Backscatter absorption spectroscopy for process monitoring in powder bed fusion

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Abstract

This paper presents an optical sensor that employs backscatter tunable laser absorption spectroscopy (BTLAS) for in-situ monitoring of laser powder bed fusion (L-PBF). The measured signal depends on the conditions within the gas vapor cavity, whose dynamic interaction with the melt pool surface is known to be a major cause of defects in the final part. The sensor spectrally resolves the shape of the absorption lines of metal vapors, which is influenced by gas pressure, temperature, concentration, and velocity. This pilot study demonstrates that the absorption line strength and line shape of Ti varies significantly with changes in the process chamber pressure and laser power when processing a Ti-6Al-4V, potentially allowing the technique to be applied for process monitoring and closed-loop control. Additionally, the technique provided a signal under near-vacuum conditions, suggesting its utility for fundamental research on electron beam powder bed fusion (EB-PBF). The authors outline future steps for integrating this sensor into existing L-PBF systems for real-time operando process monitoring. Laser-induced fluorescence (LIF) was also observed during the experiments, which may provide further opportunities for in situ process monitoring.

Keywords Process monitoring, absorption spectroscopy, laser powder bed fusion, electron beam powder bed fusion, vapor plume, melt pool dynamics.

1. Introduction

Defects introduced during the powder bed fusion (PBF) process can significantly affect the quality of manufactured parts, a concern that has gained urgency as additive manufacturing enters safety-critical industries like aviation and medical devices [1,2]. Although the precise

Abbreviations: TLAS, tunable laser absorption spectroscopy; BTLAS, backscatter TLAS, LIF, laser-induced fluorescence; OES, optical emission spectroscopy

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mechanisms underlying these defects remain elusive, research has linked melt pool instabilities to a range of issues, including part roughness, porosity, cracks, and mechanical performance [2–4]. Consequently, real-time in situ monitoring of melt pool dynamics is crucial for operando quality control and parameter adjustment [1,4]. Prior studies have suggested that only a multimodal sensing approach can enhance the fidelity of process monitoring while facilitating a deeper understanding of defect-forming mechanisms [4–6].

One of the key factors contributing to melt pool instability is the dynamic interaction between the gas in the vapor cavity and melt pool, with the hot metal vapor plume exerting pressure on the melt pool surface. Traditional methods for predicting print quality, such as acoustic monitoring and measuring thermal emissions from the melt pool and vapor plume [7], provide only indirect insights into the gas vapor conditions [3,4].

This paper introduces a novel optical sensor utilizing backscatter tunable laser absorption spectroscopy (BTLAS). Distinct from previous methods, the sensor signal is directly influenced by a variety of factors within the gas vapor cavity, including temperature, pressure, gas composition, and velocity. This proof-of-principle study investigates the relationship between the titanium (Ti) optical absorption signal in the vapor cavity and the processing parameters by employing a near-coaxial probe laser and process laser on a Ti-6Al-4V sample. This paper also provides a comprehensive outline of the subsequent steps required for designing and integrating BTLAS sensors into production machines to achieve real-time monitoring capabilities.

2. Backscatter tunable laser absorption spectroscopy (BTLAS)

2.1. Principle

In both laser powder bed fusion (L-PBF) and electron beam powder bed fusion (EB-PBF), the vapor plume consists of hot atomic metals found as alloying elements in the metal powder. The optical properties of the vapor are characterized by the spectral lines at distinct wavelengths that correspond to the electronic transitions of the individual components. The strength and shape of these lines are influenced by intrinsic and extrinsic conditions of the plume such as the composition, pressure, temperature, and flow velocity. In the past, spectral measurements of the plume have been reported by optical emission spectroscopy (OES), in which the light emitted from the metal vapor plume and the melt pool is collected and analyzed in spectrometers [8,9] or using multiple detectors equipped with spectral filters [10,11]. However, while the OES signal is indicative of plume composition and temperature, it provides only

indirect insight into parameters such as pressure and gas velocity. This information is encoded in the shape and precise spectral position of the atomic lines, which typically cannot be resolved by OES.

Recently, tunable laser absorption spectroscopy (TLAS) has been applied to EBM processes [12,13]. In this method, spectral lines are probed by measuring the transmission of laser light through the vapor plume. The spectral line shape can be measured by recording the transmission signal while varying the probe laser wavelength. The authors recently demonstrated time-resolved temperature measurements by applying TLAS directly above the vapor cavity in a single-track EB-PBF experiment by rapid wavelength tuning of a vertical cavity surface-emitting laser (VCSEL) [14].

Typically, absorption-based sensors require a line of sight between the light source and a detector [15,16]. However, efforts have been made to develop single-ended sensors that can detect light reflected or backscattered from rough surfaces even in harsh environments such as combustion chambers and reacting flows [17–20].

In this paper, the authors propose a novel method for measuring the absorption within the vapor cavity in powder bed fusion below the metal surface by measuring the light from a probe laser backscattered from the melt pool surface, as shown in Fig. 1. Here, an input probe beam is focused into the vapor cavity and the resulting backscattered TLAS (BTLAS) signal is recorded after passing through the plume twice. This paves the way for a novel sensor that takes advantage of the recently developed single-ended sensor approach [19] for in-situ process monitoring.

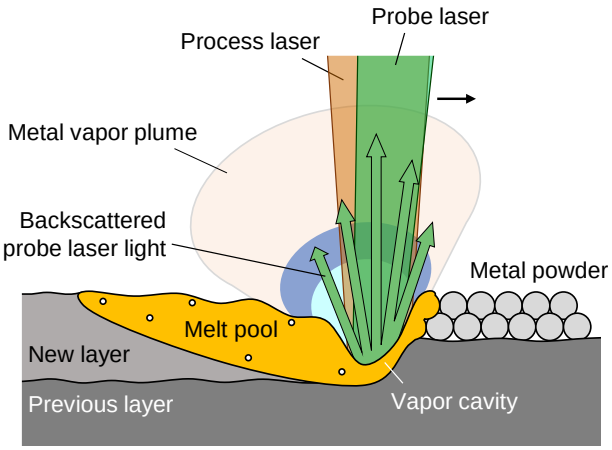

Fig. 1: Backscatter absorption spectroscopy.

2.2. Theory

The attenuation of light traversing through a material is described by Beer's law (Eq. (1)) where I_0 is the initial light intensity, I the intensity after passing through an absorbing medium of thickness L, and S is the line strength. The number density N (particles per unit volume) is proportional to the density, and for an ideal gas, it depends on the gas pressure p, temperature T, and molar fraction x of the absorber. The (base-e) absorbance A is defined as the negative natural logarithm of the transmission I/I_0.

$$-\ln\left(\frac{I}{I_0}\right) = N(T,p,x)\phi(T,p,\lambda)S(T)L = A(T,p,\lambda,x) \tag{1}$$

Although spectral lines arising from electronic transitions within the atoms have discrete wavelengths λ, the experimentally observed absorption lines exhibit a finite width owing to various line-broadening mechanisms [21]. Their influence is collectively described by the line-shape function $\boldsymbol{\phi}$.

While natural broadening, owing to the uncertainty principle, is mostly negligible at elevated temperatures and pressures encountered in laser processing, pressure and Doppler broadening significantly affect the line shape as follows [21].

Pressure broadening results from particle collisions and increases with increasing gas density and temperature, resulting in a Lorentzian line shape. Equation (2) describes its full width at half maximum (FWHM_p), where γ is a broadening coefficient defined at a reference temperature T_{ref} and n is a temperature exponent dependent on the collision partner.

$$\mathrm{FWHM}_p(T,p) = 2\gamma\left(\frac{T_{\mathrm{ref}}}{T}\right)^n p \tag{2}$$

Doppler broadening occurs from the thermal motion of particles, causing spectral lines to undergo a blueshift or redshift, depending on the motion of the particle relative to the observer. This effect leads to a Gaussian line shape, with its full width at half maximum ($\mathrm{FWHM}_{\mathrm{D}}$) described in Eq. (3). where M denotes the atomic weight of the absorber.

$$\mathrm{FWHM}_{\mathrm{D}}(T) = 7.16\times10^{-7}\lambda\sqrt{\frac{T}{M}} \tag{3}$$

An additional Doppler shift arising from the gas velocity relative to the propagation of light, distinct from thermal Doppler broadening, can induce a spectral shift in the line center. In backscatter measurements, where light enters the vapor cavity against the bulk flow of expelled

gases and exits in the same direction, this results in additional line broadening due to the overlap of the red and blue shifts. The nonrelativistic spectral Doppler shift is given by Eq. (4).

$$\lambda_{\text{obs}} = \lambda \sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}} \tag{4}$$

As illustrated in Fig. 2, the observed absorbance depends on several factors including the number density of the absorber, absorption path length, and gas density or pressure. The resulting line shape function ϕ from Doppler and pressure broadening is a convolution of the Gaussian and Lorentzian profiles, commonly referred to as the Voigt profile [21]. While it is challenging to isolate each of these effects for quantitative measurements, especially in the backscatter configuration where strong gradients may exist, the signal is significantly influenced by gas properties, providing a means for process monitoring or control.

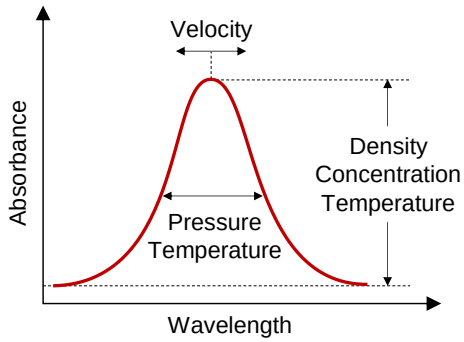

Fig. 2: Effects of gas properties on the spectral profile of atomic transitions under conditions relevant to metal PBF.

3. Experiment

3.1. Optical testbed

The testbed shown in Fig. 3a is designed to provide optical access to a stationary melt pool and vapor plume under conditions similar to L-PBF and EB-PBF. It consists of a process laser mounted on top of a vacuum chamber. While the process beam is static, the sample, in the form of a solid Ti-6Al-4V metal disk, is mounted on a rotating and translating motion stage to simulate the motion of the process beam scanning over the powder bed. The chamber is connected to a vacuum roughing pump and an Ar gas cylinder allowing the chamber pressure to be adjusted between 0.1–760 Torr. The vacuum chamber has various ports that can be equipped with optical windows.

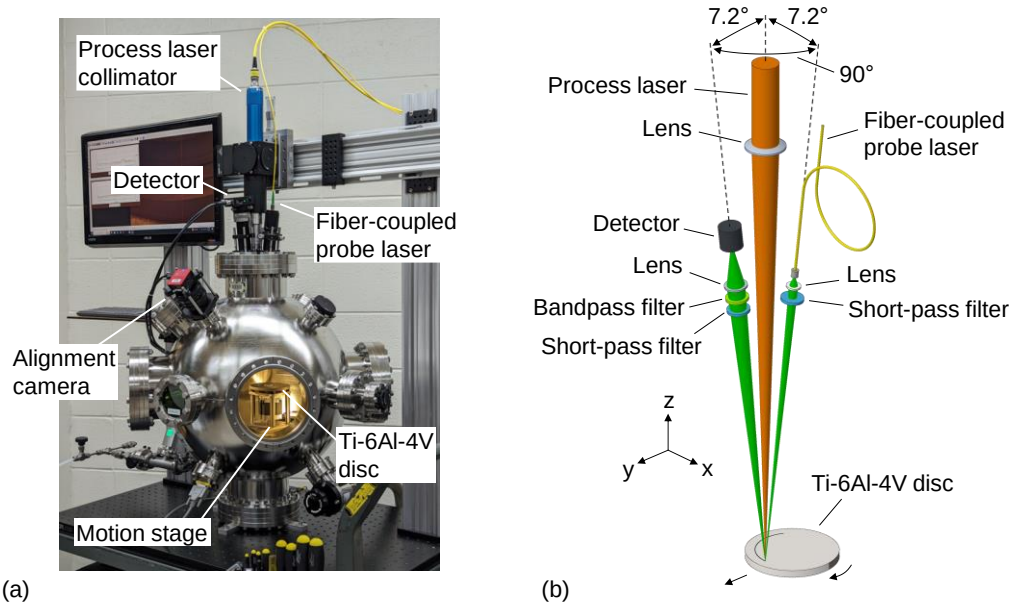

Fig. 3: (a) The optical testbed and (b) the optical arrangement for the BTLAS approach.

As shown in Fig. 3b, the process laser, a Yb:YAG fiber laser (IPG Photonics YLR, λ_p = 1070 nm, 500 W, beam quality M_q^2 = 5.9; IPG P30 collimator: f = 40 mm, d_0 = 20 mm exit beam diameter), was focused on the sample disk with a focal length f_f = 500 mm lens. The $1/e^2$ spot size calculated using Eq. (5) is d_s ~ 200 µm.

$$d_s = \frac{4 f_f \lambda_p M_q^2}{\pi d_0} \tag{5}$$

The top flange of the chamber has viewports that provide optical access nearly coaxial with the process laser, with an offset of ~ 7.2° from the process laser axis. This angle was the smallest achievable considering the space required for the windows and optics on the top flange. One window is used for the probe laser, which is delivered via a single-mode optical fiber (see Section 3.2 for details) and focused on the melt pool using an f = 11 mm aspheric lens with focus adjustment (Thorlabs CFC11A-A), resulting in a spot size of ~ 200 µm similar to the process laser. Adjacent to this is a detector (variable-gain Si photodiode, Thorlabs PDA100A2) that captures the backscattered probe laser light through an f = 40 mm lens. There is a 90° offset between the illumination and detection ports to reduce the amount of specular reflected light reaching the detector and causing intermittent saturation. Both viewports are equipped with fused silica windows with a 30-arcmin wedge to prevent etalon effects caused by interference from light partially reflected within the glass. Short-pass filters (Thorlabs FESH1000, 1000 nm cut-off wavelength) are used to protect the fiber and detector from backscattered process laser light. In front of the detector, a narrow bandpass filter matching the probe laser wavelength (see

Section 3.3 for details) further suppresses the process laser light and blocks blackbody radiation from the melt pool and the vapor plume. With a combined optical density at process laser wavelength of 13.5, both filters effectively eliminate the influence of the process laser on the signal. All lenses and windows are anti-reflective coated for the appropriate wavelength. Unless otherwise stated, the optics are made of BK7 glass.

A camera (35 µm/pixel resolution) mounted on one of the 45° ports (Fig. 3a) was used for process monitoring and alignment of the laser beams. To align the beams, the process laser is first used to mark a spot on the metal disk. The probe beam is then adjusted until it aligns with the mark using knobs on a kinematic mount that holds the fiber and optics to the top flange of the vacuum chamber.

3.2. Probe laser

The probe laser used in this experiment was a commercial visible laser configured in a sum frequency generation (SFG) arrangement (M Squared SolsTiS and EMM, 515–661 nm). A narrow-linewidth Ti:sapphire lasing cavity first produces light between 700–1000 nm, which is then coaligned with a 1950-nm fiber laser and mixed inside a periodically-poled lithium niobate (PPLN) crystal. This setup allows for the modulation of the output wavelength over picometers. The generated visible light was coupled into a single mode optical fiber that delivered it to the optical test bed. The optical power at the fiber output was measured to be approximately 10 mW (Thorlabs PM160 power meter). For all absorption measurements in this paper, the tuning bandwidth was set to 20 GHz, corresponding to a tuning range of 18.2 pm at 522 nm. The tuning rate was set to 10 Hz, i.e., the frequency at which the wavelength is modulated from the lowest to the highest wavelength and back.

To evaluate the wavelength tuning stability, the output of the laser system was monitored with wavemeter (HighFinesse WS6-600, 600 MHz accuracy) over a time span of 30 min while the laser was tuned (Fig. 4). Since the sampling rate of the wavemeter was limited to 25 Hz, the tuning rate and range were determined by fitting a symmetrical sawtooth function to the under-sampled data for small time windows of 10 wavelength sweeps each, as shown in Figs. 4a and 4b. The resulting tuning rate from the individual fits averaged 10.000 Hz over the whole dataset with a standard deviation of 0.0016 Hz, while the tuning range was 17.3 pm with a standard deviation of 0.32 pm, slightly less than the target tuning range. However, the tuning rate was also observed to vary between measurement days. Since the experimental setup did not allow simultaneous monitoring of the laser wavelength with the wavemeter during the experiments,

the authors decided not to derive a wavelength axis from the time trace. Consequently, all signals in Section 4 are presented as a function of time instead of wavelength.

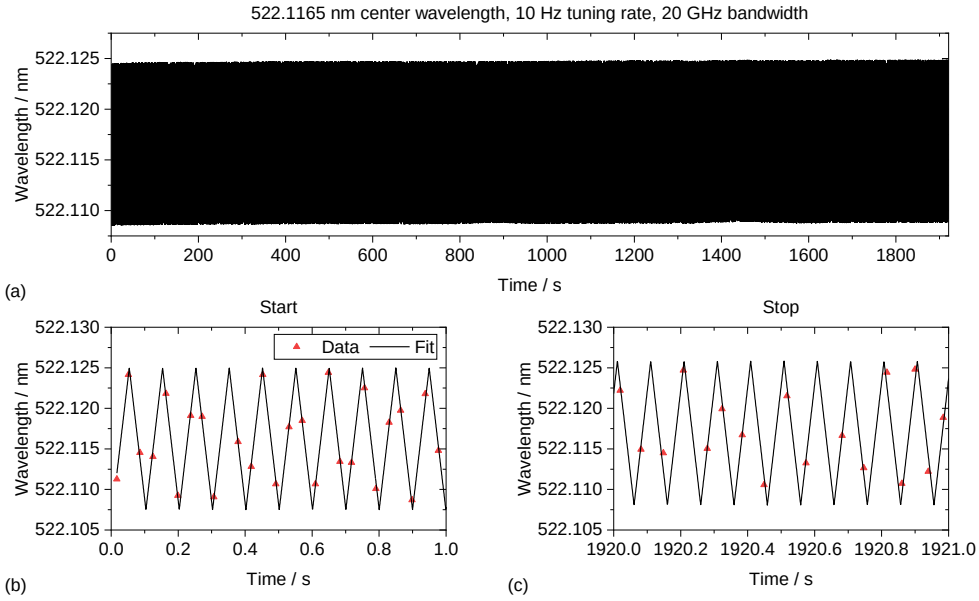

Fig. 4: Long-term spectral measurement characterizing the laser scanning method. The full trace (a) shows the overall stability and consistency despite undersampling, as demonstrated by cuts in the scan starting (b) and stopping (c) periods.

It is important to note that the probe laser power is more than four orders of magnitude lower than the process laser powers used in this work, so the influence of the probe beam on the melt pool is negligible.

3.3. Line selection

Using the gas temperature reported in previous studies [13,14], spectral simulations were performed (Fig. 5) to identify candidate Ti absorption lines within the spectral range accessible by the probe laser (see Ref. [14] for details on the simulations). Since pressure, absorption path length, and Ti concentration are largely unknown at this point and were therefore arbitrarily chosen for the simulations, the optical bandpass (Thorlabs FBH520-10, 520 nm central wavelength, 10 nm bandwidth) was chosen to accommodate multiple Ti lines with significantly different absorption (dashed green line in Fig. 5).

Initial tests (not shown) showed that the absorption of the stronger lines was too strong, causing the plume to be completely opaque. Therefore, the weakest line within this range at 522.155 nm ($3d^24s^2$ a ^3F 3 → $3d^2(^3F)4s4p(^3P°)$ z $^3F°$ 2 [22], red arrow in Fig. 5) was selected for all absorption measurements.

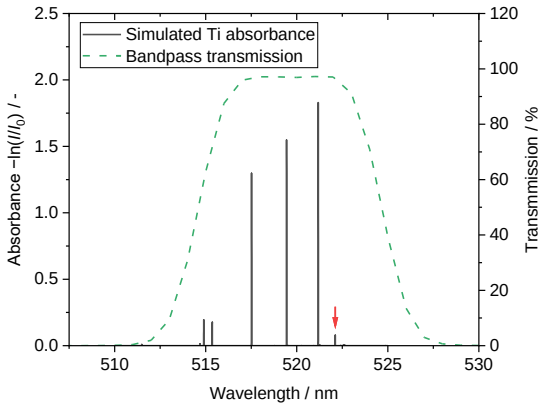

Fig. 5: Simulation of Ti absorption assuming a temperature of 3000 K at quasi-vacuum pressure for an absorption path length of 200 µm (see Ref. [14] for details) along with the bandpass transmission curve. The red arrow marks the line selected for the experiments presented in the next section unless stated otherwise.

4. Results

For each measurement sequence, the Ti-6Al-4V disk was accelerated to reach the desired speed (400 mm/s unless stated otherwise) at the process beam location. The process laser was then activated for the full rotation of the sample disk. During the entire run-up and measurement sequence, the probe laser was active and tuned over the target absorption line, while data acquisition (National Instruments PXIe-1062Q and PXI-5105) was triggered just before the process laser was activated. The hatch distance between two consecutive scans was 0.2 mm.

Figure 6 shows the raw signal recorded during a measurement sequence. As soon as the process laser is triggered, the signal level increases significantly. This is consistent with the backscattered light becoming more directional: as the vapor cavity forms, the beam angle is expected to become smaller because the light escapes mainly upward through the aperture after multiple reflections from the walls of the vapor cavity [23]. As a result, more light reaches the nearly coaxial detector.

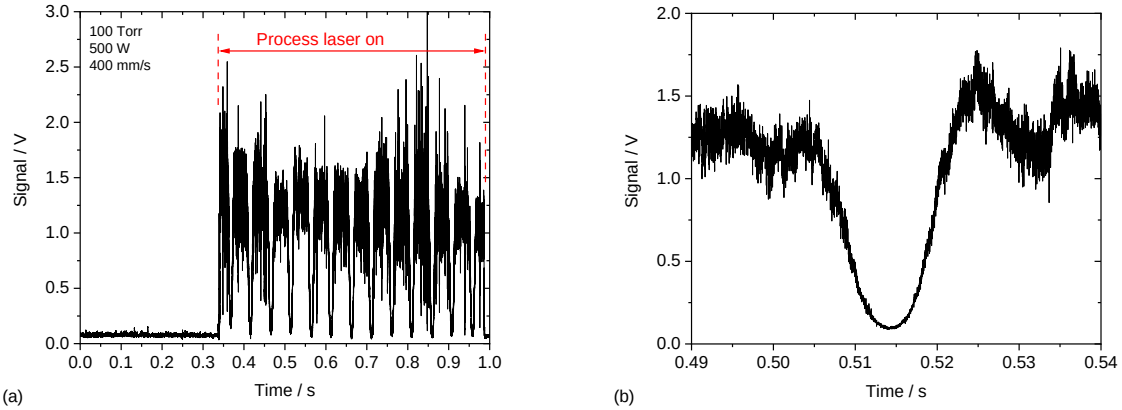

Fig. 6 (a) the raw signal versus time curve recorded at a laser power of 500 W at a scan speed of 400 mm/s in a 100-torr Ar atmosphere and (b) the same curve zoomed in on a single wavelength sweep of the probe laser across the Ti spectral line.

The intensity and shape of the recorded signal has been found to depend significantly on the process parameters applied to the signal, as described in the following sections.

4.1. Signal intensity

The intensity of the backscattered signal depends on the attenuation of the probe laser light due to absorption at the melt surface and the angle at which it is reflected depending on the shape of the vapor cavity, which depends on the processing parameters. During the experiments, the process laser power and the test chamber Ar pressure were varied. Figure 7 shows the signal ensemble-averaged over six scans for different process laser powers (a) and pressures (b). Here, the *x*-axis represents the time relative to the time at which the peak absorbance of each of the six scans is observed.

The probe laser signal level increases with process laser power at a constant pressure of 100 Torr. This can be explained by the increasing depth of the vapor cavity with increasing laser power, resulting in more directed backscatter [23], and, therefore, more light reaching the detector.

With increasing pressure, however, first an increase of the signal level between 0.1–100 Torr can be observed before it drops between 100–700 Torr. This is consistent with the simulations by Li et al. [24] who observed a shallow and round vapor cavity at 10 mbar as the vapor jet is expelled at a large divergence angle in the low-pressure environment. With increasing chamber pressure, their simulations show that the vapor cavity becomes initially steeper and deeper before it becomes shallower again at significantly higher pressure. This could be caused by the

reduced recoil pressure as the pressure difference between the vapor cavity pressure and the chamber pressure decreases.

Another explanation for the drop at higher pressure could be plasma shielding from partial ionization of the metal vapor, as the temperature in the vapor cavity increases with chamber pressure due to the higher boiling point of the metals at elevated pressure. However, as pointed out by Hanemann et al. [25], the laser fluence at L-PBF is probably insufficient for ionizing the gases. Further, the authors did not observe any optical emission from ionized Ti during this study (see Section 4.4 for emission spectra) and never observed ion emission during initial testing of the optical testbed with a high-resolution spectrometer (not shown).

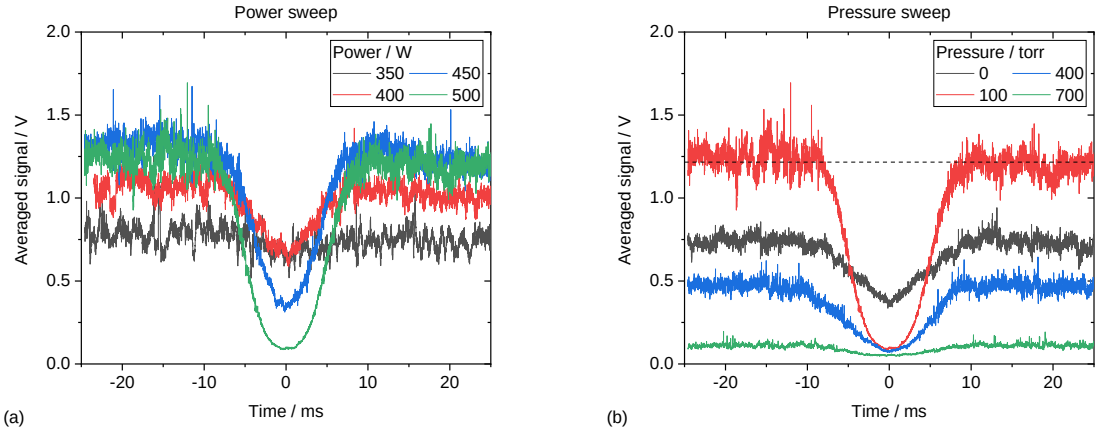

Fig. 7: BTLAS signal at 400 mm/s scan speed for varying process laser power at 100 Torr (a) and test chamber pressure at 500 W (b). The plots shown were averaged over six consecutive laser sweeps to reduce noise.

4.2. Absorbance

The absorbance is calculated using Eq. (1) using the averaged signal (Fig. 7) as I, whereas I_0 is determined by fitting a horizontal baseline to the data trace (dashed line in Fig. 7b). This baseline correction makes the calculation of the absorbance independent of the overall signal intensity.

As shown in Fig 8a, the absorbance increases with increasing laser power (Fig. 8a). This trend is consistent with previous findings, where mass loss rates increased with the process beam power [26].

For the pressure sweep (Fig. 8b), an initial increase in absorbance is observed from 0.1–100 Torr, which then decreases between 100–700 Torr. The authors attribute this behavior to two competing effects: As the boiling point shifts to higher temperature with increasing gas

pressure, the mass loss rate decreases which leads to a lower absorber concentration. At the same time, however, the increasing pressure also increases the density overall, increasing the absorber number density [24].

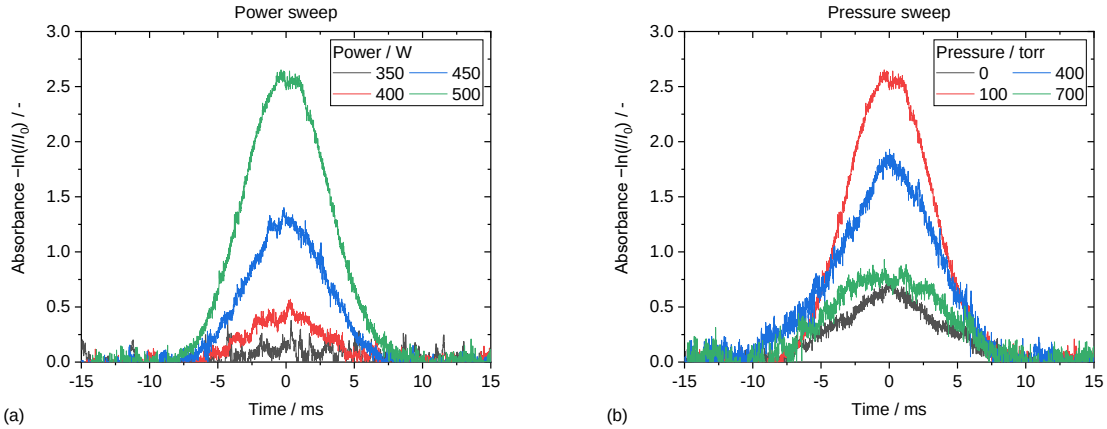

Fig. 8: Absorbance derived from the intensity data in Fig. 7 showing a significant dependence on (a) the process laser power at a constant chamber pressure of 100 Torr and (b) chamber pressure at a constant process laser power of 500 W, both at a scan speed of 400 mm/s.

4.3. Line shape

Variations in line shape are evident when the normalized absorbance is examined (Fig. 8). During the power sweep at 100 Torr (Fig. 9a), the line shape remained invariant, suggesting that the gas temperature remains constant, indicating that evaporation takes place under equilibrium conditions [13].

During the pressure variation (Fig. 9a), the Ti line width initially narrows with increasing pressure up to 100 Torr and then broadens again to 700 Torr. This behavior is attributed to the interplay of line-broadening effects: The broadening between 100–700 Torr is consistent with the increased pressure broadening due to the increased chamber pressure. Additionally, increased Doppler broadening occurs due to the rising plume temperature because of the increased boiling point at higher pressures.

The initial narrowing between 0 and 100 Torr can be attributed to Doppler shifts (not to be confused with Doppler broadening) because of the increased velocity at which the gas is expelled from the vapor cavity in vacuum: As the probe beam passes through the vapor, first against and then in the direction of flow, the signal undergoes a redshift and a blueshift, respectively. Using the gas velocity of 1500 m/s observed by Li et al. [24] at 10 mbar, the resulting Doppler shift was approximately 2.6 pm (Eq. (4)), which is similar in magnitude to the

expected linewidth in vacuum [14]. Since the gas velocity decreases with chamber pressure, the influence of this effect would explain an apparent line narrowing over the 0–100 Torr range.

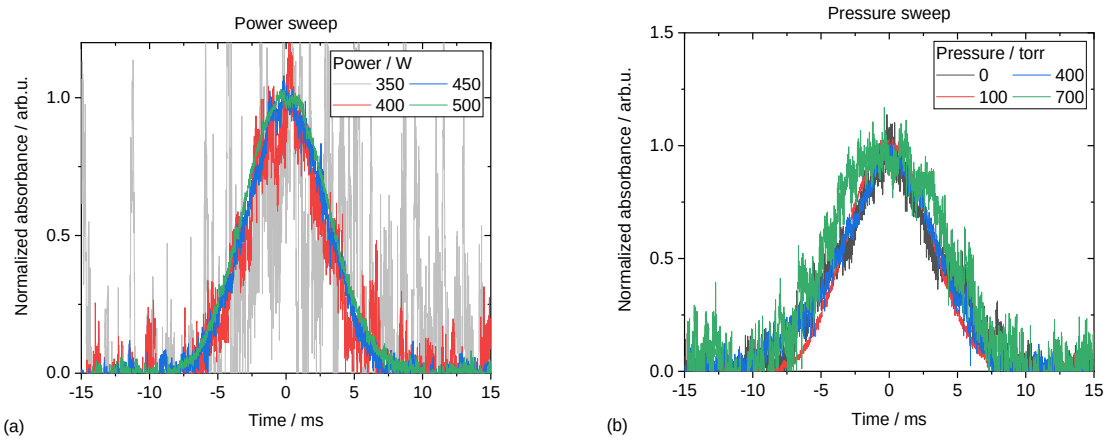

Fig. 9: Normalized absorbance during (a) the process laser power sweep at 100 Torr and (b) the pressure sweep at 500 W at a scan speed of 400 mm/s showing differences in line shape depending on the process parameters.

It is important to emphasize that the analysis presented in this chapter is largely qualitative, with some speculative elements. To fully discern the interplay of mechanisms affecting line shape and strength, alternative or supplementary measurements and a more comprehensive understanding of the dynamics between gases in the vapor cavity and the melt pool are needed. Nevertheless, the pronounced variability in the observed signals based on processing parameters highlights the potential for advanced process monitoring and closed-loop control, potentially leveraging techniques such as machine learning.

4.4. Laser-induced fluorescence

The optical emission from the plume was also measured by replacing the detector with an optical fiber (Ocean Optics XSR, 450 µm, 180–800 nm) delivering light to a spectrometer (Optosky ATP2000P, 2.1 nm resolution, 2 ms exposure time). The bandpass filter on the detection side was replaced with a neutral density filter (Thorlabs ND10) to capture light in the visible range without overexposing the spectrometer.

Figure 10 shows the plume emission spectrum both without the probe laser and with the probe laser tuned to the stronger 519.442 nm line shown in Fig. 5. In the absence of the probe laser (black curve), no emission lines were visible. However, when the probe laser was on (red curve), Ti lines became clearly visible, suggesting that these lines are due to laser-induced

fluorescence (LIF), which is the spontaneous emission of light upon stimulated excitation by absorption of laser light.

While there is likely some non-stimulated emission from hot Ti, it is not detectable with the low-resolution spectrometer used in our study. This instrument under-resolves atomic lines by about three orders of magnitude, causing the low-resolution lines to blend into the background signal and become undetectable.

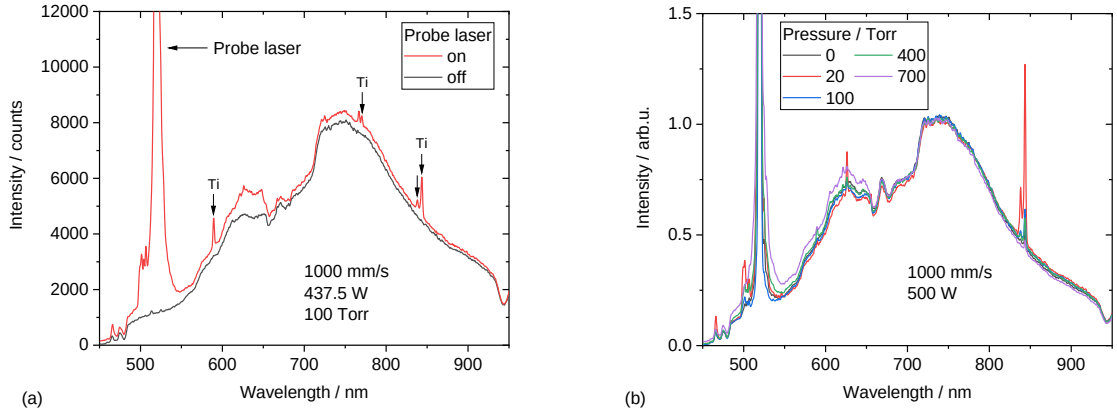

Fig. 10: (a) Emission spectrum without probe laser and with probe laser tuned to the stronger 519.4415-nm absorption line showing laser-induced fluorescence (LIF) and (b) LIF signal for varying chamber pressures at a scan speed of 1000 mm/s.

The fluorescence signal varied significantly with chamber pressure, peaking at 20 Torr. This correlates with the observations from the absorbance measurements, where the signal level and absorbance are the highest, while the line width is the lowest at intermediate and low pressures.

5. Discussion

5.1. Speckle noise

The relatively high noise level scales with the signal intensity, indicating that it is caused by speckle noise, which is expected and largely unavoidable. When coherent light is reflected from rough surfaces, speckle patterns, as shown in Fig. 11a, can be observed owing to the interference of the laser light scattered from the high and low points of the rough surface of the illuminated area. The interference pattern changes with the surface speckle, thus changing the signal reaching the detector and resulting in transient noise.

Figure 11b shows the Fourier transform power spectrum of the backscattered signal for the stationary sample disk, the moving sample disk, and during an absorption measurement. When

comparing the power spectra of the stationary disk with the moving disk, it becomes evident that the noise caused by motion extends to about 6 kHz. This is similar in magnitude to the speckle noise frequency of 2.5–25 kHz observed by Wang and Sanders [19] from a rough surface moving at 300–3000 mm/s. The noise recorded during the absorption measurement extends beyond the measurement range though also dropping at 6 kHz. This is consistent with recent research suggesting that keyhole oscillations occur at 40 kHz or faster [27], with the surface significantly changing several times during each oscillation cycle.

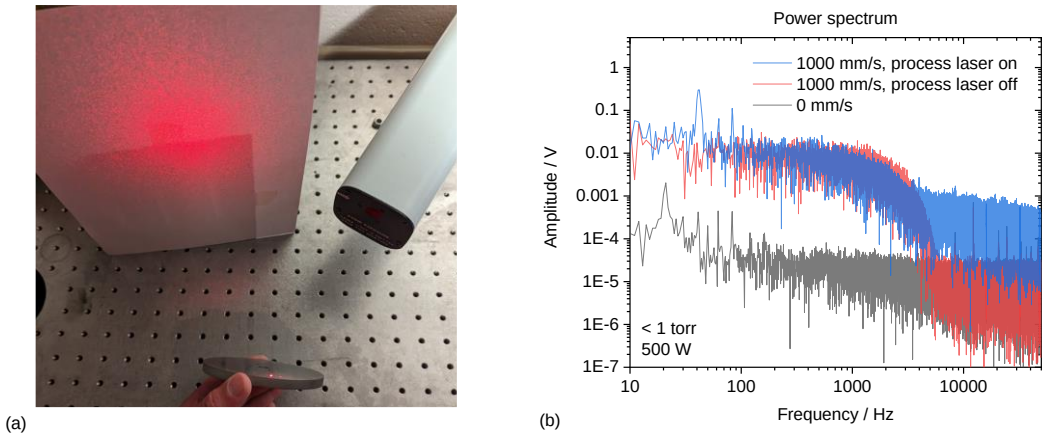

Fig. 11: (a) Speckle pattern generated by HeNe laser beam scattered off the sample disk surface; (b) Power spectrum obtained through Fourier transformation of the measured signal, comparing a stationary disk to a spinning sample disk, both with and without the process laser.

To reduce the influence of speckle noise, the laser must be tuned faster than the rate at which the surface of the melt pool changes. Here, increasing the tuning rate to values well above 6 kHz largely will eliminate the influence of the sample disk motion. To further reduce the influence of melt pool oscillations, the required tuning rate is likely to be in the range of hundreds of kilohertz. Such rates have been routinely achieved using, for example, diode lasers [28,29].

Transient speckle noise can also result from tuning the wavelength of the probe beam. Assuming a typical root mean square (rms) roughness for the powder bed PBF of h_{rms} = 20 µm (Ti-6Al-4V, D50 = 32 µm) [30], the wavelength change needed to alter the speckle pattern is $\Delta\lambda$ = ~ 1.5 nm (Eq. (6)) [19]. Since the probe laser tuning range needed for atomic line measurements is about 2 orders of magnitude lower (16 pm in this work, see Section 3.2), speckle noise originating from wavelength tuning can be safely neglected.

$$\Delta\lambda = \frac{\lambda^2}{\lambda + 2\sqrt{2}\pi h_{\mathrm{rms}}} \tag{6}$$

5.2. Representativeness

The conditions of the metal vapor in this simplified experiment differ from the still largely unknown conditions in the vapor cavity in L-PBF. The main differences are the larger spot size and slower scan speed compared to most production machines, use of a solid sample instead of metal powder, and the absence of a shielding gas flow. Further work is required to determine whether the technique is applicable to real-world conditions (see Section 6).

Furthermore, spatter and ejected powder could be additional sources of scattered light in the L-PBF process. Moreover, the absorption of light by droplets and nanoparticles of condensing metal vapor could be wavelength dependent due to size effects if the particle size is similar to the wavelength of the interrogation laser light. However, these sources of scattered light above the vapor cavity are to some extent out of focus, so that light collection is less efficient, reducing their influence on the overall signal. Further research on the influence of gas-borne particles is needed when applying the BTLAS technique to L-PBF.

6. Conclusions and path forward

The feasibility of backscatter absorption spectroscopy of gases within the vapor cavity produced during laser processing of solid Ti-6Al-4V was demonstrated. The signal stemming from atomic Ti lines varies significantly with the laser power and build chamber pressure, indicating its potential in process monitoring for quality control or closed-loop feedback in 3D printing.

For a practical impact, the technique should be integrated into existing machines and the time resolution should be increased to capture the dynamics of the melt pool/vapor plume interactions. In addition, attempts to mitigate the effects of speckle noise should be pursued. To achieve this, the following steps should be taken.

6.1. Application to PBF

Before applying the BTLAS technique to production machines, a reasonable next step could be its application to L-PBF or EB-PBF in single-track experiments with metal powders under realistic conditions. For this purpose, the probe beam can be fixed in space while the process beam is scanned across the probe beam spot, similar to previous work studying the metal vapor plume with absorption spectroscopy [12-14]. Here, the ability of single-track testbeds to apply complementary measurement techniques such as X-ray imaging [31,32] can be leveraged to test if and how the BTLAS signal correlates with defects such as pore formation.

6.2. Machine integration

Coaxial integration is an obvious solution to equip production L-PBF machines with BTLAS sensors. To this end, a dichroic mirror can be placed between the process laser collimator and the galvo mirrors in the scan head. This dichroic mirror would allow process laser light to pass through while reflecting the shorter wavelength of the probe laser. Both incoming and backscattered light would utilize the same pathway with a beam splitter reflecting the light onto the detector.

6.3. Multi-line measurements

Employing multiple probe beams concurrently can facilitate the targeting of absorption lines from different alloying elements. Signal ratios would then offer insights into the individual mass loss rates of each species. Furthermore, targeting absorption lines with variable temperature dependence could allow quantitative temperature measurements.

6.4. Laser-induced fluorescence

It should be further explored whether laser-induced fluorescence has potential as a diagnostic tool in additive manufacturing. While high-energy pulsed lasers have been successfully used for LIF experiments in laser welding [33–35], this work showed that relatively low-powered CW lasers can also be used to significantly boost the emission of the vapor plume compared with optical emission spectroscopy of thermally excited metal vapor.

6.5. Fundamental research

Attention should be paid to determining whether the gas in the vapor cavity comprises neutral atoms or plasma. The authors did not detect any ionized species in this study. Nonetheless, it remains uncertain whether the observed signal decrease at elevated process laser powers and pressures can be attributed to plasma shielding.

Disclosure

During the preparation of this research paper, the authors made use of a combination of generative AI and AI-assisted technologies, specifically DeepL Write, Paperpal, ChatGPT, and Scite. These tools were employed to enhance the quality of the writing, assist in the editing process, and validate citations. Following the use of these tools, the authors carefully reviewed and revised the content as needed and assume full responsibility for the content of the publication.

Author contributions

M. Beuting: Conceptualization**,** Investigation**,** Formal analysis**,** Writing - Original draft preparation; **A. J. Fairhall:** Investigation**,** Formal analysis**,** Writing - Original draft preparation; **R. H. Goldsmith:** Supervision, Writing - Review & Editing; **L. Chen**: Conceptualization**,** Funding acquisition, Writing - Review & Editing; **S. T. Sanders**: Conceptualization, Supervision, Writing - Review & Editing

Declaration of interests

A patent application covering the technology described in this manuscript has been filed and is currently pending (application number U.S. 18/231066). There are no other competing interests.

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