International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Review Article on the Femto-Second Laser Induced Lipss on Metal Surface

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ABSTRACT

The femtosecond laser is widely applied in biomedical fields for its unique properties, including ultra-short pulses, high peak power, and precise control. As a method for surface modification, femtosecond lasers can generate various surface patterns on metals, enhancing characteristics like wear resistance, wettability, and biocompatibility. PRI after irradiation of linearly polarized laser light are said Laser induced periodic surface structures abbreviated as LIPSSs. This article compares LIPSS generated on metallic substrates with types of LIPSS and provides experimental results of their consequences.

The work is centered with the generation of LIPSS on semiconductors, metals and dielectrics using linear polarization femtosecond laser with temporal structures, duration of each pulse 30 – 150 fs and wave length 800 nm in air ambient environment. It was observed that in metals mainly out-of-plane The periodic structures associated with low spatial frequency LIPSS have periods close to the laser wavelength. are found perpendicular to the direction of vibration of the electric field of a laser light.

Using a pump-probe setup, we monitor surface modifications in real time under varying pulse counts. Additionally, the study explores novel annular microstructures on stainless steel (SUS 304), created by directing a femtosecond laser through a microhole to the metal surface. This it is postulated that these structures are formed interference between the incident laser beam and reflecting beams from the inner surface of the microhole.

Keywords: Bismuth (Bi), laser induced periodic roughness, laser induced periodic roughness, Nano electronics and Nano photonics.

Introduction

More recently, the article reveals that Laser induced periodic surface structures (LIPSS) have received more attention by researchers., and this is attributed to the commercial availability of the femtosecond (fs) lasers and the fact that only the fs laser pulse irradiation of solid materials can produce LIPSS with spatial periods $\lambda<\Lambda$ [1]. A femtosecond laser emits pulses that last only a few femtoseconds, allowing for highly precise, ultra-short exposure times. Consequently, , LIPSS can be produced in a one step, enabling Nano scale surface structuring that can modify optical, mechanical, or chemical properties, suitable for a variety of applications [2].

Femtosecond lasers hold promising potential in the biomedical field, especially in improving the biocompatibility of medical implants. Methods to enhance biocompatibility include altering alloy compositions, designing porous structures, and employing surface treatment processes. With femtosecond lasers, distinct shapes can be etched on metal surfaces to improve properties such as wear resistance, wettability, and biocompatibility. Due to their high peak power, and ultra-short pulses femtosecond lasers can produce more regular and deeper periodic structures across diverse materials like metals, semiconductors, dielectrics, and polymers, all while minimizing thermal effects. This capability offers new possibilities for materials science and surface engineering [3].

In modern technology, the demand for surface Nano structuring and functionalization has grown, particularly with the push for simpler processing methods and smaller structural features. Femtosecond lasers, with their precision and unique advantages, have become a focal point of interest. A particularly promising approach involves generating LIPSS through a single-step irradiation process using linearly polarized laser pulses, showcasing the efficiency and precision of femtosecond lasers for surface Nano structuring [4].

Ultra-short laser irradiation provides a robust and cost-effective alternative to lithography for Nano structuring surfaces, enabling the formation of LIPSS on various materials. LIPSS create a periodic surface relief that can be categorized into two primary types: low-spatial- frequency and high-spatial-frequency distinguished by their periodicity [5].The formation of LIPSS on metals is generally attributed to the interference between the incident laser beam and surface Plasmon waves excited on the material's surface. Recent studies on LIPSS have focused on modifying the biological, optical, and mechanical properties of different materials [6].

These structures, which appear as quasi-periodic topographic lines resembling a linear surface grating, are classified by their spatial periods (Λ) and orientation relative to the polarization of the laser beam [7]. In literature, LIPSS may also be referred to as ripples, Nano ripples, near-wavelength structures, or deep-sub-wavelength structures. Other surface structures, such as hexagonally arranged nonmetric protrusions and micrometric grooves or spikes, are sometimes described as forms of LIPSS [8].

LIPSS are further categorized based on the spatial period-to-wavelength ratio (Λ/λ) and the polarization direction of the laser beam used. They are classified into two main categories: two types, including the low-spatial-frequency and the high-spatial-frequency.

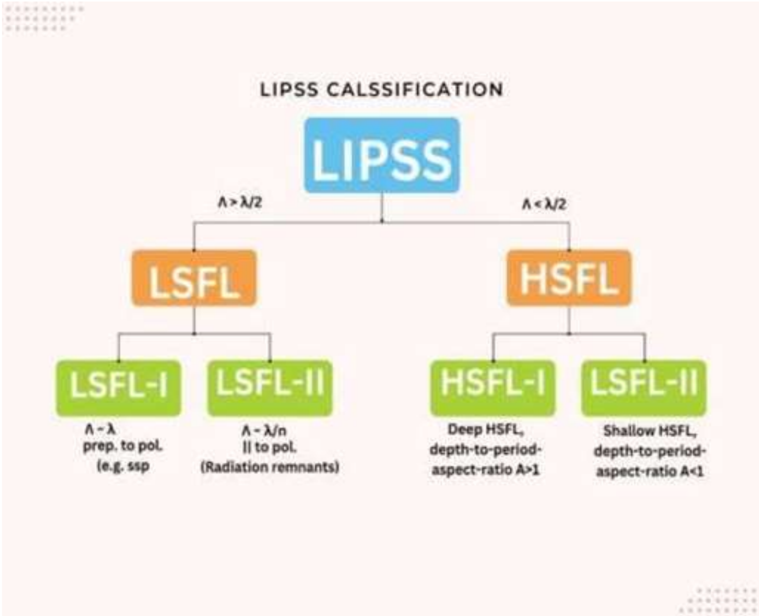

Fig. 1 - Classification of Femto laser-induced periodic surface structure

Several parameters—such as laser peak fluence, pulse count, polarization state, pulse duration, and environmental conditions—are crucial in the formation of laser-induced periodic surface structures (LIPSS).

The fluence of the laser, for example, significantly affects LIPSS morphology, allowing different LIPSS types to form on the same material by adjusting fluence levels [9]. Increasing the number of pulses leads to more regular LIPSS formation; with higher pulse counts, surface roughness rises, LIPSS periods decrease, and both pit depth and microstructure height increase [9].

The polarization state of the laser beam also influences the characteristics of the modified surface. The orientation and form of LIPSS depend on the polarization direction, with circularly polarized beams producing triangular periodic structures and elliptically polarized beams generating spherical nanoparticles [10]. Additionally, pulse duration is an important factor, as different pulse types (nanosecond, picosecond, and femtosecond) yield varied surface morphologies. Beyond laser-specific parameters, the surrounding environment plays a substantial role in determining the surface structure post-irradiation [11].

In this paper, we reviewed multiple studies on femtosecond laser-induced LIPSS on metal surfaces to identify research gaps and highlight different perspectives on the subject. Ultimately, we compared findings to determine the most effective methods for femtosecond laser- induced LIPSS, offering recommendations for future research directions to advance the field.

Literature Review

The formation of periodic nanostructures following single-beam laser irradiation is a fascinating area of study. Notably, the periods of femtosecond LIPSSs vary significantly with changes in laser fluence and pulse overlap, making the formation mechanisms of LIPSS complex to understand. A variety of experimental, theoretical, and numerical studies have been conducted, with several models proposed to explain LIPSS formation [12]. The commercial availability of ultra-short pulse lasers has recently enabled research into the use of these lasers to create periodic surface structures for functional micro-nano structure fabrication. Research has shown that femtosecond laser-generated periodic structures often exhibit ripple periods shorter than the laser wavelength [13].

Several researchers have explored femtosecond laser-induced LIPSS on metal surfaces. For instance, Chung-Wei Cheng et al. developed novel annular microstructures on stainless steel (SUS 304) by directing a linearly polarized femtosecond laser beam (800 nm, 120 fs, 1 kHz, Gaussian profile) through a microhole to the surface [14]. The results indicated that periodic annular structures, with periods of approximately 4-5 μm, were formed due to multiple reflections within the microhole or protrusion structure.

In another study, Shijie Song and Qinghua Lu [15], reviewed theories behind ultra-short pulse laser ablation and the formation of periodic structures on material surfaces. Their review covered electromagnetic and matter reorganization theories, focusing on the two-temperature model widely used in simulations of ultra-short pulse ablation. They discussed how this model aids in understanding the formation of periodic micro- and nanostructures on surfaces after ultra-short laser pulse ablation.

Yuchan Zhang and Qilin Jiang examined LIPSS formation mechanisms using pump-probe imaging techniques. They highlighted how Femtosecond laser pulse shaping—considering time/frequency, polarization, and spatial distribution—is effective for fabricating high-quality LIPSS. They also explored various applications of LIPSS and the importance of shaping ultra-fast lasers for efficient, high-quality processing [16]. Hongfei Sun, Jiuxiao Li, and Mingliang Liu reviewed the role of LIPSS in biomedical applications. They discussed the impact of laser parameters, such as energy, pulse count, polarization, and pulse duration, on LIPSS generation. This review also covered how femtosecond laser-modified LIPSS can be applied in functional surfaces, control of surface wettability, cell colonization, and enhanced tribological properties [17].

Camacho-Lopez, and Camacho-Lopez [18], have studied fabrication of the LIPSSs on bismuth thin films using the nanosecond laser. They characterized the formation and destruction of LIPSS based on establishing that the structures created were aligned perpendicular to the laser polarization and that the ripple frequencies approximated the laser wavelength.

Lipss have broad applicability in Nano electronics and Nano photonics. However, understanding the full Still, the formation mechanism of LIPSS poses a problem; the current research is mainly concerned with individual structures such as low-spatial-frequency LIPSS (LSFL) and laser-induced periodic annular surface structures (LIPASS). [19]. Real-time, in situ monitoring using pump- probe setups has been used to study surface modifications under varying pulse conditions [20].

Methodology and Results

Sub-100 nm LIPSS in titanium have been produced by J. Bonse et al., employing a one-step processing with air ambient environment. The team using commercial chirped pulse Ti Titanium: sapphire lasers to produce linearly polarized laser pulses of duration of 30 to 150 femtoseconds at a central wavelength of 790–800 nm (1.55 eV single photon energy) and repetition rate of 10 Hz or 1 kHz. For a diverse optical band gap range, they tried three different materials—titanium, silicon, and fused silica. For this study, the titanium samples used were chosen due to their high strength-to-weight ratio, high corrosion- and heat-resistance; the CTS8 titanium was machined and mechanically ground and polished into $10 \times 10 \times 1$ mm³ samples. Regarding the semiconducting armature, monocrystalline silicon wafers with 1.1 eV bandgap and 400 m thickness were incorporated, and for dielectric armature fused silica with 7.8 eV bandgap was employed.. This research provided strong evidence of the critical role of transient optical property changes in fs-LIPSS formation. Furthermore, the findings underscored the potential of ultra-short laser pulse sequences for precise LIPSS control, especially in materials with wide band gaps.

In another study, Xiaohan Yu, Dongeng Qi, and Hongyang Wang applied a pump-probe setup to enable monitoring and simultaneous, in situ characterization of surface changes at varying pulse counts. They observed that low-spatial-frequency LIPSS (LSFL) initially formed on the surface after two laser shots. As the laser shots increased, As for the nanostructure lasing, which was first reported as laser induced one dimensional periodic structure (LIOPS), has now become the dominant morphology. Due to enhanced local fields around the surface ripples. Continued laser exposure led to the mechanism of Nano pillars formation as transition from LSFL to high-spatial-frequency LIPSS (HSFL) oriented parallel to the laser polarization. The pump-probe setup revealed distinct surface morphologies—LSFL, LIOPS, and laser-induced periodic annular surface structures (LIPASS)—as a function of accumulated pulse counts, providing insights into the dynamic morphological evolution during laser ablation.

Another study focused on the formation of femtosecond LIPSS within a microhole setup. In this approach, a femtosecond laser (800 nm, 120 fs, 1 kHz, Gaussian profile, linearly polarized) was directed through a microhole to irradiate the surface of stainless steel (SUS 304) under various laser powers and pulse counts. Using an adjustable objective lens (10×, 0.26 NA), the team could focus the beam precisely, and surface characteristics were assessed with scanning electron microscopy (SEM). This novel method enabled the creation of micro/nanostructures on metal surfaces, where annular microstructures with a period of approximately 4–5 μm were observed. The formation of periodic annular structures was attributed to the multiple reflection effects produced within the microhole or by the protruding structure, showcasing the potential of femtosecond lasers in creating advanced surface patterns.

Conclusion

The femtosecond laser has become invaluable in biomedical applications, thanks to its ultra-short pulses, high peak power, and exceptional precision. Studies have investigated the formation of LIPSS across various materials—including dielectrics, semiconductors, and metals when exposed to linearly polarized femtosecond laser pulses (lasting 30–150 fs, with a wavelength of 800 nm) in an air environment. . The low spatial frequency LIPSS are observed to form with periods that are close to the laser wavelength and lie perpendicular to the polarization direction in metals.

This configuration is employed to allow monitoring of surface transformation in real-time and in situ for varying pulse number. This study also examines the fabrication of novel annular microstructures on metal surfaces by directing a femtosecond laser beam through a microhole to irradiate stainless steel

(SUS 304). It is suggested that the mechanism behind this structure formation involves the interference between the incoming laser beam and reflections from the microhole walls.

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