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Dynamics of molten pool evolution and high-speed real-time optical measurement in laser polishing

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Abstract

Laser polishing (LP) is considered an effective method for generating ultrasmooth surfaces owing to its precision, flexibility, and material compatibility. However, a lack of understanding of the evolution of surface topography during LP significantly limits the achievable surface roughness in practice. In this work, for the first time, by employing optical time-stretch quantitative interferometry (OTS-QI), we recorded the entire evolution of surface topography during LP with nanosecond-level temporal resolution, providing insight into the mechanisms involved in the surface roughness evolution, such as the Marangoni effect and the formation mechanism of mid-frequency waviness (MFW). Assisted by numerical calculations, we reveal that a ‘perfect polishing point’ exists, i.e., the optimal interaction time for LP at a specific laser power density, at which the surface roughness can be minimised without the formation of an MFW owing to the Marangoni effect and non-uniform removal. This OTS-QI system harnesses the rapid repetition rate of femtosecond lasers, achieving a remarkable measurement speed exceeding 100,000,000 times per second while preserving a measurement accuracy comparable to that of existing white light interferometers (WLIs), setting a new benchmark as the fastest recorded roughness measurement. In addition to LP, the proposed method can be applied for real-time and in situ monitoring of many machining scenarios involving highly dynamic phenomena.

Keywords: Laser polishing, Molten pool dynamics, Ultrafast measurement, Surface roughness, Optical time-stretch quantitative interferometry

Introduction

Laser polishing (LP) has recently emerged as a promising advanced manufacturing technology for producing ultra-smooth surfaces owing to its non-contact operation, high efficiency, environmental friendliness, and

compatibility with complex surfaces and materials. LP has gained attention in various fields, such as additive manufacturing^{1–6}, optical components^{7–12}, mould manufacturing^{13–16}, and biomedical engineering¹⁷. However, LP has not yet achieved industrial success compared with other types of laser heat processing techniques, attributed to several factors, including its relatively short development time, unclear mechanisms, and the lack of specialised equipment¹⁸. LP was introduced approximately 20 years ago, after other laser heat treatment processes, and

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has not received sufficient attention from scientists and engineers. Additionally, the absence of specialised equipment to observe real-time changes in the molten pool morphology during LP, similar to the use of X-ray diffractometers in additive manufacturing, significantly limits our understanding of the LP mechanism, which involves rapid dynamic changes in material properties under laser irradiation. For most metals and glass materials, the viscous flow of molten materials driven by surface tension is generally considered the main contributor to smoothing^{2,19–21}, while many studies have reported that the evaporation of materials also plays a significant role^{22,23} and is even the leading polishing mechanism for some materials such as diamond^{7,24–26}. In addition, the formation mechanism of mid-frequency waviness (MFW), which limits the performance of LP on a large spatial scale^{27,28}, needs to be clarified. Current viewpoints on MFW include the Marangoni effect¹⁹, non-uniform removal of materials²⁹, surface vapour pressure³⁰, and fictive temperature (for glass)^{31,32}. The role of the Marangoni effect remains controversial, with some researchers believing that it directly leads to the formation of MFW¹⁹, while some argue that it can accelerate the smoothing process, thus playing an active role in LP³⁰. Finally, considering LP is the result of the combined action of a series of thermal physical phenomena, including heat conduction, convection, radiation, surface tension, phase change, gravity and melt flow, evaporation, and surface vapour pressure, understanding when and how these effects occur is critical for optimising the resultant roughness.

To gain a deeper understanding of the underlying mechanisms of LP, efforts in two directions are critical: establishing more accurate multi-physics models to replicate thermal and fluid physical processes of LP and conducting real-time in situ monitoring of the process parameters and results. Most studies have focused on the former direction^{22,23}, with early LP models primarily reliant on analytical³³ and statistical³⁴ models, which depend heavily on summarising experimental process parameters and measurement results. In recent years, progress in commercial finite element software has advanced the development of LP modelling. This mainstream research method uses multi-physics finite element models (FEM) to calculate heat transfer, phase changes, flow fields, and weak liquid-phase viscous forces during the heating process before mutually corroborating the surface morphology after cooling with experimental results^{3,5,35}. For example, we modelled and experimentally verified LP for glass and titanium alloy materials and, from the perspective of the surface smoothing time scale, proposed that the optimal irradiation time in LP is jointly determined by the

liquid-phase viscosity of the material and the laser power density^{27,36}. However, the lack of complete/comprehensive temperature-related material physical parameters necessitates using an empirical simplification in the model, and an indirect comparison between simulations and experiments limits its effectiveness in guiding specific processing parameters.

While real-time and in situ measurements of various key process parameters are crucial, similar to other thermal-based manufacturing processes (such as welding), only a few LP parameters can be accurately and immediately measured, with the surface after polishing requiring evaluation at the submicron or even nanometre scale. The most commonly measured parameter is temperature^{12,37}; however, the relationship between the temperature and polishing quality is still not sufficiently direct. Direct imaging observation of the processing area and high-speed dynamic measurement of the surface morphology evolution are highly attractive. The difficulty lies in the LP-specific small molten pool, nano/micron-level accuracy, and extremely fast process, which requires extremely high temporal and spatial resolutions. High-speed X-ray imaging technology has shown promise as it captures the evolution of keyhole formation in additive manufacturing with microsecond-level temporal resolution and micrometer-level spatial resolution^{38–40}. However, the complexity of the X-ray equipment (large accelerators) and sample preparation makes it almost impossible to apply it to industrial equipment. While the optical holographic online measurement system developed by the Fraunhofer Institute is highly practical⁴¹, CMOS-based imaging restricts the upper limit of the observation rate. OCT methods can conduct most of the monitoring during laser processing but cannot fulfil the need for nanoscale resolution⁴². The current consensus is that further development of LP strongly depends on high-speed, high-resolution online measurement technology.

In this study, to reveal the nanosecond-scale dynamics in LP, we employed optical time-stretch quantitative interferometry (OTS-QI) to monitor the evolution of the material surface topography during LP in real time. Benefiting from the high spatial resolution ($< 1 \mu\text{m}$), high temporal resolution ($< 10 \text{ ns}$), and the capability of continuous image acquisition of OTS-QI⁴³, we investigated the entire laser-material interaction process during the quartz glass surface polishing with a CO_2 laser. Specifically, we recorded the thermal expansion, surface smoothness, Marangoni flow, and evaporation removal after laser irradiation on a glass surface. To the best of our knowledge, this is the first time LP dynamics were quantitatively and virtually measured at the nanosecond

level. Additionally, we compared the measurement results with that of our self-built multi-physical field model, yielding highly consistent results. This study clarifies the time scales and effects of various phenomena (mechanisms) in LP, which can be utilised to optimise processing parameters. Specifically, we confirmed that the formation of MFW in the LP is primarily attributed to two mechanisms: the Marangoni effect and non-uniform evaporation. Fortunately, they occur after surface smoothing, thus providing a favourable polishing window. This window facilitates reducing surface roughness to a minimum and suppressing MFW by manipulating the process parameters. Furthermore, the OTS-QI used in this study was confirmed as a promising candidate for real-time, in situ, and quantitative laser processing measurements.

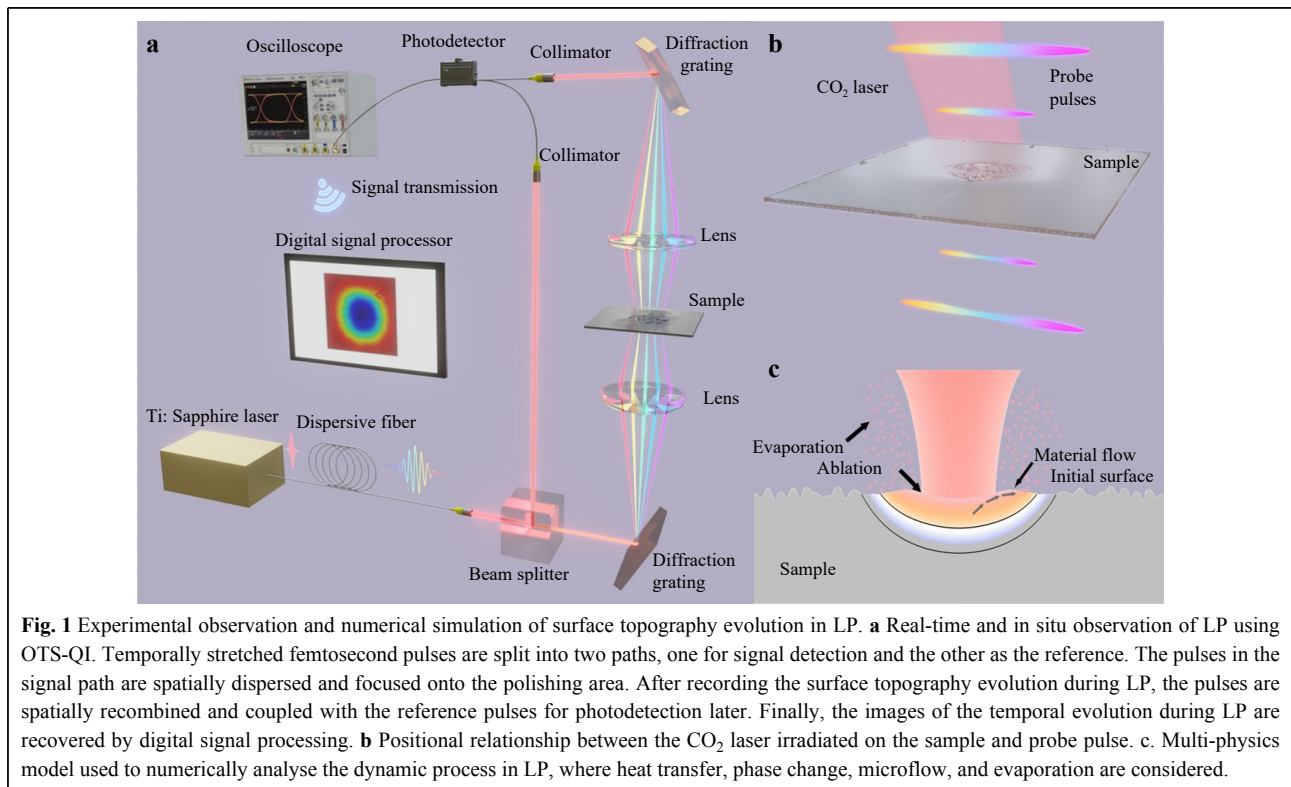
Results

Measurement and simulation of LP with OTS-QI and numerical model

A schematic diagram of the experimental setup is shown in Fig. 1a. The glass sample is irradiated using a CO₂ laser with a centre wavelength of 10.6 μm and a maximum power of 30 W. In this configuration, the CO₂ laser beam was maintained in the horizontal plane at an angle of

approximately 15° relative to the vertical axis of the sample. To measure the dynamics during irradiation, the temporally stretched femtosecond laser-chirped pulse was first split into signal and reference paths. In the signal path, the pulse was spatially dispersed and focused on the surface of the glass by the first diffraction grating and objective lens, respectively. Therefore, variations on the glass surface were mapped onto the probe-pulse spectrum. Subsequently, the 1D rainbow pulse was collected and spatially recombined by the second objective lens and diffraction grating with the same parameters as the first. Considering temporal stretching, also known as dispersive Fourier transform, has already linked the temporal and frequency domains of the pulse, the spatial information of the glass was mapped onto the temporal waveform of the pulse. To acquire the intensity and phase of the pulse simultaneously, the pulses of the signal and reference paths were coupled and detected by the photodetector. Finally, the 1D interference signal $I(t)$ is sampled by a digitiser and processed in the digital domain to recover the images of the glass.

To better capture a real-world scenario, as depicted in Fig. 1c, a multi-physics FEM was designed as a reference. A two-dimensional model of a full-size sample was established to accurately calculate the solid heat transfer, thereby overcoming the drawback of inaccurate boundary



conditions observed in most micro-area models. Subsequently, a micro-area was selected within the laser irradiation area for mesh refinement and dynamic analysis, which included the phase transformation, flow field, evaporation, and other pertinent factors. Detailed information regarding the specific boundary condition settings and control equations is provided in Fig. S1 and Table S1. The physical parameters of the materials are listed in Table S2. In the calculation time range, large-scale Marangoni flow and material evaporation are also accounted for, as these phenomena can occur readily despite not being the intended outcome of the LP process.

Quantitative imaging of OTS-QI

To demonstrate the performance of the OTS-QI, we measured the images of quartz glass processed with the CO₂ laser using an optical microscope, a 3D optical surface profiler, and an OTS-QI. As shown in Fig. 1, in OTS-QI, the probe pulse exhibited a linear shape as it passed through the sample. Therefore, in this experiment, we mounted a glass sample on a one-dimensional (1D) y-axis-moved motorised translation stage. As shown in Fig. 2a, each pulse measured one cross-section of the sample. The pulses covered the entire sample surface as the stage moved from the top to the bottom. By stacking $z(x, t_0)$, the 2D surface topography $z(x, y)$ of the sample could be

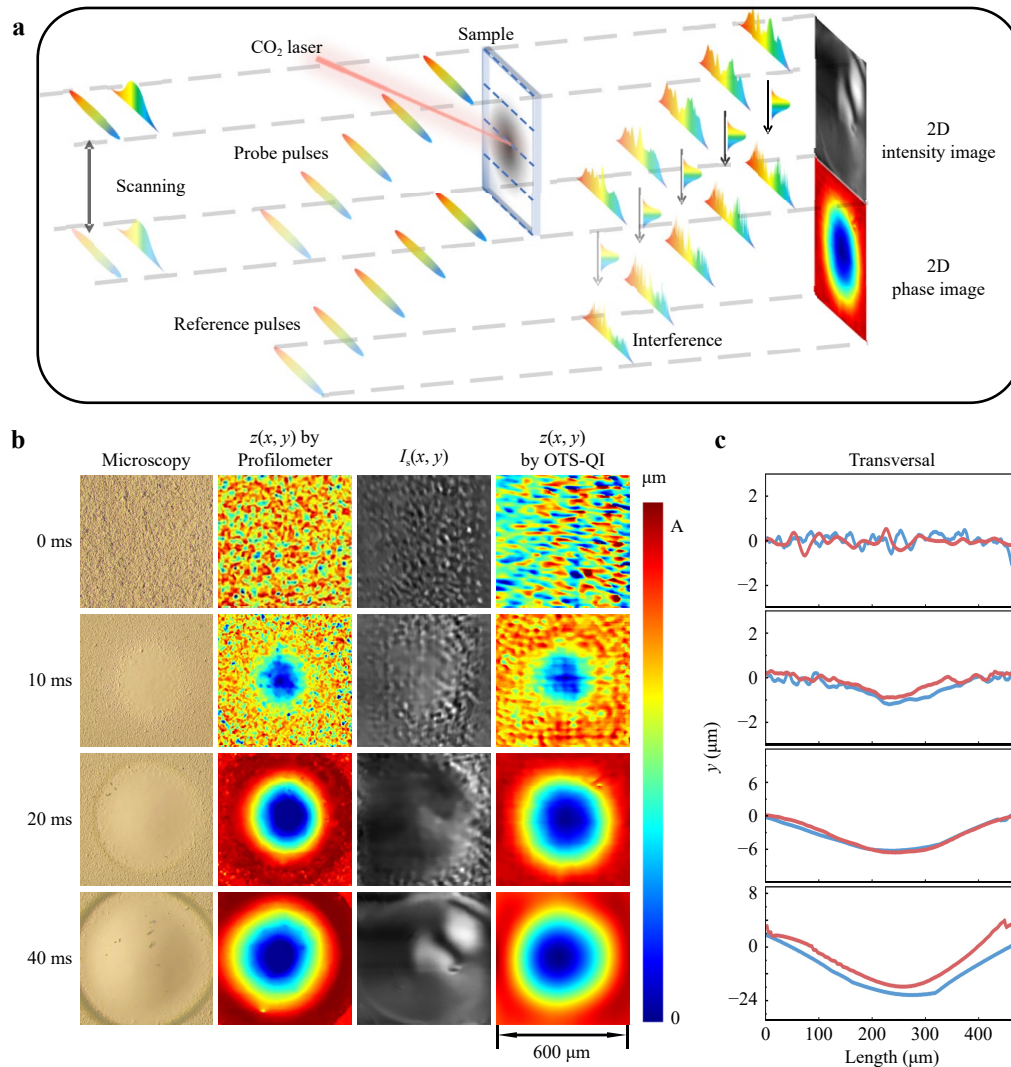


Fig. 2 Imaging performance of OTS-QI. **a** Principle of 2D image recovery. **b** 2D surface topography of glass acquired using a conventional microscope, a 3D profilometer, and the proposed OTS-QI with a processing time of 0 ms, 10 ms, 20 ms, and 40 ms at a power density of $7.0 \times 10^4 \text{ W/cm}^2$, respectively. **c** Cross-sections of the images acquired by the 3D profilometer and proposed OTS-QI.

recovered on the y -axis (see Materials and Methods). The inset of Fig. 2a shows the image of the standard USAF-1951 resolution chart, and the spatial resolution of the OTS-QI is $7.81 \mu\text{m}$. The lateral spatial resolution of the system can be readily enhanced to the optical diffraction limit corresponding to the detection wavelength. However, this enhancement necessitates a trade-off in the spatial range of measurements. The initial roughness of the glass surface was $0.22 \mu\text{m}$, and the power density of the laser beam was $7.0 \times 10^4 \text{ W/cm}^2$. We irradiated the glass surface for 10 ms, 20 ms, and 40 ms, with the images of the glass samples acquired using the three different methods shown in Fig. 2b. The intensity and phase images acquired with OTS-QI exhibited high similarity to those obtained using a microscope and 3D optical surface profiler. These images reveal that, with an increase in processing time, the central region of the sample undergoes successive stages of smoothing and ablation.

Furthermore, in Fig. 2c, we depict the cross-sections of the images acquired with our OTS-QI and the 3D optical surface profiler with different processing times. We employed the relevant factor, defined as

$$\rho_{xy} = \frac{\sum_{n=1}^N (x_n - \bar{x})(y_n - \bar{y})}{\sqrt{\sum_{n=1}^N (x_n - \bar{x})^2 \cdot \sum_{n=1}^N (y_n - \bar{y})^2}} \quad (1)$$

to quantitatively evaluate the differences between the curves. In Eq. 1, x_n and y_n represent the 1D data of the curves acquired using the OTS-QI and optical profiler, respectively. The results show that the relevance of all the curve pairs in Fig. 2c is greater than 0.9, indicating that the accuracy of our OTS-QI is almost identical to that of the optical profiler.

Temporal evolution of the material surface during LP

Alternatively, as shown in Fig. 3a, we can also fix the position of the 1D rainbow beam on the surface of the glass and then start laser processing and measurement simultaneously. Owing to the high repetition rate of the probe pulse ($\sim 100 \text{ MHz}$), each pulse measures $z(x, t)$ at a specific time t . Hence, by stacking the pulses, an image recording the temporal evolution of the material surface during LP can be obtained. In the experiment, the glass sample was illuminated by a CO_2 laser with a power density of $7.0 \times 10^4 \text{ W/cm}^2$ for 50 ms before turning off the laser. The surface evolution over 100 ms, including 50 ms

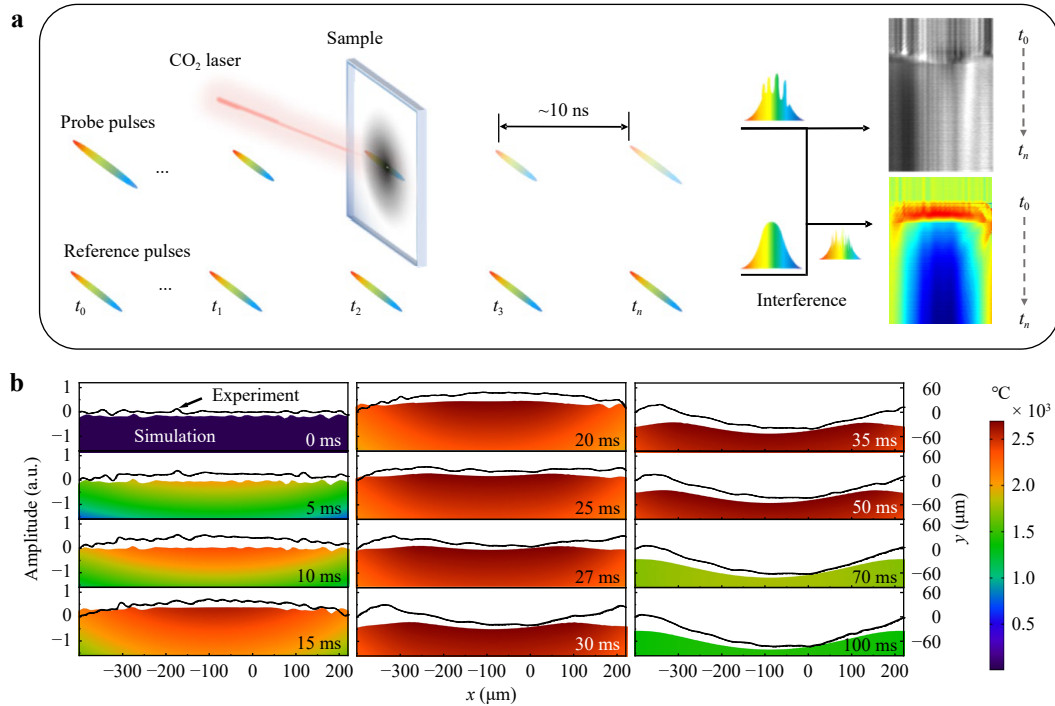


Fig. 3 Temporal evolution of glass surface topography during LP. **a** Image construction of glass surface topography evolution during LP. **b** Numerical (colour regions) and experimental (black curves) results of the glass surface topography at different time points during LP. As LP starts, surface thermal expansion occurs first, followed by the smoothing process of shallow melt microflow at 20–25 ms, the Marangoni flow from 27 ms, and ablation from 30 ms to 50 ms. As the laser is turned off at 50 ms, the surface starts to cool down, eventually resulting in a crater shape at 70 ms.

for processing and 50 ms for cooling, was measured by our OTS-QI, and $z(x, t)$ at different times is plotted as black curves in Fig. 3b. We simulated the same process using the numerical model and show images of the glass sample at the corresponding times in Fig. 3b. Both the experimental and numerical results showed that, as the processing started, the centre part of the glass bulged owing to an increase in the local temperature. When the temperature reaches the glass softening point, the material tends to flow towards a smaller surface area owing to surface tension, decreasing the roughness. The roughness of the glass surface reached its minimum value at approximately 25 ms. As heating continued, the temperature at the centre reached the evaporation point. The Marangoni effect causes the liquid in the molten pool to flow from the centre to the sides while simultaneously ablating the pool centre. Combining these two factors results in the gradual formation of a pit at the laser irradiation centre, with a convex edge commonly known as a ‘crater’ shape. Thus, the formation of the MFW is primarily attributed to the Marangoni effect and ablation, both of which occur over prolonged interaction times. After laser irradiation was terminated, the material was rapidly cooled. The correspondence between the experimental and numerical results indicated that the OTS-QI system accurately and efficiently captured and recorded the evolution of the surface topography during the LP in situ and in real time.

These findings provide a comprehensive picture of the evolution of surface topography during LP. As shown in Fig. 4, the glass surface underwent a sequence of transformations, including thermal expansion, smoothing flow, wavy flow, and ablation, from the beginning of the process. Thermal expansion does not directly affect the

final processing outcome. Although Marangoni flow is always present in physics, in the early stages, the smoothing process driven by the surface tension was dominated by the shallow molten pool. As the molten pool expanded, the disadvantages of the Marangoni effect began to emerge, leading to the formation of waviness on a large spatial scale. As the temperature of the molten pool needs to be controlled just below the evaporation point in LP, the fluctuations in laser power (e.g., the typical stability of industrial CO₂ lasers is $\pm 5\%$) and the differences in thermal processes at different locations unavoidably cause slight ablation in random areas, resulting in random MFW. Therefore, the smoothness achieved depends strongly on when laser processing is terminated.

Perfect polishing point under different laser power

The aforementioned phenomenon indicates the existence of a ‘polishing window’, which facilitates controlling the interaction time between the laser and the material, thus allowing the processing area to begin cooling just as the roughness decreases to its minimum value, thereby avoiding uneven flow and material removal. This window constitutes an essential foundation for the theoretical feasibility of LP processes. We refer to this window as the ‘perfect polishing point’, denoting a specific action time for a given laser power density at which roughness can be reduced to its lowest value. As illustrated in Fig. 5a, we measured the temporal evolution of the laser-polished glass surfaces at different power densities ranging from 3.5×10^4 W/cm² to 1.4×10^5 W/cm². The four critical time points—T1, T2, T3, and T4—represent the moments when the measurement starts, heating starts, heating stops, and the measurement ends, respectively. Except for the power

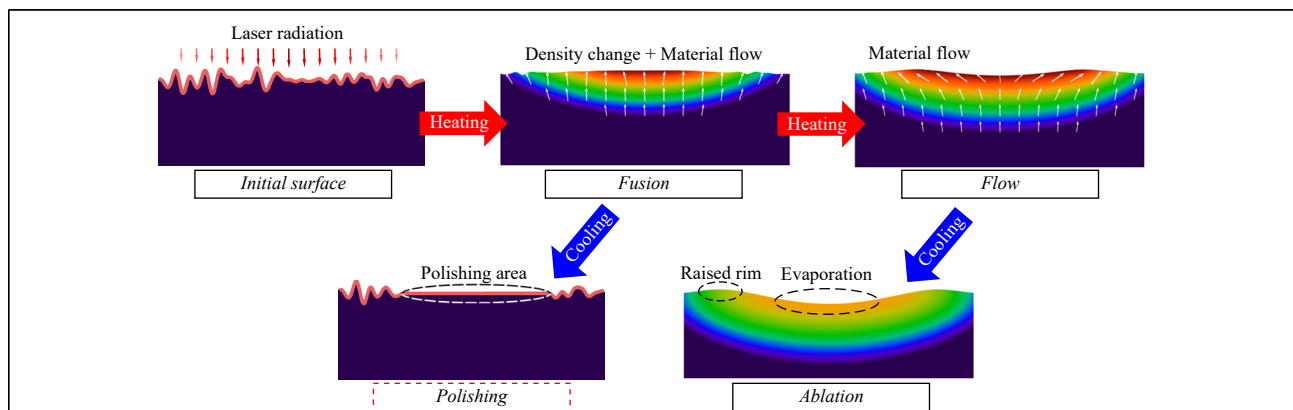


Fig. 4 Schematic diagram of the surface topography evolution of quartz glass during LP. As LP starts, a series of transformations occur successively, including melting, flow, smoothing, and ablation processes. Notably, the process of shallow melting and surface smoothing is transient. Therefore, the achieved surface roughness highly depends on when the heating is terminated. The minimum surface roughness can be acquired when the processing is terminated at a certain point; otherwise, Marangoni flow and ablation will occur on the surface, resulting in MFW.

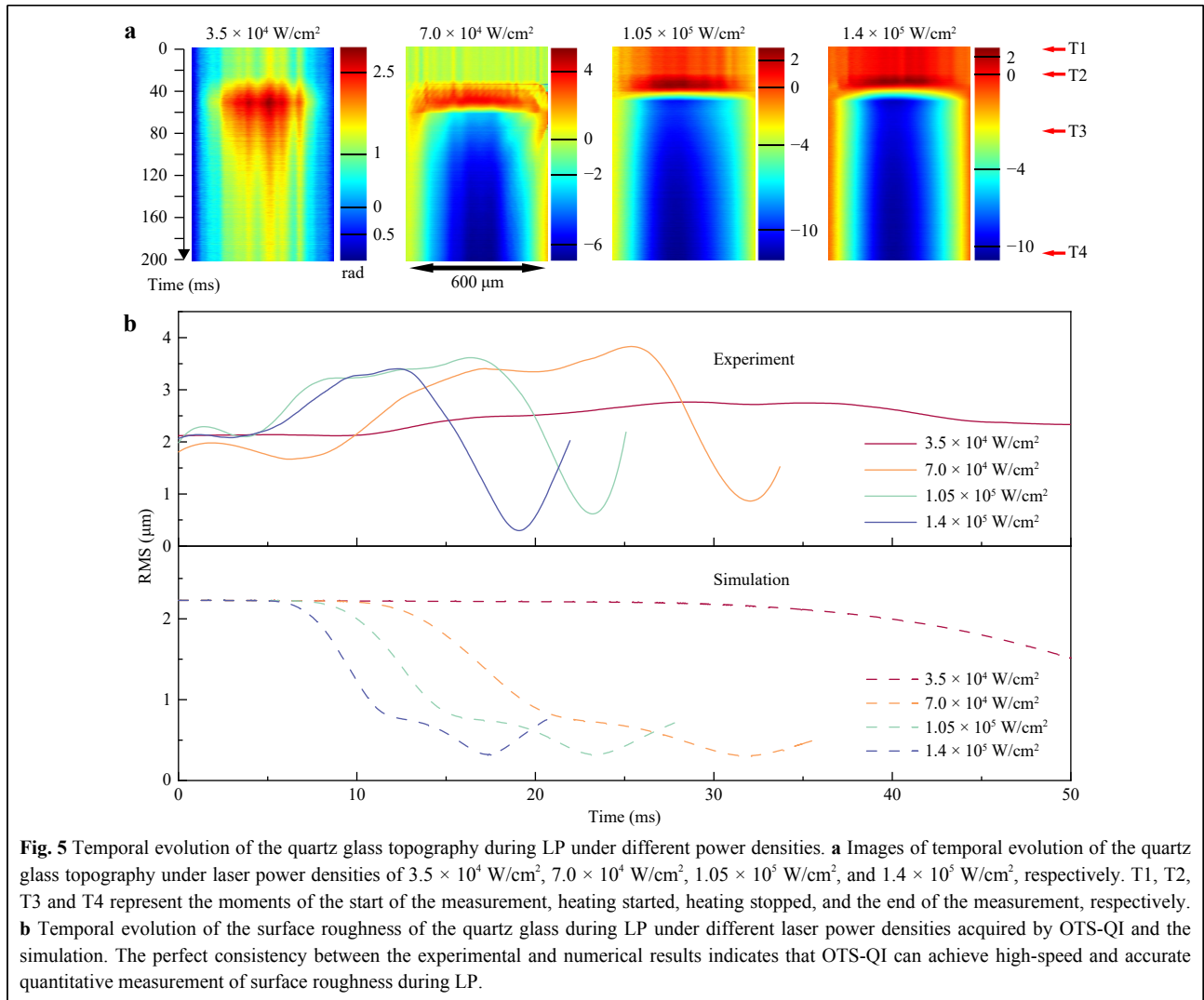
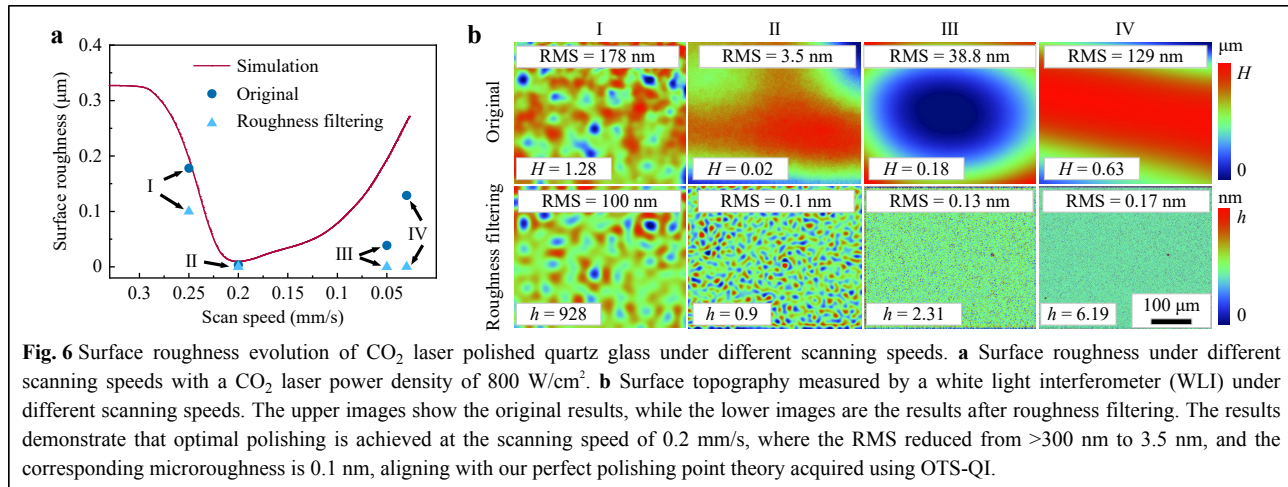


Fig. 5 Temporal evolution of the quartz glass topography during LP under different power densities. **a** Images of temporal evolution of the quartz glass topography under laser power densities of $3.5 \times 10^4 \text{ W/cm}^2$, $7.0 \times 10^4 \text{ W/cm}^2$, $1.05 \times 10^5 \text{ W/cm}^2$, and $1.4 \times 10^5 \text{ W/cm}^2$, respectively. T1, T2, T3 and T4 represent the moments of the start of the measurement, heating started, heating stopped, and the end of the measurement, respectively. **b** Temporal evolution of the surface roughness of the quartz glass during LP under different laser power densities acquired by OTS-QI and the simulation. The perfect consistency between the experimental and numerical results indicates that OTS-QI can achieve high-speed and accurate quantitative measurement of surface roughness during LP.

density of $3.5 \times 10^4 \text{ W/cm}^2$, insufficient to melt the surface within the given processing time, the other three figures exhibit a similar trend as that in Fig. 3. Additionally, owing to the quantitative measurement capability of OTS-QI, the specific values of surface roughness directly correspond to $z(x, t)$, allowing us to detect changes in roughness with nanosecond accuracy, as shown by the solid line in Fig. 5b. To facilitate the comparison, we included the results generated by the numerical model (shown as dashed lines). Both the experimental and numerical results demonstrate the existence of a perfect polishing point, which represents the processing window we strive to achieve in practice.

In practice, the beam scanning of a material surface is necessary to polish a specific surface area, with the interaction time determined by the size of the light spot and the scanning speed; therefore, a ‘perfect polishing point’ can be considered an optimal combination of power density

and scanning speed. Fig. 6 presents the experimental results of the scanning polishing process conducted at a peak power density of 800 W/cm^2 and scanning speeds ranging from 0.03 mm/s to 0.25 mm/s . To analyse the data, we converted the X-axis in Fig. 5b from time to scanning speed, with the calculated surface RMS variation curve shown in Fig. 6a. We selected four typical scanning speeds and measured their corresponding surface topographies. The measured topographies before and after applying the roughness filter are shown in Fig. 6b, with the calculated RMS values indicated for comparison in Fig. 6a. The results indicate that excessively high scanning speeds result in insufficient re-melting flow (Fig. 6bI), whereas excessively low scanning speeds lead to Marangoni flow (Fig. 6bIII) and significant material removal (Fig. 6bIV). The optimal scanning speed corresponded to the proposed ‘perfect polishing point’ (Fig. 6bII). In Figs. 6bIII, IV,



despite a pronounced MFW caused by Marangoni flow and non-uniform removal, the micro-roughness does not exhibit a significant increase. This finding aligns with our theoretical predictions using FEM and the observations using OTS-QI.

Discussion

The proposed concept of a ‘perfect polishing point’ was explored using finite element models and indirect processing experiments in our previous research on titanium alloys and quartz glass. In this study, we directly confirmed the time scale of each mechanism during the LP for the first time using OTS-QI technology. Our observations demonstrate that the Marangoni effect and non-uniform removal are important factors in forming an MFW; however, the results also indicate the existence of an extremely narrow process window that allows us to achieve the best polishing effect through strict control of the flow field in the molten pool.

However, stopping the laser irradiation for every position at the time of the perfect polishing point by simply controlling the process parameters is challenging owing to fluctuations in the laser power, differences in the thermal course at different locations, and the potential demands of complex geometric surfaces. The liquid viscosity of glass materials is approximately three orders of magnitude larger than that of metals, making the smoothing time of quartz glass hundreds of milliseconds. As a result, although we can achieve a time resolution of 10 ns, the morphological transformation of the polishing process shown in Fig. 3 occurs on a millisecond timescale. Considering the measurement rate of this system is determined by the repetition rate of the femtosecond laser used for detection, the nanosecond time resolution of the OTS-QI is fully applicable even for metal materials with faster smoothing

flow rates (tens to hundreds of microseconds). Completing this experiment only requires changing the optical design of the system for the reflective measurement—an easy adjustment. Hence, the primary significance of OTS-QI technology is that it provides a real-time *in situ* monitoring method, which facilitates directly controlling laser power, scanning speed, and other process parameters based on real-time changes in surface roughness. Moreover, this method is cost-effective and industrially viable because of the maturity of lasers, photodetectors, and other components involved. In particular, the rapid advancement of high-repetition-rate femtosecond lasers has significantly enhanced the industrial application potential of this technology. Additionally, the system allows easy adjustment of the field of view for a single measurement via modifying the basic settings of the imaging optics and scanning strategy, thereby achieving an optimal balance between spatial resolution and sampling rate, making this method particularly well suited for multi-pass and large-area polishing processes involving moving or rotating workpieces. However, ultrahigh inspection speeds generate data streams exceeding 100 Gb/s, placing significant pressure on data transmission and processing equipment. Combining an FPGA with compressed sensing imaging can facilitate rapid data processing and transmission, enabling real-time feedback and regulation of the machining process. Hence, the OTS-QI technology is suitable for LP and offers considerable potential in any machining scenario involving high-speed detection of surface topography.

Materials and methods

Principle and parameters of the OTS-QI system

The source was a femtosecond laser (PriTel FFL-FR-

PMFA) with a central wavelength of 1555 nm, bandwidth of 15–30 nm, pulse repetition frequency of 101.7 MHz, and average output power greater than 100 mW, with an adjustable pulse width and spectral width in the range of 100–400 fs and a 3 dB spectral width in the range of 15–30 nm, respectively. Each pulse of the laser was used for time-domain stretching by a 15 km single-mode fibre (SMF) (YofcA5H02621WB1) with a group velocity dispersion (GVD) of approximately 255 ns/nm and amplified by an erbium-doped fibre amplifier (EDFA) (GT-EDFA-C-T-200-FA-FA) with an optical gain of approximately 20 dB. The dispersed amplified pulses were split into two optical paths using a non-polarised beam splitter (Thorlabs BS006) with a power ratio of 50:50, forming a signal path and a reference path. In the signal path, the optical signal pulse was spatially dispersed through a diffraction grating (Thorlabs GR25-0616) with an inscribed line density of 600 lines/mm, resulting in a one-dimensional (1D) rainbow pulse focused on the laser processing area by a lens (Thorlabs LA1509-C, $f = 100$ mm) acting as an objective lens.

Signal processing to recover images

Interferometric fringes can be extracted by applying a digital high-pass filter to remove the low-frequency components. The interferogram was then Fourier transformed to obtain the real and imaginary parts of the transform, which are used to calculate the intensity and phase signals. A phase unwrapping algorithm is employed to obtain a continuous phase image⁴⁴.

In an optical time-domain stretching quantitative phase microscopy system, the spatial information (x) of the laser processing region in intensity and phase is converted into the spectral information (ω) of the pulse via a conversion factor (B).

$$\Delta x = B\Delta\omega \quad (2)$$

The conversion factor (B), typically determined by the inscribed density of the diffraction grating (600 lines/mm), focal length (f) of the lens acting as the objective, and magnification of the 4f lens system in the system, is generally calibrated for confirmation by imaging a known resolution chart, such as the USAF-1951 resolution plate. This method is typically used to determine B in optical systems.

The temporal information of the detected signal (t) is obtained from the spectral information of the pulse (ω) via a conversion factor (C), also known as a temporal interferogram. This method is commonly used to convert spectral information into temporal information in pulse measurement systems.

$$\Delta\omega = C\Delta t \quad (3)$$

The conversion factor (C) was determined using the total group velocity dispersion (GVD) of the system. In this study, the GVD of a single-mode fibre (SMF) used for the time-domain stretching of the entire system was approximately equal to the total GVD of the system.

Eqs. 2 and 3 can be combined to obtain the following result:

$$\Delta x = BC\Delta t \quad (4)$$

According to Eq. 4, the spatial information (x) of the laser-processing region can be obtained by detecting the temporal information (t), which allows us to decode the temporal interferogram using the conventional QPI algorithm to construct an intensity and phase image of the laser-processing region. To create a frequency difference between the signal and reference path pulses, we partially aligned the reference path pulse in the time domain with the signal path pulse and adjusted the optical range difference between the reference and signal paths to s . Each temporal interferogram can be expressed as

$$I(t) = I_R(t) + I_S(t) + 2\sqrt{I_R(t)I_S(t)}\cos[K(t)\Delta s + \phi_S(t)] \quad (5)$$

In Eq. 5, $I_R(x)$ and $I_S(x)$ represent the intensity values of the reference and signal pulses, respectively. The chirp rate of the temporal dispersion pulse is represented by $K(t)$, while $\phi_S(t)$ represents the phase information of the detected laser-processing region. By utilising the conversions of x and t in Eq. 4, Eq. 5 can be rewritten as follows:

$$I(x) = I_R(x) + I_S(x) + 2\sqrt{I_R(x)I_S(x)}\cos\left[\frac{K(x)\Delta s}{BC} + \phi_S(x)\right] \quad (6)$$

Extract the intensity graph information $I_S(x)$ and phase graph information $I_R(x)$ from Eq. 6, respectively representing $I_S(x)$ and $I_R(x)$ in Eq. 6 as low-frequency components and high-frequency components, we can remove $I_S(x)$ and $I_R(x)$ by high-pass filtering and only retain the last term in Eq. 6, a high-frequency component (HFC). By applying the Hilbert transform in Eq. 6, the real and imaginary parts of the final term in Eq. 6.

$$\text{Re}[HFC] = \sqrt{I_R(x)I_S(x)}\cos\left[\frac{K(x)\Delta s}{BC} + \phi_S(x)\right] \quad (7)$$

$$\text{Im}[HFC] = \sqrt{I_R(x)I_S(x)}\sin\left[\frac{K(x)\Delta s}{BC} + \phi_S(x)\right] \quad (8)$$

Eq. 7 and Eq. 8 lead to:

$$I_S(x) = \frac{\text{Re}[HFC]^2 + \text{Im}[HFC]^2}{I_R(x)} \quad (9)$$

$$\phi_s(x) = \frac{1}{2} \tan^{-1} \frac{\text{Im}[HFC]}{\text{Re}[HFC]} - \frac{K(x)\Delta s}{BC} \quad (10)$$

Once the phase map information $\phi_s(x)$ is obtained, the phase image of the detected laser processing area can be obtained using the phase demodulation method.

The optical path difference (OPD) of the pulse after passing through the sample as a function of the phase change is given by Eq. 11

$$OPD(x) = \frac{\lambda(x)}{2\pi} \phi_s(x) \quad (11)$$

The optical path difference of the pulse can also be expressed as

$$OPD(x) = n(x) \cdot z(x) \quad (12)$$

where $n(x)$ is the refractive index of the sample at different locations and $s(x)$ is the thickness of the sample at different locations

Therefore, height fluctuations on the sample surface can be expressed as

$$\Delta z(x) = \frac{\lambda(x)}{2\pi n(x)} \Delta \phi_s(x) \quad (13)$$

A two-dimensional static height fluctuation image $\Delta z(x, y)$ of the melt pool can be reconstructed by stacking the one-dimensional height fluctuations $\Delta z(x)$ in the above equation in space, while a one-dimensional dynamic height fluctuation image $\Delta z(x, t)$ of the melt pool can be reconstructed by stacking the one-dimensional height fluctuations $\Delta z(x)$ in the above equation in time. Similarly, the 2D static-intensity image $I_s(x, y)$ of the melt pool can be obtained by spatially stacking the 1D intensity $I_s(x)$ in Eq. 9.

Considering the transmissive time-domain stretching imaging system used in this study, the detection light with a wavelength of 1555 nm must penetrate the sample to record the surface information, as shown in Eq. 13, with the magnitude of the refractive index of the sample in the imaging system related to the height fluctuation obtained from the measurements. During in situ observations, the refractive index of the glass changes with temperature at different locations, i.e., different times and locations have different refractive indices, affecting the measurement of height fluctuations on the sample surface and becoming part of the cause of the experimental error.

To avoid the effect of refractive-index changes on the measurement results, reflective time-stretch quantitative interferometry will be used in the future.

Multi-physics simulations

The simulation principles and parameters are detailed in Supplementary Sections S1 and S2, respectively. The

simulation results for quartz glass and a comparison with laser metal polishing are presented in Supplementary Section S3.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (12374295, 62075200), the National Key Research and Development Program of China (2023YFB4603803), The Fund of National Key Laboratory of Plasma Physics (6142A04230201), Fundamental Research Funds for the Central Universities (2042023kf0113), and the Shenzhen Science and Technology Program (20JCYJ20220530140601003). We gratefully acknowledge Serendipity Lab for facilitating collaboration opportunities.

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D. W. and C. L. supervised the study. D. W., M.-J. Y., and Y.-F. Y. conceived the experiments. S.-Y. W., Y.-Y. W., and F. F. constructed the experimental setup. D. W. and S. Z. developed the numerical methods for the simulation. K. G., S. L., and Z.-Q. Z. provided theoretical analysis and guidance. All authors participated in the data analysis and contributed to writing the manuscript.

Data availability

All data are available from the corresponding authors upon reasonable request.

Conflict of interest

The authors declare no competing interests.

Supplementary information is available for this paper at <https://doi.org/10.37188/lam.2024.050>.

Received: 09 May 2024 Revised: 26 August 2024 Accepted: 28 August 2024

Accepted article preview online: 29 August 2024

Published online: 14 October 2024

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