Investigation of processes occurring above laser exposed area during powder bed fusion by optical diagnostics

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Abstract. Powder-bed fusion is accompanied by the occurrence of processes such as the formation of a vapor-gas jet, the outflow of powder particles and the movement of gas masses in the laser processing zone, which must be taken into account to improve the quality of the process. In this work, the methods of optical diagnostics of the space above the processing zone were used to identify and investigate the main occurring processes. Using the Schlieren-method, it was possible to fix the emission of powder particles from the laser exposure zone and evaluate their speed and expansion angle depending on the laser processing parameters, type of material, and particle size distribution. To study the emerging vapor-gas flows, the interferometry method was used, as a result of which a spatial change in the refractive index of the gas medium was recorded. Based on the data obtained, the velocity of the jet was calculated and the flow geometry was determined. It is also shown that metal vapor makes up the majority of the observed flows.

1. Introduction
The Powder Bed Fusion process includes the following commonly used printing techniques: Direct metal laser sintering (DMLS), Electron beam melting (EBM), Selective heat sintering (SHS), Selective laser melting (SLM) and Selective laser sintering (SLS). Selective laser melting (SLM) is one of the most common additive technologies for metal parts production. The demand for this technology is constantly growing, since it allows obtaining parts of complex shape directly from computer models, excluding the time-consuming operations of manufacturing special forms, tools and equipment settings.

The interaction of laser radiation and powder material is the key element of the SLM technology. In the area of the laser beam, the melting temperature is easily reached even for refractory materials. However, the SLM process substantially depends both on a large number of technological parameters, such as laser power, beam diameter, laser scanning velocity and strategy, powder layer thickness, and on the properties of the initial material [1-3]. Their selection is one of the main tasks of additive manufacturing technology.

The modern development of SLM is aimed at constant increasing of the process productivity. Generally, it involves increasing the scanning velocity of the laser beam when growing products. Along with the laser power and its diameter, velocity is the parameter that responsible for obtaining high-quality objects without pores, cracks and other defects of micro- and macrostructures. The balance between performance and stable quality is sometimes reduced to an integral indicator characterizing the amount of energy transferred to the powder material per unit area [4]. Therefore, an increase in the scanning speed is possible only with a proportional increase in the laser power. Nevertheless, although modern scanning systems allow moving the laser on the surface of the working area at a speed of up to
6 m/s or more, the most productive SLM systems operate at a speed of ~ 500 mm/s. This limit is due to various physical aspects, such as, for instance, thermal conductivity of the material, which affects the crystallization rate of the material and its volume. There have been many studies characterizing the contribution of laser technological parameters, physical properties of the material, and aspects of their interaction to the quality of the microstructure and the stability of the formation of objects during SLM. The new knowledge about the process showed that, when critical power and speed are reached, the influence of processes associated with the movement of the surrounding gas masses and the emerging flows increases. It forced the area of observation and research to shift to the plane of the powder layer and the closest space above it [5-7].

Over the past few years, the phenomenon of intense evaporation during SLM with a high energy density has been discovered in various scientific groups [8-10]. Evaporation not only leads to loss of mass and energy in the zone of laser exposure, but causes a jet stream in the gas phase, which captures powder particles from the adjacent areas of the powder layer, thus playing a key role in mass transfer and the formation of bare zones along the boundary of the track [11-14]. The resulting vapor-gas jet is the cause of the release of powder particles and droplets of the melt from the laser exposure zone. In addition, it was shown that the vapor coil pressure significantly affects the melt pool and can lead to the formation of a vapor-gas channel [15-18]. This effect determines the stability threshold of the melt pool and the SLE process as a whole at high energy densities, thus limiting the productivity. Also, in some works it is noted that the resulting vapor-gas jet affects the absorption of laser radiation, thus reducing its useful power in the SLM process [16, 17].

Thus, it is obvious that the processes taking place in the laser melting zone and in the space above it are an integral part of the technology and can affect the quality of the products obtained. Existing work on the visualization of the jet is limited by the use of a high-speed camera and a magnifying lens, which allows only considering in detail the molten bath and the torch’s own glow. In this regard, the aim of this work is to study these processes with more advanced diagnostic methods such as the Schlieren-method and interferometry.

2. Materials and Methods
The experimental work was carried out on an experimental set-up for selective laser melting equipped with a Nd:YAG fiber laser with a wavelength of 1064 nm and a laser beam positioning system. Powders of Molybdenum (Oerlikon Metco Amdry 313X, USA, fraction d50=50 μm), Tungsten carbide with cobalt WC-Co (Oerlikon Metco Woka 3660 FC, USA, fraction d50 = 50 μm), and WC-Co (Oerlikon Metco Woka, d50=20 μm) were selected as initial powder materials. The experiments were carried out with four modes of laser radiation power at 50 W, 90 W, 130 W and 170 W, while scanning speed remained constant at 50 mm/s. The laser beam was scanned in two directions: along the recording laser radiation and perpendicular to it. Registration of gas-phase flows in the laser exposure zone was carried out using a high-speed camera Photron Fastcam SA 5 (Japan) with a recording frequency of 5000 frames per second which corresponds to an exposure time of 0.2 ms per frame. The Schlieren-method was used to visualize the process and detect all outgoing particles in a transparent medium. The optical setup is shown in figure 1. The studied region 4 in the zone of laser exposure is illuminated by a beam of light from the laser source 1. Then, using a lens 6, this beam is focused on a visualizing aperture, in the center of which a barrier is installed 7. The rays of light scattered by the optical inhomogeneities in the studied region 4 go at a certain angle to rays passing region 4 without scattering. As a result of this, after the lens, the scattered rays do not fall into its focus, pass away from the obstacle 7 installed in the focus, and then fall into the recording chamber and create an image of optical inhomogeneity there. During the experiment, the scattering angles the velocity of the powder particles from the laser exposure zone were recorded. A zone where 90% of particles were scattered was determined as scattering angle. The highest particle ejection velocity was determined by the longest track length of the ejected particle in the camera image, relative to the camera exposure time of 0.2 ms.
To register gas-phase flows in the zone of laser irradiation by the method of interferometry, a compact setup placed above the desktop of the experimental set-up has been developed (figure 2). It is based on the Jamen interferometer, in which the probing laser beam 1 (532 nm), expanded by lens 2, is divided into two beams (probing and reference) using a plane-parallel glass plate 3. After one of the beams passes through the laser exposure zone 4, both beams are brought together using the same glass plate 5. Next, the lens 6 constructs in the recording chamber 7 an image of the studied area together with a reference beam superimposed on it, creating an interference pattern consisting of fringes. For interferometry corrosion resistant powder of 12X18H10T was used with the particle mean diameter $d_{50}=63 \, \mu m$.

3. Results and discussion

3.1. Schlieren-method
The shadows of relatively large objects compared to the wavelength are not displayed in the Schlieren-method, since the shadow image carries exactly the direct beam of light that is blocked by the Foucault knife installed in the focus of the lens. At high power, the flow’s own (Planck) glow is more likely to be observed. It turns out to be much more powerful than the light scattered by the particles of this torch from a working laser. The applied imaging method at high laser power allows you to clearly capture the emission of powder particles from the treatment zone. All particles are characterized by different speeds.
of scattering and together form a region into which the vast majority of particles fly out, determined by
the angle of scattering (Figure 3).

Figure 3. (a) scattering angle, (b) plume, (c) particle outflow

As a result of the parametric analysis, it was found that the angle of expansion of particles decreases
with increasing laser power. This is primarily due to the intensification of the gas-phase flow exiting the
treatment zone. The flow itself becomes narrower. Being one of the driving forces of the powder
particles, the flow thus determines the zone of their expansion. In addition to the power of laser radiation,
the particle size distribution also affects the particle exit angle. The scattering angle of WC-Co powder
particles with an average size \(<20 \mu m\) is significantly higher than for compositions with a particle size
\(<50 \mu m\). The speed of the scattering particles grows with increasing laser power and for the WC-Co
material was 7-8 m/s, and for molybdenum powder \(~12 m/s\). Thus, the type of material being processed
also affects speed.

The behavior of the released particles is also different for different materials. Visualization shows
that a significant amount of powder particles flies out of the laser exposure zone. Some of them are
heated, as can be seen from their characteristic glow. Some of these particles are capable of "exploding"
directly in the flight phase. In this case, a gradual increase in the brightness of the object is observed,
because of which visually the object in the frame increases. This, in particular, can be due to an increase
in the particle temperature, although in figure 5 shows that the observed objects are outside the zone of
direct exposure to laser radiation. A stable phase of flight (without incrementing brightness) of particles
can last indefinitely. From the beginning of a gradual increase in brightness to the explosion takes about
0.6 - 1.2 ms. Such an effect is more characteristic of molybdenum powder, although it was observed in
all experiments.

Figure 4. The influence of laser power on the scattering angle (a) and plume velocity (b)
3.2. Interferometry

A study of the emerging gas-vapor jet was carried out by interferometry. The method allows to record any changes in the refractive index of the observed region of the air environment, as a result of which it is more accurate than the Schlieren-method concerning gases. The interpretation of the interferogram allows to obtain the spatial distribution of the change in the optical path caused by the presence of a gas-phase jet. A global calculation of the magnitude of the change in the refractive index $\Delta n$ in each pixel of the interferogram allow to transform the pattern of interference fringes into a pattern of distribution $\Delta n$. A detailed algorithm for obtaining and decoding interferograms is presented in [19].

Earlier work on the studying of gas-phase flows during SLM revealed several aspects associated with their formation: changes in pressure, temperature and concentration of metal vapors. These three components affect the refractive index of light as well. Therefore, unlike ordinary high-speed recording, detecting spatial change in the refractive index carries more information about the plume. The obtained interferograms after processing made it possible to visualize a vapor-gas jet (figure 6). The differential interferogram (figure 6b) shows the presence of a bright spot near the substrate, the width of which correlates with the diameter of the torch at its base in figure 6 c, d and probably is an evaporation spot. On the obtained interferograms it is seen that the optical path length of the probe beam increases in the zone of the torch expiration compared to the beam length in the unaffected zone outside the plume. In this regard, in the gas-phase flow shown in figure 6, the phase increment $\Delta \phi$, due to a change in the optical path, reaches ~ 45 radians.

![Figure 5. Consecutive frames of heating-up and blowing a scattered particle](image)

![Figure 6. (a) as-obtained interferogram, (b) differential interferogram, (c) spatial distribution of phase increment, (d) pseudo-colored interferogram](image)
Figure 7. (a) gas-phase flow at laser power 50 W, (b) gas-phase flow at laser power 90 W, (c) gas-phase flow at laser power 130 W, (d) gas-phase flow at laser power 170 W

At laser power of 50 W, stable plume formation and particle emission are not observed (figure 7 a). Figure 7 also shows that the most intense refractive region begins to develop at a certain distance from the treatment zone. With increasing power, the distance from the substrate to the maximum value $\Delta \phi$ increases as well as this value itself, and the gas flow becomes more stable (figure 7).

To evaluate the velocity of the jet, 10 consecutive frames of processed interferograms were analyzed (figure 7). Having the exposure time of the frame and the scale of the observed region known, tracking the movement of characteristic inhomogeneities made it possible to calculate the speed for all processing modes (table 1). For parameters from 90 W to 170 W, the average calculated time is presented over 10 frames, however, the nature of the jet indicates the presence of acceleration of the jet as it moves away from the substrate. At a laser power of 50 W, there is no plume movement and the behavior of its outflow does not change over the entire period of laser exposure.

According to calculations in absolute terms, the pressure change is small and amounts to about 1 Pa [19]. Such a difference is not able to significantly increase the refractive index of the gaseous medium through which the recording laser passes. An increase in temperature, which sharply increases in the laser irradiation zone and reaches several hundred degrees at a distance from the substrate [8], is a factor that reduces the $\Delta \phi$ parameter. Nevertheless, the optical path length in the plume itself increases, which can be explained by an increase in the concentration of metal vapor due to its evaporation from the molten bath. Based on the estimated refractive index of the metal vapor, the volume fraction of iron...
vapor in the gas-vapor stream was calculated (table 1). This shows that a significant part of the flow is made up of vaporized metal vapor.

| Plume parameter | Laser power, W |
|-----------------|---------------|
|                 | 50 | 90 | 135 | 170 |
| Average velocity, m/s | 0.35 | 1.8 | 2.3 | 2.6 |
| Max Δφ, rad     | 40 | 39 | 42 | 48 |
| Metal vapor content, % | - | 53.7 | 52.2 | 54.5 |

Table 1. Gas-phase flow parameters

Metal vapor can affect the intensity of laser radiation in the case of resonance absorption. Open sources do not provide data on the absorption of laser radiation with a wavelength of 1064 nm in iron vapor and are limited to 926.3 nm [19]. However, it is seen from [19], that the data presented indicate a tendency toward a decrease in the absorption intensity with increasing laser wavelength. This indirectly confirms the absence of noticeable absorption lines in the range of the Nd:YAG laser. Given the short laser path inside the plume (~ 1 cm), the absorption of laser radiation is most likely negligible.

4. Conclusion
The main processes that occur in the area immediately above the laser melting zone of the powder are the release of powder particles and the formation of a vapor-gas jet. For their study, the Schlieren-method and interferometry were used, which provide more information than conventional high-speed shooting. Using the Schlieren method, it was possible to visualize the SLM process, register the emission of powder particles, and determine their main parameters. The expansion angle decreases significantly with increasing power. At the same time, there is an effect of particle size distribution on this parameter: the finer the powder, the larger the angle. Particle ejection speed is mainly determined by the power of laser radiation.

Interferometry is more sensitive to a change in the refractive index in the observed zone, as a result of which it is possible to observe optical inhomogeneities associated with the formation of a gas-phase flow from the treatment zone. The critical power for its formation is in the range from 50 W to 90 W. The average velocity of its outflow depends on the laser power and at 165 W is 2.6 m/s, which is 2-3 times lower than the velocity of scattering particles. The main part of the vapor-gas jet consists of an evaporating metal; the rest of the volume is gas from the ambient atmosphere. The jet causes gas flows in the treatment zone, which, in turn, affect the movement of powder particles.

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References
[1] Yadroitsev I., Gusarov A, Yadroitsava I., Smurov I. Single track formation in selective laser melting of metal powders. Journal of Materials Processing Technology. 2010; 1624:210.
[2] Yadroitsev I., Bertrand Ph., Smurov I Parametric analysis of the selective laser melting process. Applied Surface Science. 2016; 8064-8069.
[3] Yap C.Y., Chua C.K., Dong Z.I., Liu Z.H., Zhang D.Q., Loh L.E., Sing S.I. Review of selective laser melting: Materials and applications. Applied Physical Review 2. 2015;041101.
[4] Zhirnov I.V., Podrabinnik P.A., Okunkova A.A., Gusarov A.V. Laser beam profiling: Experimental study of its influence on single-track formation by selective laser melting. Mechanics & Industry. 2015; 709.
[5] Zhirnov I.V., Kotoban D.V., Gusarov A.V. Evaporation-induced gas-phase flows at selective laser melting. Applied Physics A. 2018;124:157.
[6] Gusarov A.V., Yadroitsev I., Bertrand Ph., Smurov I. Model of radiation and heat transfer in laser-power interaction zone at selective laser melting. Journal of Heat Transfer. 2009; 131: 072101.

[7] Verhaege F., Craeghs T., Heulens J., Vandelaers L. A pragmatic model for selective laser melting with evaporation. Acta Materialia. 2009; 57: 6006-6012.

[8] Ly S., Rubenchik A.M., Khairallah S.A., Guss G., Matthews, M.J. Metal vapor micro-jet controls material distribution in laser powder bed fusion additive manufacturing. Scientific Reports. 2017; 7:4085.

[9] Gunenthiram V., Peyre P., Schneider, M., Dal M., Frederic C., Fabbro R. Experimental analysis of spatter generation and melt-pool behavior during powder bed laser beam melting process. Journal of Materials Processing. Technology. 2018; 251: 376-386.

[10] Simonelli M., Tuck C., Abdoulkhair N.T., Maskery I., Ashcroft I., Widlman R.D., Hague R. A study on the laser spatter and the oxidation reactions during selective laser melting of 316L stainless steel, Al-Si10-Mg, and Ti-6Al-4V. Metallurgical and Materials Transactions A. 2015; 46: 3842-3851.

[11] Low D.K.Y., Li L., Byrd P.J. Spatter Prevention During the Laser Drilling of Selected Aerospace Materials. Journal of Materials Processing. Technology. 2003; 139: 71-76.

[12] Li S.C., Chen G.Y., Katayama S., Zhang Yi. Relationship between spatter formation and dynamic molten pool during high-power deep-penetration laser welding. Applied Surface Science. 2014; 303: 481-488.

[13] Kaplan A.F.H., Powell J. Spatter in laser welding. Journal of Laser Applications. 2011; 23: 032005.

[14] Khmyrov R.S., Protsav K.E., Gusarov A.V. Influence of the conditions of selective laser melting on evaporation. MATEC Web of conferences. 2018; 224: 01060.

[15] Zhang M.J., Chen G.Y., Zhou S.C., Deng Li, H. Observation of spatter formation mechanisms in high-power fiber laser welding of thick plate. Applied Surface Science. 2013; 280: 868-875.

[16] Nakamura H., Kawahito Y., Nishimoto K., Katayama S. Elucidation of melt flows and spatter formation mechanisms during high power laser welding of pure titanium. Journal of Laser Applications. 2015; 27: 032012.

[17] Fabbro R., Slimani S., Doudet I., Frederic C., Briand F. Experimental study of the dynamical coupling between the induced vapour plume and the melt pool for Nd–Yag CW laser welding. Journal of applied physics. 2006; 93: 394-400.

[18] Gusarov A.V., Smurov I. Gas-dynamic boundary conditions of evaporation and condensation: Numerical analysis of the Knudsen layer. Physical Fluids. 2002; 14: 4242.

[19] Podrabinnik P., Shtanko A., Khmyrov R., Korotkov A., Gusarov A. Interferometry of gas-phase flows during selective laser melting. Applied Sciences. 2020; 10(1): 231.

[20] Zaidel A. Tables of spectral lines. 1st ed.; Springer US: NY, USA, 1970; p. 782.