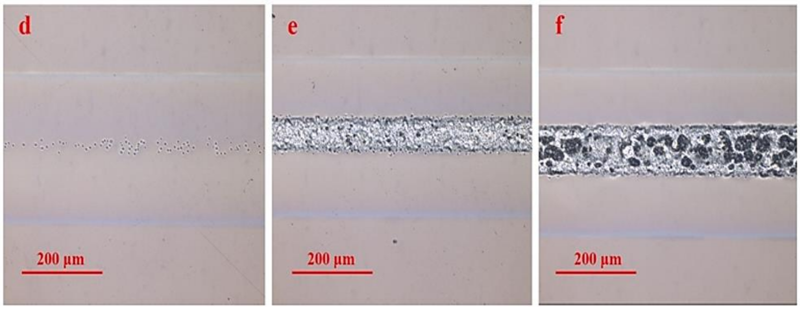


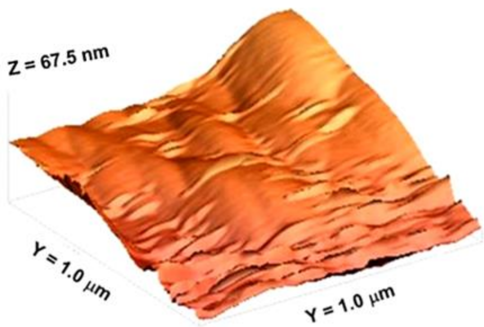
Fig. 16 – Ablation morphology on the surface of PMMA obtained with a multi-pass laser scanning system with the following scanning speeds, scanning numbers, and total laser energy density: (a) 3000 mm/s, 1 pass, 1.86 J/cm^2; (b) 3000 mm/s, 2 pass, 3.71 J/cm^2; (c) 3000 mm/s, 3 pass, 5.57 J/cm^2; (d) 6000 mm/s, 5 pass, 4.64 J/cm^2; (e) 6000 mm/s, 6 pass, 5.57 J/cm^2; (f) 6000 mm/s, 7 pass, 6.50 J/cm^2.

Thermal analysis of polymers is essential for understanding phase transitions, thermal stability, and the impact of laser irradiation. DSC and TGA allow for the optimization of material processing, and the use of CO_2 laser can be adjusted to achieve precise structures while minimizing undesirable thermal effects.

2.4. The Influence of LST on Surface Wettability

Laser Surface Texturing (LST) is a versatile technique used to modify the wettability of surfaces of various materials, influencing the contact angle (CA) between liquids and the surface. Studies have shown that, by optimizing laser parameters, surfaces can become superhydrophobic or superhydrophilic. When analyzing the hydrophobicity of polycarbonate glass treated with a CO_2 laser, the formation of micro/nanometric pores and an increase in roughness are observed (Fig. 17). Contact angle measurements on treated and untreated surfaces revealed significant differences (Fig. 18), (Yilbas *et al.*, 2014).

a)



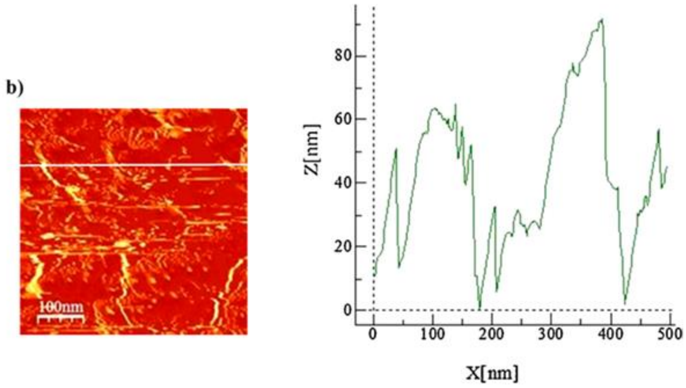


Fig. 17 – AFM images of laser treated surface: (a) 3-dimensional view of laser treated surface, (b) imaged use for surface roughness, and (c) surface roughness along the line shown in the image.

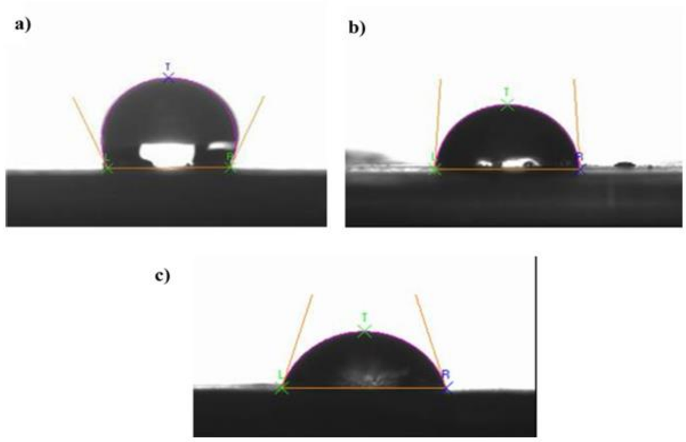


Fig. 18 – Optical images used for contact angle measurements, (a) 125◦contact angle at the laser treated surface, (b) 86.5◦contact angle at the laser treated surface, and (c) 68.4◦contact angle at the untreated surface.

In the study of the influence of processing parameters on the wettability of PTFE, it was demonstrated that higher laser power increases the contact angle due to increased roughness (Fig. 19). The treated surfaces exhibited high chemical and mechanical resistance, making them suitable for self-cleaning applications (Riveiro *et al*., 2020), while for the PVD polymer, the "lotus" effect was observed, where the contact angle increased from 65° to 110° (Choi *et al*., 2021). Another analysis focused on modifying the roughness and wettability of thin films of poly(L-lactic acid) (PLLA) through CO_2 laser irradiation, observing an increase in microstructures and variation in wettability (Figs. 20 and 21), (Tomanik *et al*., 2020).

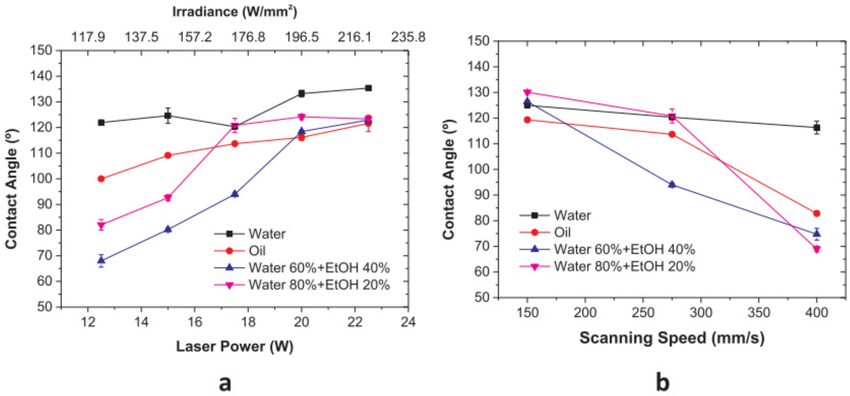


Fig. 19 – Influence of the laser power (Processing conditions: Δx = 0.250 mm, v = 275 mm/s) and scanning speed (Processing conditions: P = 17.5 W, Δx = 0.250 mm) on the contact angle using: water, oil, Water 60%+EtOH 40%, Water 80%+EtOH 20% as test fluids.

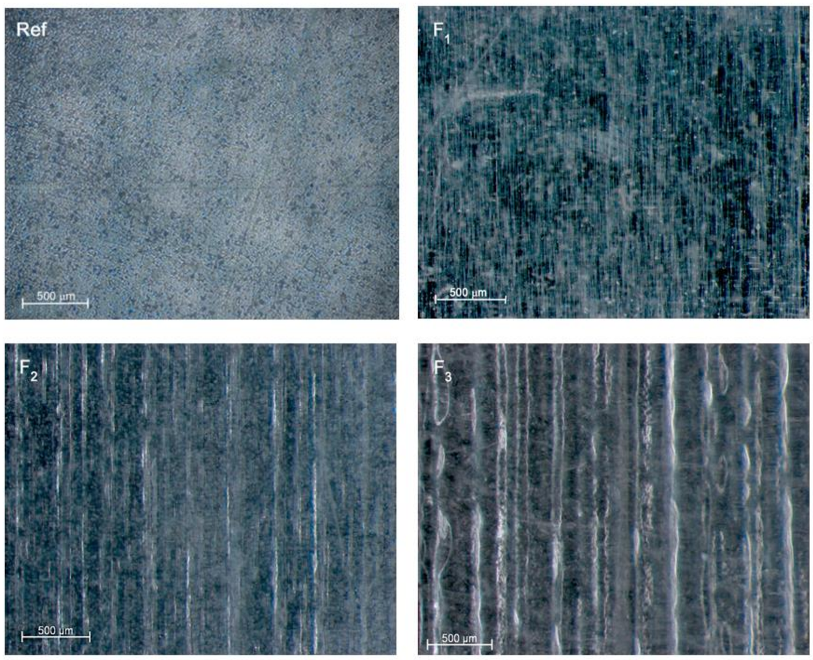


Fig. 20 – Microscopic images of the obtained surfaces (magnification 100×) recorded for the reference material (Ref) and laser-treated with cumulative fluences of 24 J/cm² (F1), 48 J/cm² (F2), and 71 J/cm² (F3).

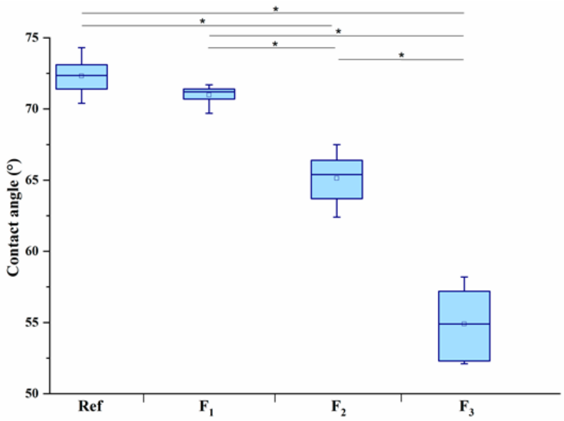


Fig. 21 – Surface wetness modified with different laser parameters; statistical significance between study groups for water and PBS, obtained through one-way ANOVA and post-hoc Tukey tests.

Singh *et al.* (2021) investigated the influence of laser texturing on the wettability and antibacterial properties of metallic, ceramic, and polymeric materials, demonstrating that triangular microtextures reduce hydrophilicity and bacterial density (Fig. 22). Meanwhile, Mazurchevici *et al.* (2023) studied the laser texturing of the biodegradable material Arboblend V2 Nature, highlighting the impact of geometries on the contact angle (Fig. 23). Other studies (Ghadiri Zahrani *et al.*, 2024) used femtosecond lasers to generate spherical and pyramidal textures on polymers, influencing their hydrophobic properties (Fig. 24).

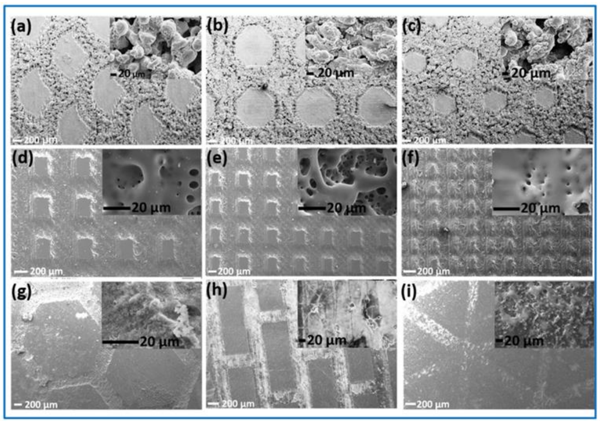


Fig. 22 – SEM images of Ti–6Al–4V: (a) fishscale, (b) octagonal, and (c) hexagonal features, and textured PMMA: (d) large, € medium, and (f) small rectangular features, and textured HAp: (g) hexagonal, (h) brick, and (i) triangular features.

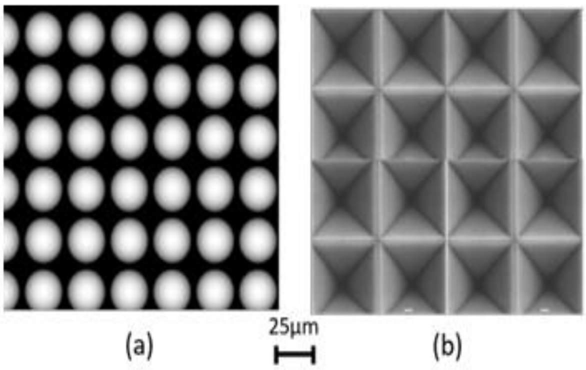


Fig. 23 – Patterns used for laser texturing:
(a) Ball and (b) Pyramid

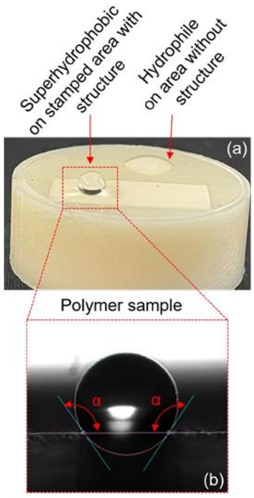


Fig. 24 – (a) Comparison between hydrophobic and hydrophile areas and (b)Measurement of contact angle.

3. Conclusions

Laser surface texturing represents a versatile and powerful method for tailoring the properties of biodegradable polymer surfaces. By precisely controlling the laser parameters, significant improvements in mechanical strength, friction reduction, thermal stability, and wettability can be achieved. The reviewed studies highlight that while moderate laser fluences enhance hardness and reduce friction, excessive fluence may lead to undesirable degradation. Furthermore, the ability to modify surface wettability–ranging from superhydrophilic to superhydrophobic states–opens new avenues in self-cleaning materials and biomedical applications. Future research should focus on further optimizing processing parameters and evaluating long-term performance under operational conditions.

The presented results validate the remarkable potential of Laser Surface Texturing (LST) for the controlled modification of the mechanical properties of polymers, offering the possibility of fine-tuning surface characteristics for specific functional applications. The evident benefits in reducing wear and enhancing surface durability position LST as a viable technological solution for optimizing material performance under demanding industrial conditions.

Moreover, LST's ability to regulate wettability through the manipulation of surface roughness and microstructures opens significant prospects in emerging fields such as advanced materials, self-cleaning surface technologies, and biomedical engineering.

Thus, there is a clear need for continued research to expand the applicability of this technique by optimizing process parameters and exploring its interaction with new classes of materials, in order to fully harness its industrial and scientific potential.

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CARACTERIZAREA SUPRAFEȚELOR TEXTURATE CU LASER – O REVIZUIRE

(Rezumat)

Texturarea suprafețelor cu laser (LST) reprezintă o tehnică avansată și extrem de versatilă pentru modificarea proprietăților suprafețelor biopolimerice, cu aplicații largi în domeniile biomedical, auto și industrial. Această lucrare de sinteză investighează influența LST asupra proprietăților mecanice, tribologice, termice și de umectabilitate ale suprafețelor polimerice și biopolimerice, având ca scop principal îmbunătățirea performanței și durabilității acestora. Metodologia se bazează pe utilizarea ablației laser pentru a genera microstructuri cu diverse geometrii, prin optimizarea parametrilor de procesare esențiali precum fluenta laserului, viteza de scanare și durata pulsului. Studiul

include o gamă variată de materiale, printre care PLA, PHA, PEEK, HDPE și PET, analizând modul în care acestea răspund la modificările induse de texturarea cu laser. Investigațiile experimentale includ teste mecanice (microduritate, rezistență la tracțiune), evaluări tribologice (coeficient de frecare, rezistență la uzură), analize termice (DSC, TGA) şi măsurători de unghi de contact pentru evaluarea umectabilității. În plus, se analizează impactul diferitelor modele de texturare – cum ar fi structurile liniare, hexagonale și circulare – asupra comportamentului materialelor.