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Perspective

Delving into the science of capillary effect for laser polishing

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Abstract:
Laser polishing techniques offer promising solutions for enhancing surface quality in precision surface finishing. By harnessing laser beams, this method provides efficient and controllable surface treatment, which is crucial for achieving desired surface smoothness and optical performance. Central to this process is the capillary effect driven by surface tension, which facilitates fluid flow on solid surfaces. Despite advancements, challenges persist in predicting and controlling capillary flow due to its complex nature. This paper explores the role of the capillary effect in laser polishing, outlining fundamental principles, discussing influencing factors, and proposing strategies for optimizing polishing outcomes. Understanding and manipulating the capillary effect holds the key to unlocking the full potential of laser polishing, offering avenues for improving surface finishes and material properties across various applications.

1. Introduction

High-performance optical components find widespread applications in various fields, particularly in high-precision optical imaging (Pan et al., 2022), optical sensing (Dorrah and Capasso, 2022), optical communication (Liu and Lin, 2024), and space exploration. These applications demand stringent requirements for the surface quality of optical components, including extremely low surface roughness, defect-free surface structures, and outstanding optical performance (Huang et al., 2024). Traditional polishing techniques such as mechanical polishing, chemical mechanical polishing, and ion beam polishing have been extensively studied and applied to meet these requirements. However, these techniques have certain limitations in handling complex-shaped components with desired efficiency environmental sustainability.

In recent years, laser polishing technology has garnered considerable attention as an emerging surface treatment method (Li et al., 2020; Cui et al., 2021; Tan et al., 2022; Yu et al., 2023). It utilizes laser beams to process the material surface, achieving effective control and improvement of surface roughness through the interaction between laser and material (Fig. 1). Laser polishing technology offers advantages such as non-contact operation, high efficiency, strong controllability, and environmental friendliness, effectively addressing some of the issues faced by traditional polishing techniques. Moreover, the versatility of laser polishing allows it to be applied to nearly all types of materials (Shao et al., 2005; Niitsu et al., 2019; Zhao et al., 2019; Zhang and Chen, 2020; Zhang et al., 2020; Xu et al., 2021a; Mushtaq et al., 2023) (Fig. 1), making it an extremely broad-spectrum surface treatment solution.

Laser polishing is a special type of polishing method. Based on the interaction between laser and material, laser polishing can be classified into two categories: thermal polishing based on thermal effects, such as laser ablation (Peng et al., 2023), laser melting (Xiao et al., 2022); and cold polishing based on nonlinear optical effects (such as multiphoton absorption, tunnel ionization, or super barrier ionization), such as photochemistry (Sato and Nishio, 2001) and photoionization (Chen et al., 2022) (Fig. 1). Among

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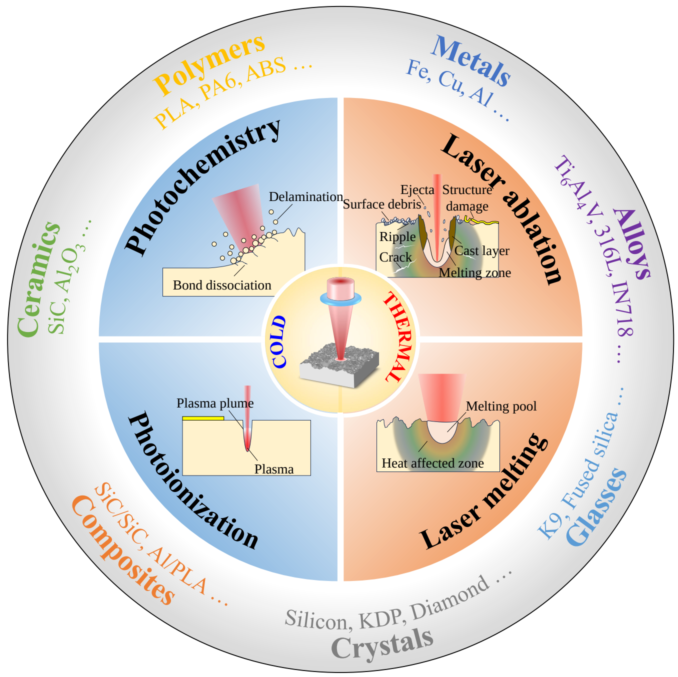

Fig. 1. Laser polishing classification and applicable materials.

them, laser melting, as a non-material removal laser polishing method, has its unique characteristics and advantages. Non-material-removal laser polishing involves using a laser to control the melting and solidification of the material, filling in minor surface defects, and achieving surface smoothness. Non-material-removal polishing typically does not introduce new surface defects, thus enabling higher surface quality to be achieved. Surface tension plays a crucial role in this process. Capillary effect is the spontaneous flow phenomenon of fluid on a solid surface driven by surface tension, influenced by factors such as liquid viscosity, density, solid surface shape and roughness, temperature distribution (Cai et al., 2021). During laser polishing, by controlling the capillary effect, significant improvement in surface smoothness of the material can be achieved (Xiao et al., 2022), enhancing its optical performance (Temmler et al., 2021), and microstructural changes (Huang et al., 2024) at the material surface can be controlled to improve surface hardness (Hong, 2024) and corrosion resistance (Li et al., 2023).

Significant progress has been made in the research on capillary effect recently. A combination of experiments and numerical simulations have been employed to delve into the physical mechanisms of capillary flow. For instance, by varying parameters such as laser power (Chang et al., 2016), pulse width (Temmler et al., 2020), and focusing conditions (Zhang et al., 2022), the influence of these parameters on capillary flow has been revealed. Additionally, by studying the thermal and physical properties of different materials (Li et al., 2019), such as melting point, thermal conductivity, specific heat capacity, and surface tension, a deeper understanding of capillary flow behavior in different materials has been attained.

Despite the progress made in the research on capillary effect, there are still some deficiencies and challenges in existing studies. Firstly, the physical mechanism of capillary flow is complex, influenced by multiple factors such as material microstructure, surface condition, laser parameters, making prediction and control of capillary flow difficult. Furthermore, existing research primarily focuses on the fundamental laws of capillary flow and surface treatment of single materials, while research on capillary flow in composite materials and complex surfaces is relatively lacking (Cai, 2021). This limits the broader application of laser polishing techniques.

This paper aims to investigate into the surface tension-driven surface topological dynamics in the laser polishing process. It elaborates on the basic principles of laser polishing, including the melting process and capillary effect dynamics, and discusses the influence of surface tension on surface morphology at different stages. Additionally, we discuss possible surface defects that may occur during the laser polishing process and how to optimize polishing effectiveness by adjusting laser parameters and process routes.

2. Surface topography evolution driven by capillary flow

In laser melting-based polishing, surface tension stands as one of the fundamental driving forces for surface morphology flattening. Surface tension arises from the mutual attraction between surface molecules of a substance and is typically expressed by:

$$\sigma_n = k\gamma \tag{1}$$

where σ_n is the surface tension, k is the curve of the surface profile, and γ is the surface tension coefficient. The direction of surface tension is perpendicular to the liquid surface and points towards the interior of the liquid. The action of surface

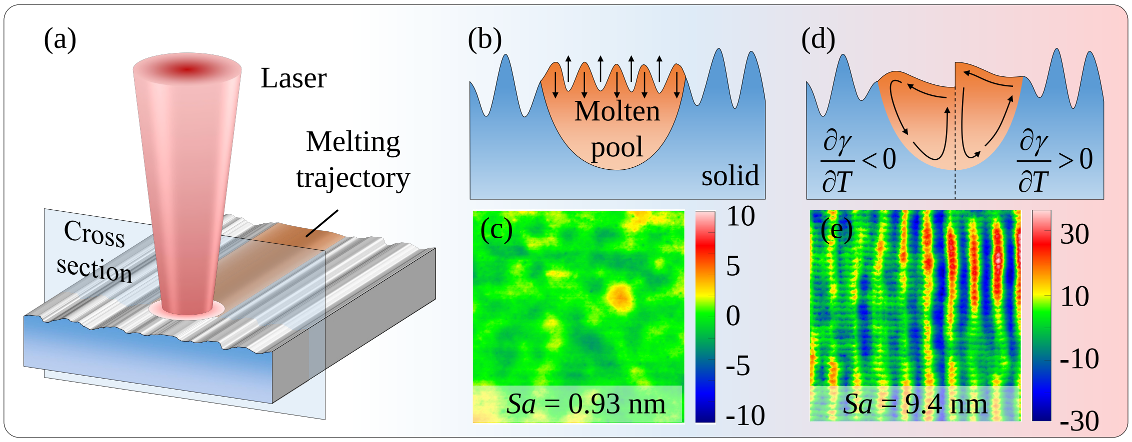

Fig. 2. (a) Schematic diagram of laser polishing, (b) the effect of surface tension, (c) the corresponding polished surface, (d) the effect of thermal capillary force and (e) the corresponding polished surface.

tension results in the surface exhibiting a characteristic of minimizing surface area, known as the principle of minimum surface energy (Huang and Zhou, 2020; Huang et al., 2022). The surface energy of a rough surface is greater than that of a smooth surface, thus during the laser polishing process, surface tension propels the material in the molten pool from high areas to low areas, filling in surface grooves and depressions to achieve surface smoothness (Figs. 2(b) and 2(c)). Metaphorically, laser polishing is akin to the melting of cheese shreds on a pizza in an oven, spreading evenly over the crust.

Laser polishing is the outcome of multiple pulse cycles superimposed. Within a single pulse cycle, the laser beam irradiates the material surface, and the input energy is absorbed and converted into heat energy, rapidly raising the material surface temperature above the melting point. At this point, the surface layer material transitions into a molten state, forming a molten pool. The formation and evolution of the molten pool involve a complex thermofluidic dynamic process, encompassing phenomena such as heat conduction, melting, flow, and solidification.

The effect of surface tension manifests itself in the initial formation of the molten pool. As the material begins to melt, surface tension drives the surface morphology of the molten pool towards minimizing surface area. With continuous laser irradiation, the depth and width of the molten pool gradually increase, and the action of surface tension also changes accordingly. Some scholars approximate this surface smoothing process as a finite-time decay problem of capillary waves (Vadali et al., 2012). The amplitude for effective decay yields a critical frequency λ_{cr} for the minimum surface morphology, correlated with material viscosity (μ), density (ρ), and process parameters, which can be described as:

$$\lambda_{cr} = \sqrt{\frac{8\pi^2 \mu t_d}{\rho}} \tag{2}$$

where t_d is the melting duration. In the later stages of laser polishing, as the laser ceases and the molten pool solidifies, the surface morphology is ultimately determined. During the solidification process, material volume shrinks, which may lead to the formation of tiny cracks or voids on the surface. To minimize these defects, adjusting laser parameters such as power, scanning speed, and pulse frequency can optimize the cooling rate of the molten pool and the solidification process (Wang and Wang, 2016). Appropriate laser parameters can ensure that the molten pool maintains sufficient fluidity during solidification so that surface tension can continue to play a role in the final stage, recover any potential defects that may arise. The time from melting to solidification of the material is termed as the melting duration, which is related to laser power, frequency, pulse width, beam waist size, and scanning speed, serving as a key parameter determining the surface morphology of polishing. The evolution from melted rough surface to minimum surface area state takes time. Suppose the time required for flattening a certain size of morphology is denoted as t^*. In that case, when $t^* < t_d$, surface tension has sufficient time to allow the surface to evolve fully to a flat state; when $t^* > t_d$, the rough structure solidifies before complete flattening, failing to achieve the optimal polishing effect.

3. Surface morphology evolution driven by thermal capillary flow

At this point, it may seem reasonable to infer that longer melting durations allow rough surface structures more time to evolve towards minimum surface area, and the spatial wavelength of recoverable rough structures becomes larger, which also aligns with the relationship expressed in Eq. (2). However, reality proves otherwise. Increasing the melting duration primarily involves two main methods: firstly, increasing the pool temperature to prolong cooling time; secondly, enlarging the pool size to extend solidification time. This can lead to three related operations: increasing laser power, enhancing laser pulse width, and expanding beam diameter. Both the first and second methods aim to raise the pulse energy density to increase the pool temperature. Typically, laser beam energy follows a Gaussian distribution, with energy density decreasing from the center to the edge. Therefore, higher power can result in higher temperature gradients, thereby exacerbating the Marangoni effect, i.e. surface flow in the presence of surface tension gradient. Increasing pool size can further be subdivided into two approaches: increasing energy, which is similar to the first method, and enlarging beam diameter. Laser beam diameter is usually defined as the size corresponding to the maximum power attenuation value of $1/e^2$, hence larger Gaussian beam diameters tend towards uniform energy distribution. In theory, uniform energy distribution is conducive to reducing temperature gradients. Still, increased pool size can elevate the Marangoni number, leading to Marangoni instability-induced surface ripples (Xu et al., 2023). Therefore, the comprehensive impact of pool size on polishing effectiveness remains inconclusive (Temmler et al., 2020):

$$\sigma_\tau = \frac{\partial \gamma}{\partial T} \nabla T \tag{3}$$

In summary, increasing melting duration may enhance thermal capillary forces, the mechanism of which can be understood from the temperature dependence of surface tension and is expressed as Eq. (3). Temperature gradients induced by laser irradiation cause surface tension gradients within the pool, driving liquid flow from high surface tension areas to low ones (termed thermal capillary flow or Marangoni flow). Under the action of shear forces between fluid layers, this flow drives the redistribution of solutes throughout the molten pool. During laser polishing, a certain degree of thermal capillary flow can facilitate the redistribution of fluid within the pool, aiding in filling surface depressions and irregularities, thus improving material surface quality. However, excessively intense thermal capillary flow can lead to pool deformation. For most materials such as metals, crystals, and ceramics, surface tension is negatively correlated with temperature, i.e., $\partial \gamma / \partial T < 0$, driving the material flow from the center to the edge of the pool, causing central depression (Figs. 2(d) and 2(e)). Rapid outward flow near the pool edge abruptly slows down, resulting in unstable rising pools and oscillations under continued thermal capillary flow. These oscillations may persist for a short time after the pulse ends, disrupting solidification at the pool edge and leading to ripple formation (Anthony and Cline, 1977). If the material is doped with surfactants such that $\partial \gamma / \partial T > 0$, the situation is reversed, and rapid inward surface flow can cause the pool surface to bulge (Fig. 2(d)). Although the bulging pool surface near the center may oscillate, its effect is limited since solidification occurs at the pool edge, resulting in no significant ripples post-solidification (Kou et al., 2011). Additionally, there exists a scenario where the trend of surface tension development is opposite before and after the critical temperature T_c, i.e., $\partial \gamma / \partial T \mid_{T=T_c} = 0$, $\partial \gamma^2 / \partial T^2 \mid_{T=T_c} \neq 0$, termed mixed thermal capillary temperature gradient (Shen et al., 2017; Xu et al., 2021b). Due to the opposite direction of thermal capillary flow before and after the critical temperature, it can alleviate the height of protrusions to a certain extent, and the resulting temperature gradient changes and solidification rate variations may affect crystal growth and microstructure formation during solidification, possibly resulting in different scale solidification microstructures in different regions of the pool (Lee and Farson, 2015).

Surface structures generated by thermal capillary flow are typically above the hundred nanometers scale, which is advantageous for applications with surface roughness greater than this magnitude, such as additive manufacturing. However, for nanometer or even sub-nanometer level roughness, where surface tension primarily governs, thermal capillary flow may deteriorate surface quality.

4. The role of Capillary effect in laser polishing

Given that thermal capillary flow may increase surface roughness (Figs. 2(c) and 2(e)), can polishing parameters be controlled to allow the polishing process to be solely governed by surface tension, thus achieving optimal surface roughness? The answer is negative. Avoiding thermal capillary flow implies low power density, resulting in smaller pool sizes and melting durations. Taking single crystal silicon as an example, when polishing with a nanosecond pulsed laser at a wavelength of 532 nm, with surface tension dominance, the melting depth is in the hundreds of nanometers, and the melting duration is around 100 ns (Xiao et al., 2022). Despite achieving sub-nanometer surface roughness, the disadvantages are evident, it requires preprocessing to provide a relatively good initial surface quality. If there are micrometer-level protrusions or depressions on the surface to be polished, low-power energy cannot completely melt the rough structure, resulting in limited reduction of roughness. The peak flow velocity at the pool surface is of the order of meters per second, meaning that even if micrometer structures are completely melted, the extremely short pool duration cannot meet the need to achieve minimal surface area fully. Therefore, solely relying on low-power polishing dominated by surface tension is insufficient for all situations.

Since capillary force and thermal capillary force dominated polishing processes are geared towards different scales, deficiencies of a single recover method can be compensated for by employing a relay polishing approach (Pfefferkorn et al., 2013). Initially, high-power lasers are used to redistribute solutes driven by thermal capillary flow, reducing surface peaks and valleys to depths within the melting depth that low power can cover, with the spatial frequency of protruding structures exceeding the critical frequency. Subsequently, low-power lasers are utilized to further reduce surface roughness on structures that have already reached the surface tension polishing capability. If necessary, this process can be further subdivided, employing a multi-step laser relay approach to polish. Therefore, in practical applications, it is essential to comprehensively consider the initial morphology of the sample and the target roughness, and to coordinate the effects of surface tension and thermal capillary forces on surface structure appropriately.

5. Conclusions

In summary, surface topography evolution driven by capillary effect plays a crucial role in laser polishing. By comprehensively considering laser parameters and material characteristics, the laser polishing process can be optimized to maximize surface quality. Additionally, utilizing a multi-laser relay polishing approach can effectively overcome the limitations of a single polishing method, achieving a higher level of surface roughness control. Given the current research status and application demands, there is a need to develop more precise multiscale simulation methods to comprehensively understand the physical mechanisms of capillary flow from the micro to macro scales, especially under complex material and surface conditions. Research is also needed on how to optimize material surface conditions through preprocessing and real-time monitoring methods to improve the effectiveness of capillary flow and the quality of laser polishing.

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Conflict of interest

The authors declare no competing interest.

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