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Laser polishing of hard and brittle materials: A review

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Abstract

Hard and brittle materials (HBMs) are widely employed across various industries due to their exceptional mechanical properties. However, their inherently high hardness and brittleness pose significant challenges in machining, often resulting in surface and subsurface damage during production, particularly in mechanical operations. Such damage degrades surface roughness and compromises overall surface integrity. Laser polishing has emerged as a promising solution to mitigate fabrication-induced defects and enhance both surface quality and accuracy. This review examines recent advances in laser polishing of HBMs, focusing on the principles of laser polishing mechanism, heat transfer and fluid flow including analytical and numerical modelling. Also, experimental studies to enhance surface integrity including surface roughness, morphology, microstructure, and hardness are discussed. The paper concludes by outlining potential future directions and research prospects aimed at overcoming current limitations and further advancing laser polishing techniques for HBMs.

Keywords: Laser polishing; Hard and brittle materials; Heat transfer and fluid flow, Surface integrity

1. Introduction

Hard and brittle materials (HBMs), such as ceramics, glasses, semiconductors, etc., are widely used in a broad range of various industries such as aerospace, power electronics, semiconductors, medical implants, military etc., due to their excellent chemical and physical properties such as chemical stability, high thermal resistance, low thermal conductivity, high hardness, wear resistance, wide energy bandgap, etc [1]. Although HBMs are considered preferred candidates for key components, especially those operating in harsh and elevated temperatures, they usually show poor machinability because of their hard and brittle properties. Damages such as surface and subsurface damage often occur during machining of hard and brittle materials, which not only leads to the degradation of surface quality, but also directly influences the function and performance of the HBMs components. To overcome these challenges, conventional polishing process as well as several newly developed polishing processes such as chemical-mechanical polishing (CMP) [2], plasma-assisted polishing (PAP) [3], magnetorheological finishing (MRF) [4], etc., have been used to remove above-mentioned surface/subsurface damages. Laser polishing is a newly promising approach that can be used to polish a wide range of workpiece materials especially those that are difficult to polish by conventional manufacturing techniques. However, the wide application of laser polishing in HBMs is limited by the several challenges including temperature control, melt pool evolution dynamics, and the formation of heat-affected zones (HAZs). Moreover, the selection and precise control of laser processing parameters are critical to maintaining optimal surface integrity.

This paper provides a review on recent advances in laser polishing of HBMs. It begins by examining a summary of the fundamental principles of laser polishing and the mechanisms governing laser polishing. The discussion then focuses on the heat transfer, fluid flow, melt pool evolution, and HAZs.

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Analytical and numerical models for the heat transfer and melt pool dynamics are highlighted. The review further addresses the influence of laser processing parameters on the surface integrity including surface roughness, morphology, microstructure, and hardness. The paper concludes with an overview of the key findings and prospects for future developments in laser polishing of HBMs.

2. Laser polishing mechanism

Laser polishing is a surface refinement technique that relies on localized remelting rather than material removal, distinguishing it from conventional polishing methods. Figure 1 presents a schematic of the laser polishing process. Upon laser irradiation, the surface layer rapidly absorbs heat, inducing localized melting or vaporization, depending on the laser intensity and pulse duration. The phase transition from solid to liquid or gas facilitates material flow, and as the laser beam traverses the surface, capillary pressure, surface tension, and gravity redistribute the molten layer, resulting in a smoother finish. Laser polishing can be categorized into thermal polishing (photothermal effect) and cold polishing (photochemical effect) [5]. In thermal polishing, a continuous wave (CW) laser generates a high-power density, melting surface asperities and allowing material flow into valleys, thus reducing roughness. This process follows two mechanisms: surface over-melting (SOM) and shallow surface melting (SSM). In SOM, the melted layer depth exceeds the peak-valley height, leading to full surface liquefaction and periodic structures under thermal capillary forces. In SSM, partial melting occurs, with the melted layer depth equal to or less than the peak-valley height, enabling roughness reduction under capillary pressure, surface tension, and gravity. In contrast, cold polishing employs short and ultrashort pulse lasers, where photon energy exceeds the material's bond strength, disrupting the lattice structure and removing surface imperfections via vaporization. This photochemical process results in a refined surface topography without significant thermal effects. Although thermal polishing has been used for HBMs [6], its associated large HAZs and defects (e.g., debris, microcracks, oxidation) [13], limit its application. Short/ultrashort wavelength lasers (nanosecond, picosecond, femtosecond) are preferred for micro-polishing due to reduced thermal impact, making cold laser polishing more suitable for HBMs. Table 1 summarizes the advantages and drawbacks of both approaches.

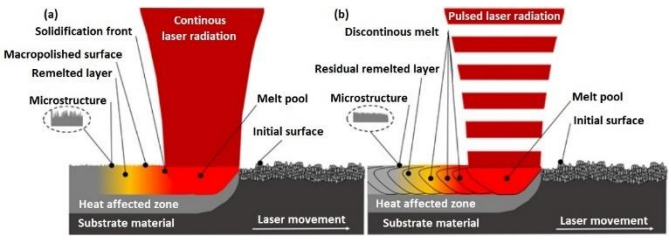

Fig. 1. Schematic of laser polishing; (a) continuous laser radiation and (b) pulsed laser radiation [7].

Table 1. Advantages and drawbacks of thermal and cold polishing [8].

Polishing	Thermal polishing	Cold polishing
Mechanism	Thermal accumulation, the surface material is melted and evaporated.	Chemical bonds rupture, causing the molecules to dissociate and subsequently vaporize.
Type of laser	Continuous or long-wavelength or long-pulse lasers	Short/ultrashort laser pulse, high pulse energy, short/ultrashort laser wavelength
Advantages	High polishing efficiency	Easy to control polishing thickness, no micro-cracks
Drawbacks	Substantial temperature gradient, internal stresses, micro-cracks	Low polishing efficiency
Application	Rough polishing of materials with better physical properties	Material difficult thermally polished, fine polishing of precision instruments

3. Heat transfer and fluid flow

Laser polishing relies on localized heating, melting, and flow of the surface layer. Understanding temperature gradients, melt pool evolution, and surface tension is vital for controlling surface quality. Accurate heat-transfer and fluid-flow modelling clarifies how process parameters influence these phenomena, enabling defect minimization and process optimization, particularly for hard and brittle materials with unique thermal and mechanical sensitivities. Researchers employ both analytical and numerical modelling to investigate the underlying physics.

3.1. Analytical modeling

The analytical modeling of laser polishing can be categorized into two distinct components: laser beam model and laser polishing model [9].

3.1.1. Laser beam model

Most laser polishing models link the beam to its energy source, commonly using Gaussian or top-hat profiles, Gaussian being more studied [10]. The power per unit volume of a Gaussian beam in cylindrical coordinate system is defined as [11]:

$$I(r,z) = I_0 exp\left(-2\frac{r^2}{\omega^2}\right)^2 \quad (1)$$

Where I_0 is peak power, r is the distance from the laser beam center, and ω is the Gaussian beam waist radius. The peak power peak is defined as [12]:

$$I_0 = \frac{2P}{\pi\omega^2} \quad (2)$$

Where P is the laser power. For a top-hat (flat-top) profile, the Beer-Lambert law implies exponential intensity decay with depth z [10]:

$$I(z) = I_{surf} e^{-\omega z} \quad (3)$$

Where I_{surf} represents surface intensity and ω represents attenuation coefficient.

For pulsed lasers, time is crucial in modeling, with such lasers represented as volumetric heat sources (q_v) in the enthalpy-based energy balance equation [13]:

$$q_v = I_0 A(1-R)exp(-zA)exp\left(-\left(\frac{r}{\omega}\right)^2\right)f(t) \quad (4)$$

Where, R represents the reflectivity, A represents the absorptivity, and $f(t)$ represents the distribution of laser pulse intensity. The pulse lasers typically adhere to a trapezoidal temporal distribution, which is expressed as [13]:

$$f(t) = \begin{cases} 0, & t = 0 \\ 1, & t_r < t < t_f \\ 0, & t = t_p \\ 1, & t_p < t < t_c \end{cases} \quad (5)$$

Where t_r is pulse rise time, t_f is pulse fall time, t_p is pulse length, and t_p is cooling period.

Some researcher tried to develop some models based on the principle of this analytical modelling. Niitsu et al. [12] optimized laser recovery of silicon wafers, achieving a minimum surface roughness (Sa) of 1.1 nm within a peak irradiance range of 3.92×10^7 to 5.23×10^7 W/cm² and a pulse width of 38 ns. Chen et al. [14] utilized a two-temperature model (TTM) to predict selective polishing of RB-SiC, demonstrating significant differences in ablation thresholds between Si (0.066 J/cm²) and SiC (0.168 J/cm²). Acosta-Zepeda et al. [15] developed an analytical model to describe the evolution of interfacial melt pools and subsequent thermocapillary flows, accurately predicting the formation of dimple-shaped surface topographies. Xu et al. [16] proposed a mathematical model to elucidate the mechanism of roughness formation during femtosecond polishing, emphasizing the importance of optimizing lower laser energy utilization through careful selection of offset distance.

The majority of the currently available models establish a connection between the laser beam and the energy sources. The current models are based on the either Gaussian or Top-hat laser beam distribution. These models use the parameters of laser beam sources such as power, radius of beam, wavelength, etc., in order to calculate the energy applied to the surface material. However, the main limitation of these models lies in their neglect of the main driving forces such as Marangoni force (thermocapillary force), surface tension (capillary force), recoil pressure, and fluid flow, which significantly impact laser polishing performance.

3.1.2. Laser polishing model

Accurately formulating heat transfer equations is essential for describing laser beam energy generation and transfer. Figure 2 presents a schematic of the melt pool and its boundary conditions. The governing equation for heat transfer within a fluid is defined as [17]:

$$\rho C_{mp}\left(\frac{\partial T}{\partial t} + \nabla.(uT)\right) = \nabla.(k\nabla T) \quad (6)$$

where ρ represents density, T represents temperature, t represents time, k represents thermal conductivity, u represents velocity in the melt pool, and C_{mp} represents modified heat capacity, which can be expressed as [18]:

$$C_{mp} = C_p + L_m \frac{df_L}{dT} \quad (7)$$

Where C_p represents heat capacity, L_m represents latent heat of melting, and f_L represents fraction of liquid, which is defined as [17]:

$$f_L = \begin{cases} 0 & T \le T_s \\ \frac{T-T_s}{T_L-T_s} & T_s \le T \le T_L \\ 1 & T \ge T_L \end{cases} \quad (8)$$

where T_s and T_L represents the solid and liquid temperature of material, respectively. As depict in Fig. 2, there are 4 boundary conditions. The boundary 2 is affected by the heat flux of laser beam, convection, and radiation from surface to ambient, which can be described as [19]:

$$-k\nabla T = \alpha I - q_e + h(T - T_a) + \varepsilon\sigma(T^4 - T_a^4) \quad (9)$$

Where α represents the material absorption, q_e represents heat flux of evaporation, h represents the coefficient of convective, T_a represents the temperature of ambient, ε represents the emission of radiation, σ represents the constant of Stefan–Boltzmann, and I represents the heat flux of laser beam with Gaussian distribution, which can be expressed as [19]:

$$I = \frac{2P}{\pi r_b^2} exp\left\{\frac{-2(x-vt)^2}{r_b^2}\right\} \quad (10)$$

Where P represents laser power, r_b represents laser beam radius, v represents laser scanning speed. The boundaries 1 and 3 are subjected to convection and the radiation from surface to ambient There is an adiabatic boundary at boundary 4.

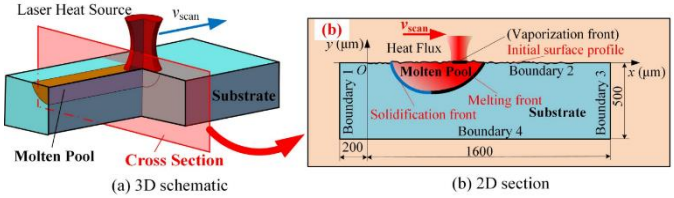

Fig. 2. Schematic diagram of melt pool and boundary conditions in laser polishing [17].

The mass and momentum conservation equations used in a fluid is expressed as [17]:

$$\rho\frac{\partial u}{\partial t} + \rho(\mathrm{u}.\nabla u) = \nabla.\left(-PI_m + \mu(\nabla u + \nabla^T u)\right) + F_v \quad (11)$$

Where P represents pressure, I_m represents identity matrix, μ represents dynamic viscosity, and F_v represents body force. Boundaries 1, 3, and 4 are no-slip walls, whereas the top surface (boundary 2) is free and deformable, as shown in Fig.

2(b). The stress (σ) exerted on the top free surface of the melt pool can be described as [19]:

$$\sigma = \sigma_n + \sigma_t \quad (12)$$

Where σ_n and σ_t are the normal and tangential stress, respectively. Normal stress (σ_n) arises from capillary forces, whereas tangential stress (σ_t) depends on the thermocapillary (Marangoni) force governed by temperature gradients along the surface.

Based on the literature, a significant gap exists in laser polishing models for hard and brittle materials (HBMs), as the existing models have predominantly been developed for metals. This highlights the need for further investigation to address this gap.

3.2. Numerical modeling

By simulating the complex physical phenomena involved in laser polishing, researchers can gain valuable insights into the process and optimize laser parameters to achieve desired results.

Wang et al. [20] investigated Laser-polished ground fused silica using top-hat and Gaussian beams, reducing roughness from over 500 nm to below 0.5 nm. Simulations linked surface smoothing to increased temperature and decreased viscosity. Zhao et.al. [21] developed a numerical model for CO2 laser polishing of fused silica optics, demonstrating a significant rise in surface temperature gradient during pulsed laser irradiation, as shown in Fig. 3.

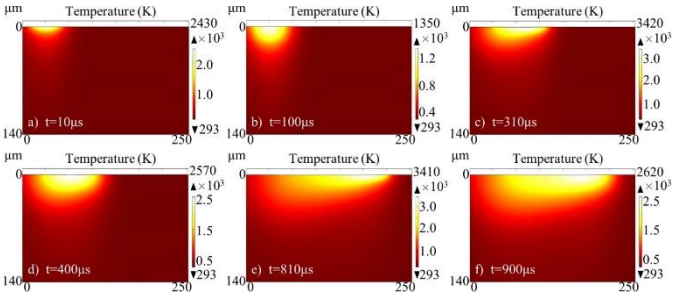

Fig. 3. Schematic diagram of melt pool and boundary conditions in laser polishing [21].

Wei et al. [22] employed a multi-physics model to examine the effects of surface tension, Marangoni flow, light pressure, and gravity in CO_2 laser polishing of fused silica. Figure 4 highlights surface tension as the dominant force for achieving sub-nanometre roughness, with the model accurately predicting final surface quality. Wang et al. [23] developed a 2D heat-transfer and laminar-flow model for laser polishing of alumina ceramic, predicting capillary-driven fluid flow from peaks to valleys and achieving surface smoothing. Simulations closely matched experiments, with depth/height deviations of 13.9% and 17.8%.

A significant research gap exists in understanding the influence of process parameters on melting depth, melt pool evolution, and HAZ formation during HBM laser polishing. Further research should explore their impact on solidification and surface roughness, particularly considering the crystalline nature of most HBMs. Investigating the effects of temperature gradients, melt pool dynamics, and fluid flow on microstructure and recrystallization is crucial. Furthermore, current numerical models, largely focused on glasses and fused silica, need expansion to encompass other HBMs.

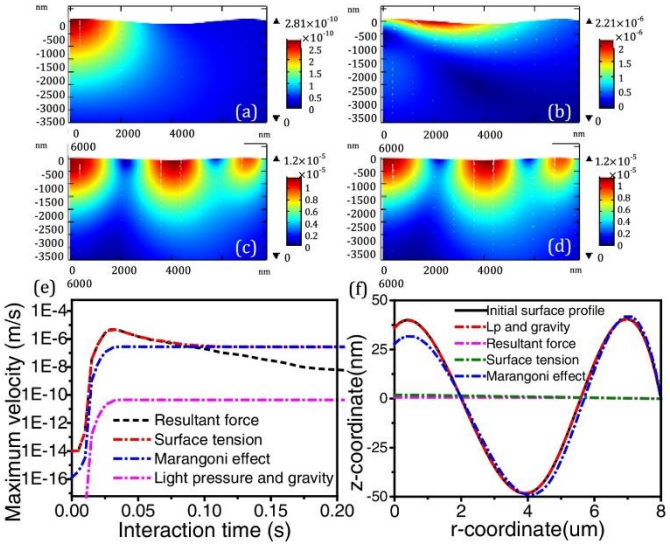

Fig. 4. Surface profile and velocity field distribution under various forces at 21 ms: (a) light pressure and gravity, (b) Marangoni effect, (c) surface tension, (d) resultant force, (e) Maximum velocity evolution of the fluid field for various forces, and (f) Surface profile of the laser-polished surface under various forces [22].

4. Surface integrity

Experimental studies of using laser polishing to enhance surface integrity of HBMs towards reducing roughness, minimizing defects, and improving material properties, essential for high-performance applications, will be reviewed in this session.

4.1. Surface roughness

Zheng et al. [24] optimized femtosecond laser polishing of SiC ceramics, achieving a Sa of 0.187 μm and Sz of 2.313 μm at 10° incidence, 100 kHz, 200 mm/s, and 60 μJ, as shown in Fig. 5. Zhang et al. [25] demonstrated significant surface roughness reduction (82%) of Al_2O_3 ceramics using picosecond laser, achieving an SRa of 0.32 μm. Lu et al. [26] investigated CO2 laser polishing of fused silica glass, reporting a minimum Sa of 0.22 μm with optimized parameters: 100 mm/s, 15 kHz, 50% duty cycle, +5 mm defocus, 0.01 mm track pitch, 40 mm length, and 36 mm width.

4.2. Morphology

Zheng et al. [27] observed a correlation between scanning speed, void size, and surface morphology during laser polishing of SiC ceramics. Zheng et al. [28] demonstrated that femtosecond laser polishing of SiC ceramics in water resulted in crack and pit formation at 10 kHz. However, increasing the frequency to 40 kHz yielded a smooth, crack-free surface with minimal particulate deposition. Zhang et al. [29] reported that

low pulse energy during femtosecond laser polishing of SiC ceramics in air resulted in insufficient ablation, leading to the persistence of initial voids, pits, and cracks on the surface.

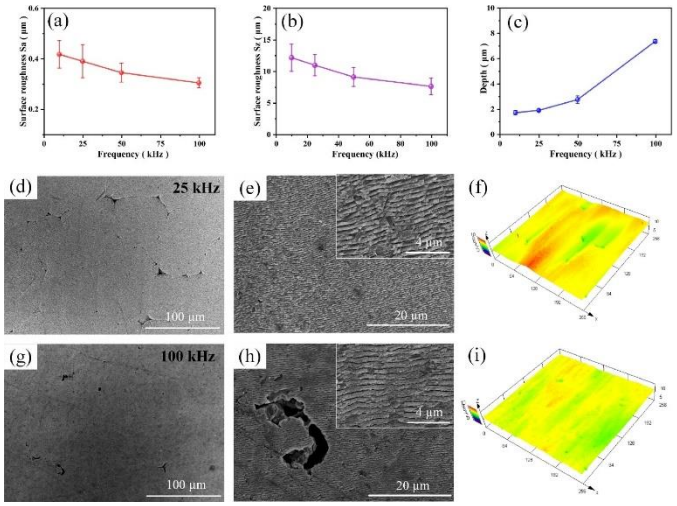

Fig. 5. Effects of laser frequency on (a) Surface roughness (Sa), (b) surface roughness (Sz) and (c) removal depth of SiC. Surface morphologies, SEM images and three-dimensional profiles of SiC ceramics under various frequencies; (d–f) 25 kHz, (g–i) 100 kHz [24].

4.3. Microstructure

Zhang et al. [25] proposed a picosecond laser polishing mechanism for Al_2O_3 involving the recrystallization of nanoparticles generated during ultrafast laser scanning, observing the formation of numerous spherical nanoparticles (10-500 nm) at the treatment edge. Niitsu et al. [30] employed nanosecond laser irradiation on boron-doped silicon wafers with a Gaussian beam (48.4 ns pulse, 1.94 J/cm² fluence, 2.27 kW peak power), achieving a 909 nm recrystallized depth and eliminating grooves and pile-up.

4.4. Hardness

Hong et al. [31] demonstrated that laser polishing significantly improved the surface quality and hardness of WEDMed Zr-based MG. Surface roughness was reduced from 1.27-4.58 μm to 0.09-0.21 μm, while hardness increased from 6.30 GPa to 8.99 GPa. Liu et al. [32] investigated laser polishing of LSPed Zr-based MG, observing a hardness recovery trend (5.77 GPa to 6.05 GPa) with increasing laser power (2.9-5.0 W), attributed to residual stress relaxation and laser annealing. However, the final hardness remained slightly lower than the initial state due to the inherent softening effect of laser polishing. Figure 6 illustrates the influence of laser parameters on post-laser polishing hardness.

4.5. Optimization

Yan et al. [33] optimized femtosecond laser polishing of RB-SiC using design of experiments (DOE) method, identifying an optimal parameter set, 0.62 J/cm² fluence, 4 μm scanning interval, two scanning passes, 150 mm/s scanning speed, and 100 kHz repetition frequency. Lu et al. [34] used the Taguchi method to optimize fused silica laser polishing, reducing surface roughness (Ra) from 0.157 μm to 0.005 μm.

In HBMs, laser-induced recrystallization is the primary defect recovery mechanism, necessitating further investigation into the influence of temperature on this process. Key areas requiring deeper exploration include the interaction of SSDs from prior processing with laser polishing and the effect of initial laser scan point on surface integrity. In addition, existing research on HBMs has largely focused on glass, highlighting the need to examine other materials. Finally, integrating data-driven methods such as machine learning into laser polishing strategies for HBMs represents another promising avenue for future work.

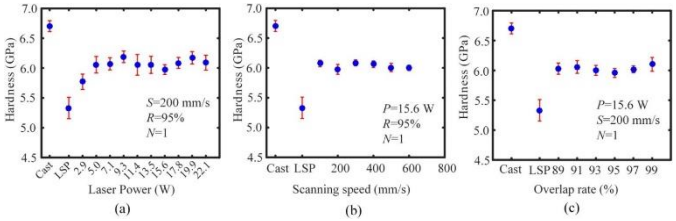

Fig. 6. Effects of (a) laser power, (b) scanning speed, and (c) overlap rate on the surface hardness after laser polishing [32].

5. Conclusion and future perspectives

Hard and brittle materials (HBMs) are extensively used in various industries but suffer from poor machinability, often leading to surface and subsurface damage. Laser polishing offers a promising solution to mitigate these defects, yet challenges remain:

- **Thermal Control and Process Parameters Selection**: There is a lack of research examining how temperature gradients and process parameter selection influence recrystallization. Maintaining temperatures within a narrow range prevents excessive heat-affected zones and microcracking, while carefully balancing laser processing parameters fosters uniform melting and solidification. Together, these factors reduce surface damage and yield optimal finishing.
- **Pre-Existing Defects**: Limited research exists on how cutting, grinding, or lapping flaws affect laser polishing performance. Defects acting as stress concentrators necessitate further study of thermal shock, stress waves, and their influence on damage growth.
- **Modelling Gaps**: Current analytical approaches often overlook key forces, Marangoni flow, surface tension, recoil pressure, that govern melt pool dynamics. Incorporating these factors in simulations can enhance predictions of melting depth, surface roughness, and SSDs recovery.
- **Simulation and AI Integration**: Advanced modelling methods (e.g., FEM, CFD) are essential for precise temperature gradient control, while emerging AI techniques, including machine learning and data-driven approaches, hold great promise for parameter optimization and predictive modelling.

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