

Article

A Review: Laser-Processed Polymers for Biomedical Applications

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Abstract: In addition to their usage in the creation of medical devices, polymer materials hold great promise for advancing a number of critical biomedical applications, most notably tissue engineering. This paper comprises of a general review on laser applications for biomedical using biopolymers, which are natural or synthetic polymers derived from biological sources. They are safe, less toxic and comparatively simple. In this paper, laser processes of polymer biomaterials for hard and soft tissue applications are discussed based on a set of criteria, with biocompatibility being the most important aspect. The paper concludes case studies of laser operations involving different types of medical polymers, as well as the challenges and future directions facing biomedical applications.

Keywords: Biopolymer Materials, Laser Biomedical Applications, Tissue Engineering, Polymer Biomaterials, Medical Polymer Processing

1. Introduction

Over the last decades, the processing of materials by means of lasers has experienced an increasing interest and rapid advances in both scientific research and industrial applications. Ablation with laser pulses, for example, provides very accurate control over the removal of material, which makes it widely used to micro-machine and pattern polymers. Lasers have a very important role in the manufacturing industry owing to their high accuracy and repeatability. Polymers are one of the most important classes of materials for the design and fabrication of scaffolds for tissue engineering, drug delivery platforms, and medical devices. Thus laser interaction with polymers for the modification and functionalization of their surfaces and structures has attracted a growing interest in the last few decades.

Polymers employed in biomedical applications exhibit a delicate balance of properties. Mechanical properties should closely match those of the replaced or repaired tissue. Thermal properties are important during process shaping and sterilization to preserve structural integrity. Surface characteristics critically influence cell interactions; the material must be free of contaminants and maintain biocompatibility, minimizing the immune response. These precautions in selecting polymers are essential for biomedical devices, reinforcing the need for controlled processing techniques such as laser-based modification [1].

2. Overview of Laser Processing Techniques

Laser processing techniques form a vast and interesting field, going far beyond the only possibility of cutting objects, and open many routes to add new functionalities to otherwise conventional surfaces. The large array of materials of interest for biomedical applications including metals, ceramics, polymers, polymeric-ceramic composites, etc., and the several laser-texturing approaches developed to treat them offer a wide range of possibilities. Research on laser structuring of biobased polymers for biomedical and tissue engineering applications has been expanding over the last years. Usually, such polymeric materials are formed and consolidated by processes requiring polymer melting, such as injection moulding, extrusion or hot pressing, causing the loss of biopolymer nanostructures that dictate their final properties. Laser surface texturing might represent a solution at low cost and with minimal environmental impact [2]. Various laser-assisted techniques including surface modification of biomaterials through plasma technologies and laser irradiation have been explored. Laser interference lithography makes possible the micropatterning of biopolymer surfaces; applications include the modification of surface energy and wettability, which, in turn, influence cell adhesion and hydrophilicity. Laser microfabrication and etching allow for controlled cell growth on biopolymers, in addition to the fabrication of nano-structures and surface gratings. Full and open access methods, such as excimer laser patterning of polymers and precision laser micro-processing of polymer surfaces, have been used for polymer surface modifications involving processes like polymer ablation, radiation-induced polymer cross-linking, and polymer crystallization. Laser surface treatments applied to biomedical polymers can improve properties relevant to tissue engineering and bio-implant applications. Such techniques influence surface wettability, adhesion, and biocompatibility, playing a key role in the development of biomedical devices [1].

2.1 Types of Laser Systems

Laser treatment is an advanced, non-contact technique to improve surface characteristics of diverse materials and increase functionality. This technique is a powerful tool for microstructuring surfaces, and many parameters, such as laser energy or number of pulses, can be varied to develop a well-controlled method of surface functionalization. Compared with conventional techniques, ultrafast laser surface treatment offers several advantages: the process is clean, versatile, highly reproducible and reliable, and environmental friendly. Three main types of lasers are used for material processing: continuous-wave (CW), long-pulse (nanosecond to picosecond), and ultrafast-pulse (femtosecond). These laser systems provide a variety of capabilities, such as ablation, drilling, cutting, marking, welding, and surface modification [1]. For many years the most common laser sources in polymer material processing were mainly CO₂ and Nd:YAG laser systems. CO₂ lasers generate high-power laser radiation at around 10.6 μm and are among the most versatile lasers used across the scientific world and industry. Due to their versatility and the high powers achievable, CO₂ lasers have been implemented for many years in the general field of materials processing. They emit radiation within the infra-red (IR) region of the electromagnetic spectrum on rotational-vibrational transitions with wavelengths ranging from 9 to 11 μm. Specific to polymers, IR lasers give rise to resonant coupling in the form of bond and lattice vibrations allowing the processing to be thermolytical [2]. Femtosecond lasers offer the capability of precise processing with negligible collateral damage to the sample. Materials processing at such short durations allows for fast, extremely localized deposition of energy before transfer out of the focal volume occurs. Ultraviolet (UV) excimer lasers represent an extremely versatile tool: they offer relatively small operating wavelengths and high energies per pulse and have been employed for materials processing, medicine, photolithography, and pumping dye lasers. In the processing of polymers, UV lasers lead to the absorption of light through electronic excitation, often within delocalized electron configurations, allowing polymers to have broad absorption features and to directly break polymer bonds due to the high photon energy. Most lasers achieve features on the micron scale; however, nano-structures have been created with lasers emitting at 157 nm.

2.2. Laser Parameters and Their Effects

Laser modification of polymer surfaces is influenced by the type and composition of the polymer, laser parameters, and modification mode. A shift in fluence changes the dominant

modification mechanism from ablation towards melting. Variation in pulse duration affects the heat-affected zone; polymers with high melting temperatures tend to exhibit larger zones, whereas those with moderate melting points and high molecular mass display smaller zones. Materials with higher thermal conductivity produce larger heat-affected zones at long pulse durations but smaller zones at short durations [3].

Generally, increasing pulse duration from femtoseconds to microseconds at constant fluence decreases the ablation rate, while the heat-affected zone grows larger. Elevated fluence and multiple passes (i.e., increased accumulated fluence) enhance ablation depth and material removal. Lower fluences primarily favor surface texturing and structuring without significant mass loss. The emergence of a photomechanically driven ablation regime at femtosecond pulse durations introduces different characteristics compared to longer pulses.

Advanced techniques such as laser interference lithography provide the capability for micropatterning biopolymers. Laser treatment can increase surface wettability and cytocompatibility of biomedical polymers; for instance, polyethylene and poly(L-lactide) films exhibit improved cell interactions and mechanical properties after laser texturing. The combination of ultrashort pulse durations and specific wavelength choices enables non-contact, precise surface functionalization useful in photonics and tissue engineering applications. Alteration of surface energy and wettability through controlled irradiation facilitates enhanced adhesion and growth of biological cells on implants and scaffolds [2].as shown below {Table1}

Table 1. Factors Influencing Laser Modification of Polymer Surfaces.

| Category | Influencing Factor | Effect on Laser Modification |
|--------------------------------|---------------------------------------|---|
| Polymer Properties | Polymer type and composition | Determines dominant mechanism (melting vs. ablation) and thermal behavior |
| | Melting temperature | Higher melting temperature larger heat-affected zone. |
| | Molecular weight | High molecular weight moderate melting point smaller heat-affected zone. |
| | Thermal conductivity | Long pulses: high conductivity larger heat-affected zone Short pulses: high conductivity smaller heat-affected zone. |
| Laser Parameters | Fluence (energy density) | High fluence -ablation dominates Low fluence -surface texturing with minimal mass loss. |
| | Accumulated fluence (multiple passes) | Increased passes deeper ablation and more material removal. |
| | Pulse duration | Longer pulses decrease ablation rate and increase heat-affected zone. |
| | Femtosecond pulses | Introduce photomechanical ablation distinct from longer pulses |
| | Wavelength selection | Enables precise, non-contact surface functionalization |
| Modification Techniques | Laser interference lithography | Enables micro patterning of biopolymers. |

| | | |
|--|---|---|
| Biological and Functional Effects | Surface energy and wettability modification | Improves cell adhesion and growth on biomaterials. |
| | Laser treatment of biomedical polymers (PE, PLLA) | Enhances wettability, cytocompatibility, and mechanical properties. |
| | Ultrashort-pulse treatment | Useful for photonics and tissue-engineering applications |

3. Properties of Polymers Used in Biomedical Applications

Polymers have been largely employed in a wide range of applications, from common packaging materials to highly demanding advanced biomedical devices. With the continuous progress of microfabrication techniques, the use of polymers as substrate materials in micro-electromechanical system (MEMS), microfluidics, microsensors, and micro-optics has steadily increased. Properties such as biocompatibility or optical transparency make certain polymers particularly well suited for applications in biotechnology and biomedical engineering. Biopolymeric materials are increasingly used for varieties of applications as in general they display lower toxicity and higher biocompatibility as compared to conventional materials and often present super hydrophilic or super hydrophobic surfaces. Polymers also exhibit other important properties such as high flexibility, excellent corrosion resistance, and low weight.

Laser surface processing techniques allow the modification of depending on the target polymer properties such as wettability, biocompatibility, reflectance and absorbance, etc. These surface property changes come into advantage for extensive application in areas such as metallization, etching, surface roughening, and surface hardening. In biomedical applications, polytetrafluoroethylene (PTFE) (also known as Teflon) is highly attractive, having excellent properties such as corrosion resistance, high thermal stability, excellent anti-adhesive properties, outstanding biocompatibility, and a low coefficient of friction. For the mentioned features, PTFE finds applications as anti-adhesive coating in instruments, implants, or surgical operating room linen. It is used both in the form of films and membranes.

3.1 Mechanical Properties

Laser processing is an effective technique to tailor the surface of polymers for biomedical applications. Such laser modifications enable precise control over surface properties without affecting the bulk material [4]. Although polymers generally exhibit lower mechanical strength compared to metals or ceramics, outstanding mechanical performance can be achieved by carefully selecting the base polymer and the fabrication method. Besides the intrinsic properties of the bulk polymer, laser processing parameters significantly influence the mechanical response. For example, different beam focusing or scanning speeds may alter residual stresses and, consequently, the final mechanical behaviour [5].

3.2. Thermal Properties

The thermal characteristics of polymers are of paramount importance when considering laser treatment due to their influence on phenomena such as melting, flow, evaporation, and molecular rearrangement during heating. Differential scanning calorimetry (DSC) is a critical analytical technique employed to determine melting temperatures of polymers. Figure 4c,d illustrate the thermograms obtained from the DSC analysis. A single melting endotherm at (177–178)°C is characteristic of the current poly-3-hydroxybutyrate (P(3HB)) samples, aligning with values reported in other studies [3]. The glass transition temperature (T_g) occurs at 60 °C. The crystallinity degree remains at a high level of 76% and exhibits only slight variation regardless of film fabrication method.

3.3 Biocompatibility

Biocompatibility is a crucial property governing the interaction of polymers with a biological environment. Tissue construction is directly influenced by the material's biocompatibility and specific surface properties. Consequently, polymeric biomaterials for tissue engineering are expected to

guarantee biocompatibility, require specific surface properties, and facilitate the formation of tissue on the surface [6]. Adequate biocompatibility can be achieved either by introducing functional groups, such as $-\text{COOH}$ or $-\text{OH}$, into the polymer, or by modifying surface morphology to enhance cell adhesion, proliferation, and infiltration.

4. Applications of Laser-Processed Polymers

The demand for biomedical materials with complex surface morphologies and controlled physico-chemical properties continues to grow exponentially in medical research. Laser processing of polymers encompasses a suite of surface-modification techniques for the fabrication of functional materials, including microstructuring, nanostructuring, and polishing.

Micro-roughness of the surface is of prime importance for biomedical applications, especially when the chemical composition and bulk properties of the material cannot be changed because of strict requirements (e.g., transparency, food contact, and biocompatibility). Surface improvement can be achieved by applying a short-pulse laser to slightly ablate the surface, producing a rough, buttresslike texture that influences the growth of the cells [1]. Nanostructuring of the polymers by laser-induced periodic surface structures (LIPSS) leads to a variety of industrial applications, particularly in biomaterials science. Absorption of the incident laser in the material surface triggers self-organized growth of periodic surface structures whose geometrical/morphological features can be easily varied by controlling the processing parameters [2]. Laser polishing can eliminate the roughness of otherwise smooth polymer surfaces without detrimentally affecting surface chemistry or transparency.

4.1 Tissue Engineering

Scaffolds designed for tissue regeneration are important to tissue engineering. Selective laser sintering is a method used to fabricate biocompatible polymer scaffolds for tissue engineering applications [7]. The biocompatibility and osteogenic potential of human fetal femur-derived cells have been studied on surface selective laser sintered scaffolds. Polycaprolactone scaffolds fabricated through selective laser sintering are widely used in bone tissue engineering. Solid freeform fabrication of hyaluronic acid scaffolds, solvent-free fabrication of porous polymers using solid-state foaming, and laser-guided direct writing of living cells are additional approaches in tissue engineering. Surface functionalization introduced by precisely-defined surface structures is dependent on surface texture and quality. Laser treatment is an advanced, non-contact technique for improving biomaterials surface characteristics. Femtosecond laser modification has been applied to fabricate diverse structures on biodegradable polymer thin films and their ceramic blends [1]. Assessment of surface roughness by atomic force microscopy reveals changes with increasing laser energy and number of applied laser pulses. Induced morphologies produced under different laser parameters are compared via scanning electron microscopy and confocal microscopy analysis. The chemical composition of exposed surfaces is examined by FTIR, X-ray photoelectron spectroscopy, and XRD analysis. Laser microstructuring enables surface functionalization that enhances cellular attachment and orientation. Cultured cells exhibit extended shapes along laser-modified surface zones compared to non-structured areas and demonstrate parallel alignment to the created structures. Considerable processing quality is achievable with femtosecond laser structuring.

4.2 Drug Delivery Systems

Laser processing techniques enable medical-grade polymers to be modified for precise cell growth and drug delivery systems. Selective laser patterning adjusts the degree of hydrophilic modification on polymers utilizing the photo-Fenton reaction and UV irradiation on polyamide 6.6 (PA66), influencing drug release based on the surface chemistry. Controlled hydrophilic patterns facilitate assembly of polymer-liposome blends into locally defined cell culture scaffolds, allowing for independent control of cell adhesion through lipid incorporation [8].

Light-based activation allows for the spatial and temporal regulation of drug delivery in vivo. Used in the fabrication of microchips for on-demand drug delivery, laser-induced two-photon absorption activates polymer-based drug delivery platforms. The technique overcomes the limitations of high-energy UV or visible wavelengths by exploiting the deeper tissue penetration and reduced photodamage associated with near-infrared two-photon radiation [9].

4.3 Medical Devices

Laser processing methods produce a range of structures, from smooth surfaces with micron-sized roughness to microchannels with typical widths of 30 μm , depths up to 10 μm , and minimal heat-affected zones. Patterns of trenches separated by 30 μm can isolate neuronal cell bodies, facilitating studies of cell-to-cell connectivity and neuronal communication. The creation of free-standing, three-dimensional micro-stencils with complex channel shapes aids in cell-growth patterning.

Surgical tools require high strength and corrosion resistance, along with biocompatibility. Laser technologies improve biomedical alloy hardness and surgical tool performance. Fiber lasers offer precise cutting; ultraviolet and ultrashort-pulsed lasers enable clean processing, reducing bacteria and infection risk during surgery. Lasers also facilitate smart cutting, marking, and micro-machining of polymers, ceramics, and composite materials.

Medical implants often benefit from polymer use. Examples include anterior cruciate ligament reconstruction, pacemakers, and recanalization of occlusive blood vessels. Laser processing modifies surface characteristics such as roughness, wettability, and chemical composition, thereby enhancing biological responses. Patterns combining microchannels and micro-holes guide skin cell growth, enabling the development of improved biomaterials for wound healing and tissue engineering. Laser-modified polymers include biodegradable and biocompatible resorbable PEU, PEUU, and PEUOU, in addition to polycaprolactone and poly(3-hydroxybutyrate) (P3HB), which support cell migration and proliferation [10] ; [3] ; [2].

5. Advantages of Laser Processing in Polymer Fabrication

Experimental investigations and numerical simulations conducted with flat-top laser beams have shown that, at sufficiently high laser fluences, there exists a threshold energy density dependent on the beam radius and the probing location along the beam path. This threshold defines the bounds between energy densities leading to no modification, material densification, and void formation. Polymers processed in this manner exhibit the capability to switch between densification and void formation over relatively small spatial modulations of the radiation intensity, whereas glasses exhibit a narrower fluence range for such a transition, accompanied by a gradual recovery of the refractive index in the high-fluence regime where void formation occurs [1].

5.1 Precision and Accuracy

A decisive index of the accuracy of laser micromachining is the size tolerance of the micromachined features, which is primarily dictated by the focal spot diameter, nozzle or nozzle-to-substrate spacing, galvanometer scanning accuracy and stage movement precision. The smaller the processing-dimension scale, the higher the necessary dimensional control. Commercial CNC-laser machines can achieve accuracy within $\pm 1 \mu\text{m}$, which is adequate for machining polymer-based MEMS or microfluidic channels. If a scanning galvanometer is equipped, the large-workpiece stage can also provide local precision up to 1 μm in X and Y, which is well suited for making micro-wells and micro-tanks with high aspect ratios.

The precision and accuracy of polymer machining depend on a variety of factors including the physical and chemical properties of the polymers, the laser processing conditions and the final formation characteristics of the laser-generated features. For example, the predictor thermal displacement of the ablation micro-chamber is related to the thermal properties of materials. For a 1064 nm Nd:YAG laser, the smallest machining feature dimension of PET and PP is approximately 30 μm . Improvements in precision require more compact machine environments, engine control system upgrades to increase soldering homogeneity during part fabrication, heightened galvanometer scanning accuracy and improved stage movement procedures. A fixed-position laser nozzle offers precise mask projection due to its defined placement on the laser head. The blackbody radiation emitted post-ablation acts as a reliable real-time indicator for determining the conclusion of the machining process. If an $f = 300 \mu\text{m}$ lens is incorporated into the scanning galvanometer, the cutting resolution can be enhanced to a few microns. Integrating a throughput exhaust system helps further reduce both the surface roughness and lateral damage of the computed tomography fragment inside the pinhole. Picosecond UV-laser machining can be applied to fabricate micro-scale structures in various polymers. UV wavelengths enable lower thermal damages and sharper edges. A nanosecond UV laser can

manufacture some structures at the micrometer scale, though the structures often suffer from thermal damages, soot formation, rough walls and degraded precision and accuracy [1] [4].

5.2 Material Efficiency

There are increasing concerns worldwide about environmental problems relating to polymeric material. One strategy to alleviate these concerns is the efficient use of materials. Compared with traditional microfabrication methods (such as masks and lithography), laser processing has many advantages in terms of material efficiency. It can reduce the usage of direct materials, such as hazardous wet-etch chemicals and photoresists. Laser processing is a no-contact machining, which is advantageous in terms of minimizing wastage because no physical stress is applied to the sample. Laser processing can directly convert the sample surface into the desired shape, providing a clean and strong surface and resulting in no release of waste materials. It provides extremely high machining accuracy with a narrow material surface-zone affected by heat. Furthermore, trim processing can be applied to the laser-machined surface to remove small surface irregularities. The full form of laser processing described here includes micromachining, cutting, cleaning, sintering, and microfabrication. Furthermore, laser modification covers the following techniques: surface modification; laser ablation; texturing; welding; sintering; and remelting [2]. The effects of laser treatment on phase separation in polymer blends have been reported [1]. Phase separation can be enhanced or suppressed, depending on blend composition, even in a region that is miscible without laser treatment. Selective laser heating was applied to continuous-wave laser modification; however, such selective irradiation can be realized using ultrashort-pulse lasers because different materials have considerably different ablation thresholds. As a result, surface modification with no thermal damage can be achieved by controlling the laser output immediately above the ablation threshold [3].

6. Challenges and Limitations

Like any polymer activation and surface modification techniques, laser processing has its own limitations and disadvantages that should be considered along with its numerous advantages for successful implementation. Problems related to the limited laser modification area and non-uniformity of modifications were listed as the main challenges [11]. Additional problems may exist in practical applications that are related to laser sources. Limited wavelength tunability of laser sources restricts the applicability of this technique to some specific molecular and lattice vibrations, which narrows the range of materials that can be used, as well as the choice of specific modification setups. Commercially available pulsed laser systems either operate at a fixed wavelength or offer only a few harmonics of a solid state source.

In many applications, laser versatility will be limited by the fixed laser repetition rate, which affects the potential operational speed of the process. Moreover, for longer pulses accessible with most free-running solid state lasers, minimized heat diffusion depth with constant ablation efficiency is needed. Laser surface treatment and patterning of polymeric substrates to improve biocompatibility and other properties require further research to facilitate implementation from the laboratory to real products [2]. Another limitation which can be readily overcome is related to the attachment of cells on laser processed surfaces. In nearly all previously published studies, cells usually attach on only one or several predefined laser processed areas, while the remaining surface resists cell attachment. Further experiments with polymers such as polycarbonate or polystyrene are required to assess the relationship between surface chemistry and topography to systematically study the effect of changes caused by different laser parameters and investigate the resulting spatial restriction of cell attachment. The attachment of cells only on laser-processed regions is not always desirable because it inhibits the attachment and growth of cells on the remaining surface area. PCI technology currently faces a key challenge in addressing this issue in the context of laser lithography for spatial regulation of cell attachment.

6.1 Thermal Degradation

Laser-induced thermal degradation represents a critical mechanism in the modification of biopolymer properties. Laser irradiation causes localised heating that exceeds the polymer degradation temperature, resulting in ablation and material removal from the surface. In polymers possessing chemical groups susceptible to depolymerisation, such as poly-3-hydroxybutyrate (P(3HB)), thermal

degradation proceeds via random chain scission, yielding shorter chains or monomers that volatilise. The ablation rate depends on material properties like melting temperature, thermal conductivity, and absorption at the laser wavelength, as well as laser parameters including wavelength, power, pulse duration, and the number of pulses applied [3]. Understanding the interplay of these factors enables selective surface modification with enhanced microhardness, roughness, wettability and provides control over mechanical behaviour, biodegradation and drug release characteristics [2]

6.2 Surface Modifications

Surface modification facilitates a better understanding of biomaterial biocompatibility, enabling the design of superior material surfaces. Various laser and plasma techniques are employed to alter biomaterial surfaces, including laser interference lithography for micropatterning biopolymer surfaces and laser-post treatment to influence fibroblast cell adhesion on polyethylene terephthalate. Laser ablation creates topographical modifications such as ablated structures on nylon-6,6. Laser microfabrication may establish controlled environments for cell growth. The use of laser irradiation overcomes the hydrophobicity of polymethyl methacrylate (PMMA) by enhancing its hydrophilic properties. Femtosecond laser excitation is used to fabricate engineered biopolymer/ceramic surfaces, supporting cellular adherence and orientation [1].

Polymers are widely utilized in biomedical applications due to their biocompatibility, customizable chemical compositions, and processability into complex, thin, and flexible structures, as well as extracellular matrix-like surfaces. Common biomedical polymers include poly(ethylene terephthalate), poly(ethylene oxide), polystyrene, poly(vinylidene fluoride), and poly(methyl methacrylate). The properties of polymer surfaces can be adjusted by specific modifications. Whereas surface and bulk properties typically correlate in metals, ceramics, and composites, polymer surface properties generally differ from bulk values. The implementation of polymeric biomaterials in medical fields often necessitates distinctive surface modification techniques. Laser structuring, a versatile tool for surface functionalization without employing chemicals or masks, achieves targeted microstructuring on polymers. The femtosecond laser surface structuring of polycarbonate produces hierarchical microstructures, and laser-microstructured specimens demonstrate enhanced microhardness, surface-enhanced Raman scattering, oil repellency functionalities, and improved cellular attachment. UV-based excimer radiation can generate massive microstructures on polymer foils. Laser structuring tailors specimen surface properties, enabling directed cell adhesion and orientation along modified zones [2] [11].

7. Future Trends in Laser Processing of Polymers

Progress in laser-based surface modifications of polymers aims to widen the available options for materials and low-cost surface-functionalization strategies. Laser-based surface modification permits the controllability of nanotopography, wettability, chemistry, biocompatibility, and adhesion. Plasma modification enhances surface energy, hydrophilicity, and cell attachment. Laser-interference lithography adapts the micropatterning of biopolymer surfaces, which may influence cell adhesion and proliferation.

Biomedical implants customized by precision laser microfabrication are capable of modifying surface properties and creating nano-structures and surface-relief gratings. Laser surface treatment techniques improve the biocompatibility and the interface with living tissues. Continuous developments in the control and understanding of laser-matter interaction pave the way to future competitive systems for additive and subtractive manufacturing, virtual reality, and biomedicine. Advanced engineering of biomimetic implants for personalized, modular, and smart solutions requires a significant amount of research and development.

Laser modification of surface roughness must be precisely controlled, since excessive roughness can create stress concentrators and increase fatigue damage, while microroughness enhances adhesive bonding. In contrast to plasma, ozone, and other gas-based techniques, laser technology can create micro- and nanoscale well-defined patterns with real-time control reproduced over large areas. Laser microstructuring enables non-contact processing and is free of any solution or chemical, with potential applications in the manufacturing of biomaterials with enhanced cellular attachment and

orientation. Cells grown on laser-modified surfaces exhibit an elongated morphology and tend to align parallel to the surface patterns. [11]

2D and 3D printing of polymers that possess unique properties in response to either specific laser wavelengths or the incorporation of particular chemical groups holds significant potential. When combined with advanced surface modifications, these new materials can be transformed into innovative solutions for tissue and organ replacement, biosensors, and antibacterial coatings for long-term implants. [1]

7.1 Emerging Technologies

Block copolymers have long been recognized to undergo spontaneous phase-separation: different blocks within the molecule one can separate providing well-defined, tunable-ordered morphologies. Examples of their biomedical applications include nanostructured membranes for dialysis, nanostructured materials for drug delivery or controlled release. In addition, block copolymers have also been used as lithographic masks for producing thin-film recording media because of their very small periodicity. Block copolymer films can be selectively etched or grown allowing controlled confinement of molecules or particles for biological applications. Considerable interest in block copolymers is attributable to the fact that several of these are commercial products. This has greatly stimulated research and development activities towards their large scale fabrication for various applications. Among the different processing techniques, laser melting of thin films coated onto silicon substrates offers a simple route for the production and patterning of polymer surfaces.

Rapid heating or melting of thin films coated onto a silicon wafer in a scanning mode using a focused laser beam was performed using a 2 W continuous wave diode laser, operating at 405 nm. The films undergo spontaneous confinement into generation of ordered [reflection transmission electron microscopy (RTEM)] submicrometer size polymer heights with bilateral connected cone-like shapes. These nanostructured surfaces were characterized by transmission electron microscopy (TEM) in RTEM transmission mode and scanning force microscopy. Patterned polystyrene surface was treated with chemicals to graft –OH groups in order to promote human serum albumin grafting as model protein. For this purpose, melatonin and dopamine were tested as grafting molecules in order to evaluate the possible involvement of the NH group for protein grafting.

7.2 Integration with Other Manufacturing Techniques

The high local temperatures generated by laser processing can restrict the use of certain polymeric materials or lead to damage to neighbouring regions of the substrate. The resolutions and surface finish of additively manufactured parts with complex geometry might be insufficient for certain applications. Furthermore, the availability of powders and filament materials with tailored properties for SLS or FDM is generally poor, except for a few commercial grades. The mechanical performance of laser-processed polymers, especially FDM parts, is generally poorer than that of conventionally prepared ones.

Combining laser processing with other manufacturing or surface modification technologies enables the development of advanced polymeric constructs with temporospatial control over their structure for specific applications. For example, integration of SLS with post-thermal treatment was used to prepare porous poly (ether–ether–ketone) parts with structural properties more comparable to bone, and HIPS parts with enhanced ductility. Advanced hybrid processes combining LDW and direct ink writing of polycaprolactone–chitosan scaffolds isolated and enriched human mesenchymal stem cells with a survival rate higher than 75% and an isolation efficiency higher than traditional in vitro cell culture methods by 50%.

8. Case Studies

Reconstruction of bone tissue defects remains a challenge in orthopedics; tissue scaffolds from polymers, metals, and ceramics are extensively researched to address this issue [1]. Laser modification is increasingly used in the fabrication of such functional surfaces due to its flexibility, reproducibility, precision, and the bioactivity of the processed surfaces. Various polymers, including PMMA, PLA, PEEK, PEI, PTFE, PEEK, and polycaprolactone, have been successfully modified to improve their suitability as scaffolds. Limited data are available on the impact of laser processes on PHAs, which are advantageous due to their biodegradability, biocompatibility, and natural origin.

Optimization of laser treatment parameters is essential to enhance the suitability of PHAs for biomedical applications [2]. Such tailoring at the micro- and nanoscale facilitates control over scaffold porosity, geometry, and surface chemistry, thereby improving biomaterial–cell interaction and tissue regeneration. Laser structuring of PHAs helps determine how various laser sources and techniques affect the physico-chemical and biological properties of these biodegradable polymers [3].

8.1 Case Study 1: Laser-Processed Scaffolds

A laser-foaming procedure was created to manufacture polymeric three-dimensional (3D) scaffolds with highly organised cellular structures, suitable for tissue engineering applications [7]. Polymers such as poly(ethylene-terephthalate) (PET), poly(lactic-acid) (PLA), and poly(ethylene-co-vinyl acetate) (EVA) were examined at thicknesses of 250 μm and 500 μm . It was demonstrated that laser processing could induce foaming in these materials, enabling control over the cellular architecture of the foamed products. Below the foam, a layer of unaltered polymer film provides the raw scaffold. As proof of principle, these membranes were applied to prepare open-celled or multi-layered PLA scaffolds.

Besides laser techniques, scaffolds have been fabricated via robotic assisted deposition, layer-by-layer construction, threedimensional (3D) weaving, extracellular matrix (ECM) coating, or bioprinting. Robocasting employed two separate inks composed of polycaprolactone (PCL), nanofibrillated cellulose (NFC), alginate, and calcium chloride (CaCl_2), enabling the fabrication of microporous organic/inorganic hybrid scaffolds with controlled porosity and organic/inorganic ratios [12]. The removal of planks from an expanded cellulose foam through a laser-cutting technique produced single-layer porous scaffolds. Replicas of these planks were cast in polydimethylsiloxane (PDMS) to fabricate a stacking mould for creating multi-layered cellularly structured scaffolds.

The fabrication of bone and cartilage scaffolds to substitute for damaged or malformed tissue presents a growing medical demand. Flow-directed assembly can mould zein protein gels into bulk or porous bone tissue scaffolds suitable for widespread disease treatment. Additional requirements include biological functionalisation, support for three-dimensional cell growth, enhanced cell ingress, and the ability to control tissue formation [13]. Development of complex 3D anatomical structures achieving micro/nano resolution represents a significant biofabrication hurdle.

A novel approach successfully converted computer-aided design (CAD) models into electrospun nanofibre-based hierarchical scaffolds of anatomically relevant geometries. Sheets of nanofibre meshes were laser-micromachined into layers of varying thicknesses, which assembled into sophisticated 3D patterns replicating diverse designs, such as a human ear. The laser-cut material exhibited high cell viability, with 85 % confluence achieved after three weeks, and the use of collagen bioadhesives enhanced cell migration between layers, suggesting potential for high cell growth and regeneration in chemically functionalised 3D scaffolds.

8.2 Case Study 2: Laser-Cut Medical Implants

Surgical procedures frequently demand fast, relatively inexpensive, and biologically appropriate implant materials that promote early healing and maintain long-term function. Custom-made medical implants are manufactured from patient-specific 3D scans, the basis for 3D CAD designs, which can be fabricated in metals or polymers either directly or through master patterns. In this study, the rapid prototyping of custom medical implants is enabled by the laser machining of silicone rubber and polycarbonate sheets, a combination that is presently the only rapid prototyping solution available in these two materials.

A demonstrator medical implant, extracted from a patient cranial scan, was fabricated to showcase the capability to machine patient-specific implants. SLA models of the implants and moulds for the silicone rubber prototype were also manufactured in the same patient-specific manner for transmission of dimensional information at various stages of evaluation. Medical implants, once fabricated, are sent to medical institutes for form, fit, and function evaluation.

9. Regulatory Considerations

The regulatory framework for laser-based surface modification of polymers intended for biomedical implants is still under development. Before an implant can be released to the market, it must be demonstrated that the laser-based surface modification either does not compromise or

preferably enhances the biocompatibility of the polymeric base material. Failure to deliver such evidence will prevent approval of the implant for clinical use.

Surface biocompatibility can be substantially altered by laser processing. For instance, polymer surfaces subjected to ultraviolet laser radiation often exhibit reductions in contact angle against water of up to 30°, which would be considered a marked improvement if the base material were originally hydrophobic. While such increases in surface energy are anticipated to promote biocompatibility, evaluative testing is necessary to confirm this assumption for each material and laser treatment combination [3].

The well-known ASTM F7459—“Standard Guide for Optimization of Laser-Based Additive Fabrication Methods—Considerations for Testing Biocompatibility of Implant Material” [11] — provides general guidance in this area and elaborates on testing methods that encompass cell proliferation and cytotoxicity assays, thrombogenicity, and systemic toxicity. Nevertheless, the standard does not specifically prescribe tests for implant biocompatibility, leaving the licensee to determine appropriate assays or potentially to adapt EEC specifications applicable to polymeric materials processed by other methods [2]. Consequently, specific biocompatibility evidence requirements for polymeric implants modified by laser surface structuring (LSS) remain largely open in the regulatory domain.

9.1 FDA Guidelines

In 1997, the United States Food and Drug Administration (FDA) initiated a biomedical research program to address risks related to the processing of materials used for the fabrication of biomedical devices, such as polymers, ceramics, and metals [2]. The findings led the literature to recommend that materials and processes adhere to the FDA guidelines. Various strategies have been investigated to modify the properties of materials used for biomedical devices. Material properties can be influenced by altering bulk characteristics (extrinsic factors) or by modifying surface properties (intrinsic factors). Surface-enhancing processes adopted must fulfill stringent criteria to avoid permanent modification of the bulk properties. Several surface treatment technologies—such as plasma treatment, self-assembled monolayers (SAMs), and UV treatment—have been employed [3], [14]. Although specific guidelines on methods of sterilisation are not provided in the codes, it is mandatory to validate the sterilisation process along with the choice of sterilisation method [15].

9.2 ISO Standards

Specific ISO classifications describe polymers with respect to biomedical devices that may be produced from them. ISO 10477 designates polymer materials for the manufacture of dental devices (ISO 10477:2020). All aspects of the excess medical device are covered, including any quality control on components that might be required. Medical implants classify the respective polymer according to ISO 13485 (ISO 13485:2016). This also covers all aspects of device manufacture, and any relevant testing apparatus that might be required.

Polymer qualification is a vital step in the production of biomedical devices, as polymers are produced in enormous quantities worldwide for billions of applications. A comprehensive assessment must specifically examine the relevant polymer materials designated by the manufacturer for medical device manufacture. The polymer process, quality control, and sterilization, followed by package and optical assessment, form a vital starting point in producing an excess medical device [3]. Following sterilization and package inspection, the polymer microstructure and operating principles can be included; here, problems typically occur, and the mode of failure needs assessment [4].

10. Conclusion

Laser processing of polymers offers a versatile and effective approach for improving the performance of polymer-based materials in biomedical devices and systems. Research has concentrated on laser methods and the subsequent control over surface characteristics for applications such as tissue engineering. Using a range of experimental techniques to profile materials and evaluate biocompatibility, researchers have worked to enhance surface interaction, particularly in terms of cell adhesion to polymers applied in medical implants or scaffolds.

Laser surface treatment can impart a combination of desirable characteristics to polymeric materials that cannot be achieved through additives or coating alone. Polymer processing relies upon

mechanisms that transform the polymer from a solid to either a liquid phase or a gaseous state. Unfortunately, most laser treatment schemes rely on optics that produce Gaussian spatial intensity distribution, variations in beam uniformity and intensity, and substantial fluctuations in energy output. These abnormalities produce unpredictable morphologies and surface signatures, which render laser irradiation treatment challenging for material processing of polymers. During both micro- and nanoscale laser fabrication, morphology, spatial periodicity, and chemical composition remain key features. Given the wide scope of biomaterials and the variety of materials used, creating a universal material selection and evaluation framework remains unachieved.

Lasers now make possible spatially selective and local treatments of polymers that enable significant improvements in material processing and subsequent performance. The effect of surface treatment was demonstrated on the performance of commercial polymers that include poly(methylmethacrylate) (PMMA), poly(lactic acid) (PLA), poly(lactic-co-glycolic) acid (PLGA), and poly(caprolactone) (PCL). Following laser radiation, investigation of the modified polymers reveals distinct alteration of the polymer chemical composition with respect to the untreated version. Several independent computational models that capture the polymer–biomolecule interaction were developed to gain a more fundamental understanding of the physics governing materials–cells interaction and determine the adhesion effect following laser application to the polymer surface. These numerical codes determine the range of adhesion energy and could be used as design or guideline tools in the selection and manufacturing of optimal material and surface treatment for biomedical applications [1].

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