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LASER SURFACE TEXTURING: CHARACTERISTICS AND APPLICATIONS

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Abstract: Laser surface texturing (LST) has emerged as a versatile and efficient technique for modifying surface properties across various materials. This paper provides an analysis of the characteristics and diverse applications of laser surface texturing. The paper begins by explaining the fundamental principles underlying LST, highlighting the mechanisms involved in material interaction and the resultant surface modifications. It explores the influence of laser parameters such as pulse duration, energy density, and wavelength on the texturing process, emphasizes their impact on surface morphology, roughness, and topographical features. Furthermore, this paper delves into the wide-ranging applications of LST across different industries and fields. It examines how LST enhances surface functionalities, including improvements in tribological properties, wettability, friction reduction, and biocompatibility. Additionally, the utilization of LST for creating microstructures enabling advanced functionalities in optics, electronics, biomedical devices, and energy harvesting systems is discussed. Moreover, the challenges and future directions in LST technology are highlighted, which encompass advances in precision, scalability, and integration of LST with other manufacturing processes. The potential environmental implications and economic feasibility of LST are also discussed.
In summary, this paper examines the characteristics, applications, challenges, and future prospects of laser surface texturing, showcasing its significance as a promising technology for tailoring surface properties across diverse materials and industries.
Keywords: laser micromachining, surface, texturing, tribology.

1. PRINCIPLES OF LASER BEAM TREATMENT

The principles of laser beam treatment (LBT) revolve around the interaction of high-intensity laser beams with material surfaces to induce specific changes or alterations of that surface. LBT encompasses various techniques such as laser ablation, cutting, and surface modification, each customised for specific purposes and applications. These techniques leverage the principles of laser-material interaction to achieve precise surface alterations or material removal.

LBT relies on precise control of the energy generated by the laser and directed onto the material surface. The interaction begins with the absorption of laser energy, leading to heating, melting, vaporization, or ablation of the material. The energy of the laser beam is absorbed by the material, generating a thermal response. Different materials have varying absorption coefficients, influencing the efficiency of energy transfer and, therefore, material removal or modification. The absorbed laser energy can cause material removal through processes such as vaporization, melting, or ablation.

Crucial parameters such as laser wavelength, pulse duration, energy density, repetition rate, and scanning speed are precisely controlled to optimize the machining process. These parameters influence the depth of removal of the material, the surface quality, and the characteristics of the affected zone. Different types of lasers possess varying capabilities when it comes to material processing. Laser treatment generates heat energy, and the wavelength of the laser beam significantly influences its performance on materials. Essentially, the total heat energy delivered by a laser to the work material can be divided into two components: the portion of heat energy absorbed by the work material and the remaining energy that gets reflected into the environment. The amount of heat energy supplied to polished metal surfaces depends on the material's ability to absorb heat and the wavelength of the irradiation. Typically, shorter wavelengths exhibit higher absorptivity (Jeyaprakash et al., 2020).

Laser beam texturing involves altering the surface properties of a material by modifying its texture and roughness with laser beam energy. This process uses laser ablation to create micropatterns such as dimples, grooves, or unique shapes on the surface with very high accuracy and consistent repeatability. Its applications span various improvements in properties such as adherence, wettability, thermal conductivity, and simply friction reduction.

For example, this process can enhance surface adherence before applying coatings. Laser texturing is also valuable in the preparation of surfaces for thermal spray coating, laser cladding, and optimizing the performance of mechanical seals. Unlike surface treatments that involve abrasive blasting or chemical etching and require consumables such as steel grits or acids, laser texturing operates without consumables. This results in reduced operational costs, minimal maintenance, and improved workplace safety. Operators do not need to handle chemicals, wear protective gear, or interrupt their work to replace consumables.

The process selectively removes material from specific surface areas using laser ablation, allowing for the creation of various patterns by adjusting the operational parameters of the laser. This can increase surface roughness, facilitate adhesive adherence, and provide enhanced anchoring surfaces. Pulsed lasers with a high peak power concentrate energy to reach the material's ablation threshold. Usually, these lasers have a pulse duration in nanoseconds, with an energy of the pulse in millijoules.

Applications of laser texturing include, among others, adhesive bonding, mechanical seals, and anti-wear coatings. Due to the coherent nature of the beam, LBT has inherent advantages, such as improved precision, simplicity in usage, cleanliness, and rapid processing.
Laser texturing as a surface modification technique finds wide applications in technological processes, including welding (Radek et al., 2018; Miletic et al., 2020), industry boilers (Orman and Chatys, 2011; Dabek et al., 2016; Dabek et al., 2018), preparing specialized surfaces for protective coatings (Radek et al., 2019), and DLC (Diamond-Like Carbon) coatings (Radek et al., 2020; Radek et al., 2021), where the substrate layer aspects are also significant (Ulewicz et al., 2014; Dudek et al., 2017). Low-power applications are also possible in the case of plastics (Kuciel et al., 2019; Mazur et al., 2021). Creating modified surfaces with specific tribological properties significantly impacts industries such as the automotive sector (Ulewicz, 2018; Pacana et al., 2021) and machinery (Borkowski et al., 2012; Siwiec et al., 2020).
Analyzing the factors controlling the texturing process (Pietraszek et al., 2020) and the observed sizes (Gądek-Moszczak et al., 2019) strongly influence the adaptation of classical Design of Experiments (DOE) methods and the necessary equipment (Dominik et al., 2013). Predictive models, when created, require appropriate preparation by the technicians and engineers applying them (Ulewicz, 2014; Radek et al., 2023).

2. SURFACE TEXTURING PROCESS

Recently, various methods for surface texturing have emerged, encompassing techniques such as micro-milling, hot embossing, ion beam etching, lithography, electrochemical machining, wire EDM machining, and LBT. The quality of the surface texture in material processing is significantly influenced by various process parameters. These parameters play a crucial role in determining the final texture characteristics of the material. As for LBT the main process parameters are, among others: laser output power, pulse duration, repetition rate, beam spot size, scanning speed, and wavelength.
The magnitude of generated power affects the depth and width of the heat affected zone, thereby influencing the texture's roughness and depth. Shorter laser pulses often result in finer textures, while longer pulses might cause more melting and affecting the surface finish. Higher repetition rates can affect heat accumulation and overall texture uniformity, influencing surface quality. The size of the laser beam spot determines the area of interaction, affecting the precision and resolution of the texture pattern. The speed at which the laser beam moves across the material by using a laser beam head scanner impacts heat distribution and cooling rates, influencing the surface texture quality. Another very important parameter is the beam wavelength. Different wavelengths of the laser have varying absorption rates in materials, affecting how they interact and thereby influencing the resulting texture (Convert et al., 2022).
The authors of (Jia et al., 2021) have measured how the hardness of the Alluminum alloy 5A06 had changed after treatment with different laser micromachining parameters. Nd:YVO4 nanosecond pulsed laser was used. The findings demonstrated the effectiveness of the created model in accurately forecasting the hardness of the laser-textured 5A06 aluminum alloy. Among the parameters examined, the scanning speed emerged as the most influential, followed by the pulse frequency, while the energy density exhibited minimal impact. Material removal during LBT or the laser ablation process

occurs due to the generation of nanoparticles when the focused laser pulse heats and melts the intended material, as depicted in Figure 1 (Kumar et al., 2021).

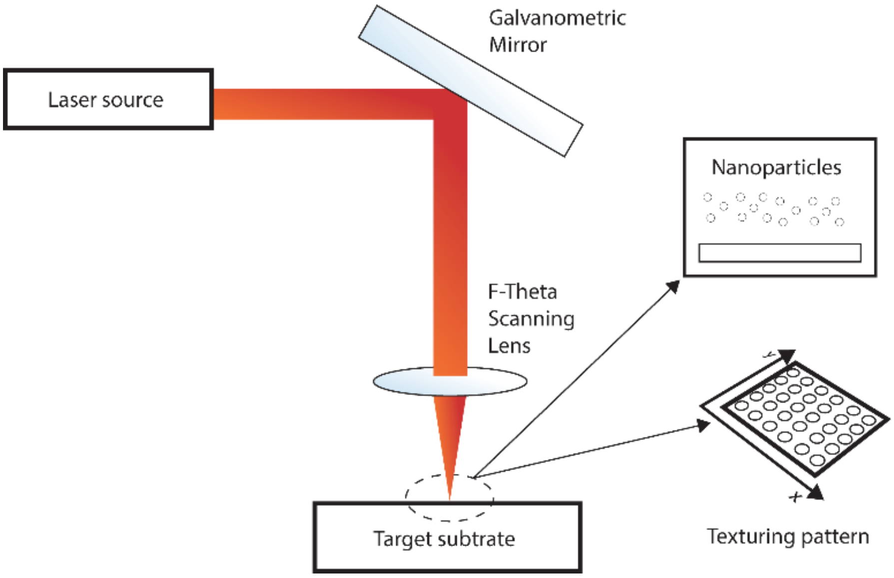

Fig. 1. Laser texturing process

3. APPLICATIONS

Laser surface modifications find predominant usage in various fields including electronics, optoelectronics, aerospace, materials processing, and automotive industries that demand exceptional precision, thereby justifying the higher cost of laser surface treatments. Laser light stands out distinctly from conventional light sources due to its unique attributes, making it highly sought-after in diverse applications. Its coherence, precise focus, and ability to perform accurate modifications distinguish lasers from other light sources, rendering them favorable for various applications. Laser surface modification can be utilized to improve tribological characteristics. It can be used to create products for biological purposes, such as dental and orthopedic implants, as well as for magnetic applications such as magnetic disks. Additionally, it is used to improve mechanical components, such as cutting tools and gears, fabricate hydrophobic, superhydrophobic, and superoleophobic surfaces, as well as to improve lubricated and resistant to wear surfaces.

Laser surface texturing allows precise control over surface characteristics such as hydrophobicity, hydrophilicity, and surface energy, which can affect the adhesion of contaminants or the ability of surfaces to repel or retain lubricants, influencing frictional behavior. That process can also influence tribological parameters such as wear resistance and coefficient of friction. Wettability stands as a crucial property of the surface with wide-reaching applications across various domains such as adhesives, lubricants, coatings, implant integration, heat conduction, corrosion prevention, and more. Laser texturing has proven to be an effective method to alter the surface wettability of various materials, including polymers, metals, ceramics, and even natural minerals. By appropriately adjusting processing parameters, laser texturing enables the transformation of surfaces into either superhydrophobic or superhydrophilic states. The authors of the paper (Riveiro et al., 2020) demonstrate that the technique of laser texture facilitates the conversion of PTFE surfaces into omniphobic materials, effectively repelling water, oil, or various water-

ethanol mixtures. Remarkably, this altered behavior remains stable even after exposure to base or acid attacks.
The relationship between the geometrical pattern, roughness, and surface characteristics of the textured surfaces was correlated with specific laser processing parameters, such as spot density and processing speed. These parameters influence the surface's wettability, which can be measured by the contact angle of the special liquid applied on the surface of the textured material. The authors of the paper (Moldovan et al., 2022) revealed that the roughness of the textured surface increased directly with the spot density (repetitions), while it decreased inversely with the processing speed.
In another paper, the Fe-based amorphous coatings underwent the successful fabrication of superhydrophobic surfaces that exhibited antifouling and anticorrosion properties. This was achieved with a picosecond pulsed laser texturing treatment, coupled with subsequent surface chemical modification. The laser texturing process resulted in the creation of trench and dimple structures covered by microsized granular deposits and nanoparticles across the coating surfaces (Wei et al., 2023).

3.1. Tribology

LSM can be used to improve tribological parameters such as coefficient of friction and wear resistance. This method significantly enhances tribological performance, mainly by generating oil reservoirs. It can be done by creating micropatterns, such as dimples, grooves, or specific textures, and therefore altering the surface morphology. These patterns facilitate the redistribution of lubricants or the retention of lubricant films, thus enhancing lubrication and reducing direct solid-solid contact and consequently decreasing friction. These reservoirs can effectively capture wear debris produced when two surfaces rub against each other, while also reducing their actual contact area. That phenomenon can have a significant impact on friction reduction. This microreservoir effect ensures a continuous and sufficient supply of lubricants at the contact interface, reducing friction by minimizing direct contact between sliding surfaces (Lazov et al., 2023) (Convert et al., 2022).
Laser beam modifications of the material surface may include changes in surface roughness, hardness, and chemical composition, all of which can also contribute to reduced friction between sliding surfaces. By altering the surface topography, the actual contact area can be reduced, leading to lower frictional forces during sliding or relative motion.
The authors in their work (Li et al., 2022) applied different surface textures featuring varied geometric parameters (such as area density, diameter, and depth) to the surface of GCr15 steel. Subsequently, friction and wear tests were performed to examine the impact of area density, diameter, and depth on lubrication performance. The friction and wear properties of the texture were predominantly influenced by the density, diameter, and depth of the area. The textured surface exhibited an increased wear diameter in contrast to the untextured surface. This increase might be attributed to the texture's ability to retain a portion of the lubricating oil, resulting in a reduction in the thickness of the lubricating oil film between the friction ball and disc. Consequently, this decreased the load bearing capacity of the oil film, leading to a slight increase in the wear diameter.
Zhou et al. presented how laser texturing of a hydrogel can change its friction properties. Hydrogels are commonly utilized as models resembling articular cartilages that share similar tribological characteristics. Through UV laser texturing, microgrooves with varying

depths and spacings were formed on PVA hydrogel surfaces. These grooves introduced a "drainage channel" effect and interlocking at the interface between the hydrogel and the titanium alloy, consistently resulting in frictional stress that was higher for textured hydrogels compared to smooth ones across different velocities. The decrease in micro-groove spacing and an increase in friction velocity amplified the frequency of interlocking between them, and this led to an increase of frictional stress. (Zhou et al., 2022).

3.2. Biocompatibility

Materials with a high biocompatibility can be used in applications related to bone and tissue transplantation. Biomaterials fall into categories such as metallic, ceramic, polymeric, and composite. Texture can be added to an implant using various techniques such as grit blasting, anodic oxidation, and chemical vapor deposition. While these methods are quick and simple, repeatability is not sufficient. On the contrary, laser surface texturing stands out as a rapid, clean, and precise method for implant modification. It can be considered a promising technique to effectively modify implants. Laser surface texturing enables the creation of controlled microstructures or surface patterns. These textures can mimic natural surfaces found in biological tissues, promoting better cell adhesion, proliferation, and tissue integration. The modified surface topography can facilitate interactions with biological entities, enhancing biocompatibility. Optimizing surface roughness to match the requirements of specific biological applications with a laser micromachining can promote cell attachment, as well as a reduction of bacterial adhesion. It can also influence protein adsorption and enhance tissue integration. These enhancements ultimately contribute to the improved biocompatibility of the material for various biomedical applications.

3.4. Future applications

Laser surface texturing has potential in various applications, yet it encounters several challenges such as selection of the optimal texture design, laser fluence, pulse repetition rate, and suitable working mediums for the desired applications. In addition, challenges with respect to the scalability of the process, cost-effectiveness, and gas emissions during plastic processing need to be incorporated into the manufacturing system. Addressing these concerns, optimizing the use of laser texturing techniques to enhance the tribological performance of engineering surfaces requires a meticulous process optimization involving the selection of suitable tribo-pairs, dimple parameters, and contact configurations. The challenge of understanding how surface texture and its pattern design correlate with mechanical properties and microstructural investigations has posed a significant obstacle in determining the optimal texture design. Researchers have dedicated substantial effort to identify the most suitable texture patterns, density, and inclination to enhance coating adhesion and lubrication. However, the challenge persists because of variations in mechanical properties between different substrates and variable applications.

Evaluating the optimal design through Laser Surface Texturing trials consumes a significant amount of time. Therefore, employing computational and numerical modelling techniques such as the finite difference method, finite volume method, and finite element method can prove beneficial in studying parametric behaviors before conducting actual experimental studies (Kumar et al., 2021).

Moreover, a rapid growth of the demand for multifunctional surfaces can be observed. Creating surfaces that simultaneously possess properties such as hydrophobicity, antibacterial characteristics, enhanced tribological performance, and improved biocompatibility presents a challenge, but offers immense potential for various applications (Goharshenas Moghadam et al., 2021).
Exploring laser texturing in novel materials, such as advanced alloys, composites, polymers, and biomaterials, is another area of interest. The adaptation of surface textures to address specific needs in diverse sectors such as aerospace, automotive, biomedical devices, and energy applications presents both challenges and opportunities. LST is not a low-cost method to adopt to optimize material parameters. Enhancing the cost-effectiveness of laser texturing processes is essential for a wider industrial adoption. Optimizing energy efficiency, reducing processing times, and minimizing material waste are ongoing challenges to make these techniques more economically viable.

CONCLUSIONS

Various material responses to laser micromachining can be attained on the basis of the material system and laser parameters, enabling the design and optimization of processes to permanently modify the surface chemistry, crystal structure, and morphology of the material to achieve desired parameters and function. Profound research is required to delve deep into the physics of Laser Surface Texturing (LST) for different materials, and, as for the biomedical field, conduct clinical trials to validate its applicability. In many papers, it has been noted that LST has emerged as a promising technique for modifying biomaterial surfaces - potentially finding successful applications in biomedicine. Laser surface processing plays a crucial role in numerous industrial manufacturing operations. At the same time, technology continues to evolve and new applications are being discovered in emerging fields. With ongoing advancements in laser technology, the improvement of material performance thanks to laser surface processing will persist. Furthermore, it will pave the way for novel materials and innovative applications that would remain unreachable without the specific capabilities offered by this form of processing.

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