Proc. 14th National Conference with International Participation "Electronica 2023", June 1 - 2, 2023, Sofia, Bulgaria

Laser surface texturing LST overview, future trends, advantages, and disadvantages

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Abstract—Laser technology has become a major tool in electronic manufacturing. The precision and flexibility of lasers is widely applicable, especially in key operations such as cutting, drilling, welding and marking of electronic components. Laser surface texturing (LST) is an advanced technique that has attracted attention in recent years and represents the modification of the topography of the surface of the material in order to achieve desired properties, such as improved functionality, performance or increased aesthetics of the product. Surface modification uses the precision and flexibility of lasers to create micro- or nanoscale patterns, textures or features on a material's surface. Understanding the various physical processes occurring during laser interaction with the material is essential to optimize laser texturing parameters, achieve desired surface characteristics, and improve process efficiency and effectiveness. This paper examines the physical processes involved in LST and their implications for surface modification. In it, we examine its applications, including surface wettability, tribology, biocompatibility, and energy conversion. We discuss the physical mechanisms governing the formation of surface textures, such as melting, ablation, and hydrodynamic instabilities. We provide a comprehensive review of recent research efforts in the field, highlighting the potential of LST to improve productivity in electronic manufacturing.

Keywords — electronic manufacturing, laser surface texturing, laser beam

I. INTRODUCTION

Laser surface texturing is a key process for modifying material properties such as controlling wettability, friction, wear, and adhesion. LST is a powerful technique enabling the creation of complex surface patterns and structures with high precision and reproducibility. It uses the precision and flexibility of lasers to modify the surface of a material at the micro- or nano-level. The technology involves the use of a laser beam to heat and melts the surface, which is then cooled and solidified or evaporated to form micro- and nanostructures. This process leads to modifications in the surface morphology, chemistry, and mechanical properties, which has a significant impact on the functionality of the materials.[1-9]

Physical Mechanisms: The physical mechanisms involved in LST vary depending on the laser parameters, such as wavelength, pulse duration, and energy density. One common mechanism is melting, which occurs when a laser heats a surface to a temperature above its melting point. This results in the formation of a molten material that rapidly solidifies to form micro- and nanostructures.(Fig.1) [10] Another mechanism is ablation, which occurs when laser energy is sufficient to vaporize the surface material, resulting in the formation of microcraters and pits [11]. Hydrodynamic instabilities can be induced, where laser energy is used to create surface waves that subsequently solidify into complex structures.

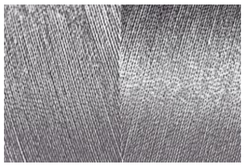

Fig. 1 Shiny-silver-thread-textured-background

The main physical processes involved in LST are laser-material interactions [12], which are categorized into two types: **thermal** and **non-thermal**. The extent of these interactions depends on various factors, such as laser intensity, pulse duration, wavelength, and material properties.

In **thermal (heat)** during laser heating, the energy from the laser beam is absorbed by the material, resulting in localized heating, thermal expansion and vaporization of the material. The expansion generates a pressure wave propagating through the material and causing ablation or surface deformation. The extent of laser-induced thermal effects depends on the laser parameters and material properties, such as thermal conductivity, melting point, and heat capacity. High-intensity lasers cause the material to vaporize, resulting in the creation of microcraters or pits on the surface.

Non-thermal interactions include plasma generation or ablation inducing shock waves that propagate through the material and cause surface deformation or removal of the material. Plasma generation is due to laser-induced ionization, which results in the formation of a high-temperature, high-pressure plasma near the surface. Plasma expansion generates a pressure wave that causes material removal or surface deformation. Similarly, laser-induced ablation involves the removal of material from a surface due to the pressure wave generated by the laser-material interaction.

The physical processes involved in LST have several consequences for surface modification. The degree of thermal and non-thermal effects is controlled by adjusting laser parameters such as pulse duration, wavelength, and power. This control allows the creation of customized surface features, such as microcraters, microgrooves or microdots, with specific functional characteristics such as controlled friction, reduced wear or improved adhesion. The non-contact nature of laser surface texturing minimizes the risk of damage to delicate materials or structures.

II. Advantages and disadvantages

A. Advantages

- **A significant advantage:** is its compatibility with a wide range of materials. Lasers are effectively used to modify metal and polymer surfaces [3,4,13] as well as ceramics or composites, LST is a non-contact process minimizing the risk of damage to delicate materials or complex structures. This allows texturing of complex three-dimensional surfaces, giving designers great freedom and flexibility.
- **Precision:** advantage of laser technology in electronics is its precision. Lasers have a high level of accuracy (when cutting and drilling small electronic components). Well-defined patterns (grooves, channels or microdots) are generated with sub-micron precision. This precision is key in microelectronic device manufacturing, where small components must be handled with care. Laser technology-based microfabrication methods have greatly improved the accuracy and precision of electronic device manufacturing. This enables customized texturing, with designers creating surfaces with specific functional characteristics (controlled friction, reduced wear, improved lubrication, improved adhesion or optimized light management). [11]
- **Speed:** LST is characterized by speed, reducing production time in electronics manufacturing. Lasers perform multiple operations simultaneously, and this increases efficiency and productivity. For example, laser cutting reduces production time for printed circuit boards. Productivity is high due to the speed of operation of the method, which makes it possible to produce a large volume of electronic devices in a short time [12,14]
- **Non-Contact**: LST is a non-contact process, which reduces the risk of damage to delicate electronic components. Especially in microelectronic device manufacturing, where even a small failure can render a component useless, this is key [12].
- **Versatility:** Lasers are used more and more seriously in electronics manufacturing especially in cutting (Fig.2), drilling (Fig.3), welding and marking(Fig.4). This makes them a valuable tool to facilitate the manufacturing process, (for example, laser drilling, which is used to create small holes in printed circuit boards (PCBs), or laser welding, which is used to join different materials in the manufacture of electronic devices) [13]. Lasers are also used to mark and etch electronic components such as IC packages to allow identification and traceability during the manufacturing process [15,16].

B. Disadvantages

- **Cost**: The main disadvantage of LST is its cost. Laser equipment and associated maintenance costs are expensive, especially for small electronics manufacturers. This is a significant barrier for companies just starting out in the electronics industry.
- **Safety:** Laser technology poses a known safety risk when used incorrectly. Lasers emit intense light that could cause eye damage, and high-powered lasers carry a fire risk. To ensure the safety of operators when working with lasers, safety guidelines must be strictly followed, and protective equipment used [17].
- **Material Limitations:** Lasers work best with certain materials and others are difficult or impossible to process with laser technology. This limits the range of materials that are used in electronic manufacturing [18].
- **Environmental Concerns**: Some laser processes (laser ablation) produce hazardous waste materials that require proper storage and disposal to prevent environmental damage. This is an expensive and time-consuming process that adds serious sums to the overall cost of laser technology in electronic manufacturing.

III. Applications

The applications of LST are varied and wide-ranging. In the automotive industry, LST is applied to piston rings or cylinder walls to reduce friction and improve fuel efficiency. In the aerospace industry, laser-textured surfaces improve airflow over wings or turbine blades, which improves aerodynamic performance. LST finds applications in mold manufacturing, resulting in improved surface properties, reduced defects, and improved replication precision of molded parts.

Fig. 2 Laser cutting

Among the most common applications of LST is controlling the wettability of surfaces. By creating micro- and nanostructures on the surface, it is possible to induce superhydrophobicity or superhydrophilicity[4,19,20], which is useful in various applications such as self-cleaning [22] surfaces, drag reduction [23] and improved heat transfer. LST is used to modify the tribological properties of surfaces, such as reducing friction [24] and wear [21]. This is achieved by creating regular or random surface patterns to trap lubricants and reduce the contact area between the surfaces.

LST has been found to be particularly useful in biomedical applications [25] where it is used to modify the biocompatibility of surfaces. Surface texturing is used to promote cell adhesion and proliferation and to reduce bacterial adhesion and biofilm formation. LST is also applied in the field of energy conversion, where it is used to improve the efficiency of solar and fuel cells. By creating surface textures on the electrodes or photoactive layers, the surface area and light absorption is increased, leading to improved performance.

Recent Advances: Recent research efforts have focused on developing new laser sources and processing strategies to improve LST performance and efficiency. For example, ultrafast lasers with pulse durations in the femtosecond range have been used to create high-resolution surface patterns with minimal thermal damage. Hybrid techniques that combine LST with other surface modification techniques, such as plasma processing or electrochemistry, have also been explored to create more complex surface structures. Advances in computational modelling and simulation have made it possible to design and optimize LST processes for specific applications.

Fig. 3 Laser engraving

Applications of laser surface texturing:

1. **Tribology**: LST improves the friction and wear properties of surfaces by creating micro- and nanoscale structures promoting lubrication and reducing contact area. It finds application in the automotive industry [20], space industry and biomedicine. [25,26,27]

2. **Prevention of fouling**: LST creates surface structures that prevent unwanted materials such as biofilms and marine organisms from adhering to surfaces. This is used in ship hulls and medical implants to prevent biofouling. [28, 29]

3. **Energy efficiency**: LST is used to improve the efficiency of energy systems, such as solar panels and heat exchangers, by creating surface structures that improve heat absorption or transfer. [27,28]

4. **Optical properties**: LST changes the optical properties of surfaces, such as reflectance and transmittance, by creating surface structures that manipulate the direction and intensity of light. This is applied in displays, solar cells, and sensors.[25]

5. **Surface functionalization**: LST is used to create specific surface chemistry and functional groups that are used as sensors and catalysts. [8, 28]

6. **Biomedical**: LST is used to create surface structures on medical implants that promote osseointegration and reduce implant failure rates. It is also used for drug delivery and tissue engineering applications [30,31,32].

7. **Aesthetics**: LST is used to create decorative and functional surface patterns on various materials, such as metals, polymers, and ceramics. This is applied in various industries such as consumer electronics, jewellery and automotive.

In conclusion, LST is a versatile and powerful technique with a wide range of applications in various fields. Its ability to create precise and complex surface structures with minimal damage to the substrate makes it a valuable tool for improving the performance and functionality of materials. With continuous advances in laser technology and surface science, it is expected that the applications of laser texturing will continue to expand and diversify in the future.

Recent advances: A major trend now is the use of ultrafast lasers, which create high-resolution surface structures with minimal thermal damage to the substrate. Ultrafast lasers allow precise control of the depth and shape of surface structures, which is important in their applications in biomedical implants and microfluidic devices.

Another recent advance is the use of hybrid laser techniques combining laser texturing with other surface modification techniques such as electrochemical etching and plasma treatment. These hybrid techniques create complex and multifunctional surface structures with improved properties, for example, antifouling and biocompatibility.

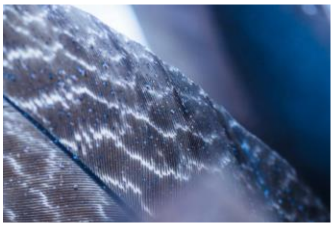

Fig. 4 Close-up laser-treated silver surface

Challenges: Despite the promising applications of LST, there are still some challenges that need to be addressed to realize its full potential. One challenge is optimizing laser parameters such as laser power, pulse duration, and repetition rate to achieve the desired surface structures and properties. Optimizing the laser parameters is highly dependent on the substrate material properties and the intended application, making it a challenging task.

Another challenge is the scalability of laser texturing, especially for large-area surfaces. LST is a time-consuming and expensive process, which makes it difficult to apply it in industrial production. Therefore, there is a need to develop cost-effective and efficient laser texturing techniques for large-scale applications.

Prospects: Despite the challenges, the prospects of LST on surfaces are promising. With continuous advances in laser technology and surface science, laser texturing is expected to become more precise, efficient, and cost-effective. This would enable its application in the automotive, aerospace, biomedical and energy industries.

In addition, the development of new materials and devices, such as 3D-printed materials and micro/nanoelectromechanical systems (MEMS/NEMS), creates new opportunities for laser texturing. Laser texturing is used to create precise and complex surface structures on these materials, which improves their performance and functionality.

IV. Conclusion

Despite its drawbacks, laser technology offers advantages that make it a valuable tool in electronic manufacturing. Its precision, speed, non-contact nature and versatility make it a preferred choice, especially for cutting, drilling, welding, and marking electronic components. However, the cost of laser equipment, safety considerations, material limitations, and environmental care must also be taken into consideration.

To address these limitations, researchers are constantly developing new laser technologies and processes to improve the efficiency and cost-effectiveness of laser technology in the electronics industry, where it revolutionary offers precision and flexibility that traditional manufacturing methods cannot. The prospects of LST are promising, driven by continued advances in process optimization in laser technology. Research into new laser sources, such as femtosecond ultrafast lasers, offer higher precision and reduced heat-affected zones during texturing, and advances in laser scanning techniques allow the creation of complex and customized surface patterns with improved efficiency. In addition, new laser systems are being developed to process a wide range of materials, including ceramics and metals.

LST is a versatile and powerful technique for modifying and improving the properties of surfaces, with applications in fields as diverse as tribology, biocompatibility, and energy conversion. It involves various physical processes (laser heating, plasma generation and ablation) that are influenced by laser parameters and material properties and have significant consequences on surface modification. The ability to control them allows the creation of customized surface features with specific functionalities, making LST a valuable tool in multiple industries.

Further research is needed to optimize the parameters of the lasers and improve the efficiency and effectiveness of the process. Its ability to achieve high precision, compatibility with different materials and flexibility in creating customized surface features gives a chance to expand its application and offers new opportunities for improved performance, in different products and systems.

ACKNOWLEDGMENT

This work was supported by the European Regional Development Fund within the Operational Programme "Science and Education for Smart Growth 2014 - 2020" under the Project CoE "National center of mechatronics and clean technologies" BG05M2OP001-1.001-0008

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