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THE USE OF LOW-POWER BLUE LASERS IN ADDITIVE MANUFACTURING OF SMALL STRUCTURES

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Abstract. *Common wavelengths λ of diode lasers are 1064 nm (infrared), 532 nm (green) and 355 nm (ultraviolet). For processing (additive manufacturing, cutting, welding) metals with laser beams, wavelengths of around λ = 1000 nm are currently used. There are two important exceptions where shorter wavelengths have clear advantages. These are for processing of gold and copper, which have absorptions A up to 60 % at λ = 450 nm (blue). For these metals, the use of blue light provides significant benefits in comparison with wavelengths near infrared light. Currently, mainly frequency-doubled green Nd:YAG lasers are used for laser processing of copper. Due to the resonator-internal frequency doubling, however, this is a comparatively complex, susceptible and expensive laser system. The solution approach of directly using low-power laser diodes with a blue wavelength simplifies the overall system decisively. Particularly interesting applications are generative manufacturing processes (e.g. Laser Powder Bed Fusion Process for Metals, PBF-LB/M) of copper, for the production of complex 3D microstructures. The aim of this work is to verify the possibility of processing copper powder with a blue laser system. The laser used for the investigations in this paper has a blue wavelength of λ = 450 nm and can be operated in pulsed or continuous mode. The diode laser achieves an output power of 10.8 watts at an operating temperature of 20 degrees Celsius. Basic investigations into the possibility of structuring with a blue laser were carried out using a copper powder with grain sizes of 45µm. This paper presents the first promising results of the research.*

Keywords: *Additive Manufacturing, Copper, Blue laser*

1. INTRODUCTION

In 2021, global sales of laser beam sources were estimated at $ 21 billion. Over 30 % of which was used for laser materials processing (Laser Focus World, 2022). When using lasers for macro and micro processing of materials, the principle of the thermal energy source is applied, by which the process result is achieved by heating the processing zone. When a laser beam hits a material, part of the energy transported in the laser beam is converted into heat in the workpiece (Callister and Rethwisch, 2009). When light strikes an interface, part of it is reflected back, which is called reflection. The other part passes through this interface, which in turn is called transmission. In electrically conductive materials, the electromagnetic wave of the light interacts with the material and is thereby attenuated. In the physical sense, this phenomenon is called absorption (Dausinger, 1995). Materials that are impervious to the transmission of visible light are defined as opaque. Bulk metals are opaque along the entire visible spectrum, which means that all light radiation is either absorbed or reflected (Callister and Rethwisch, 2009). In order for laser processing to be practical, the laser light must be absorbed by the material. Absorption is not a pure material property. It depends among another factors, e.g.: the environmental conditions (process gases, materials surrounding the workpiece, etc.), the properties of the surface (roughness, morphology, etc.), the geometry of the workpiece, the changes of the workpiece caused by the absorbed energy, as well as the physical properties of the workpiece and of the laser beam (wavelength λ, polarization, etc.) (Poprawe, 2005).

The term absorption coefficient refers to the physical effect of absorption. The ratio of the proportion of light that is attenuated to the total radiated energy is referred to as the absorption coefficient A. The absorption coefficient A of a powder also varies depending on the wavelength λ of the laser beam. The wavelength λ determines not only the color of the light but also its energy. The shorter the wavelength, the higher the energy of the light or laser. In order to be able to absorb as much of the laser energy as possible, an ideal wavelength must be selected for this purpose. This determines the type of laser to be used. If the material has a low absorption capacity, the laser power must be increased accordingly in order to be able to introduce sufficient energy into the powder for melting (Hügel and Graf, 2009).

The high thermal conductivity (401 W/(m·K) at 27°C) of pure copper makes it an ideal material for thermal application, but it is also one of the reasons why it is difficult to process by laser (Bonesso et al., 2021). In addition, copper has a lower coefficient of absorption of laser radiation compared to steel. With the use of a solid-state laser, disk laser or fiber laser (Nd:YAG or Yb:YAG, respectively), emission wavelengths of slightly above λ = 1000 nm can be used. In this case, the absorption coefficient of copper is less than 5 % and that of steel is more than 30 %. An increase in the absorption coefficient by pure copper can be achieved, by laser beam sources that emit in the "green", i.e. at a wavelength of λ = 515 nm, Figure 1. Particularly in the case of copper, these frequency-doubled systems can be used to increase the absorption of a cold copper material up to 37 % can be realized (Heß, 2012).

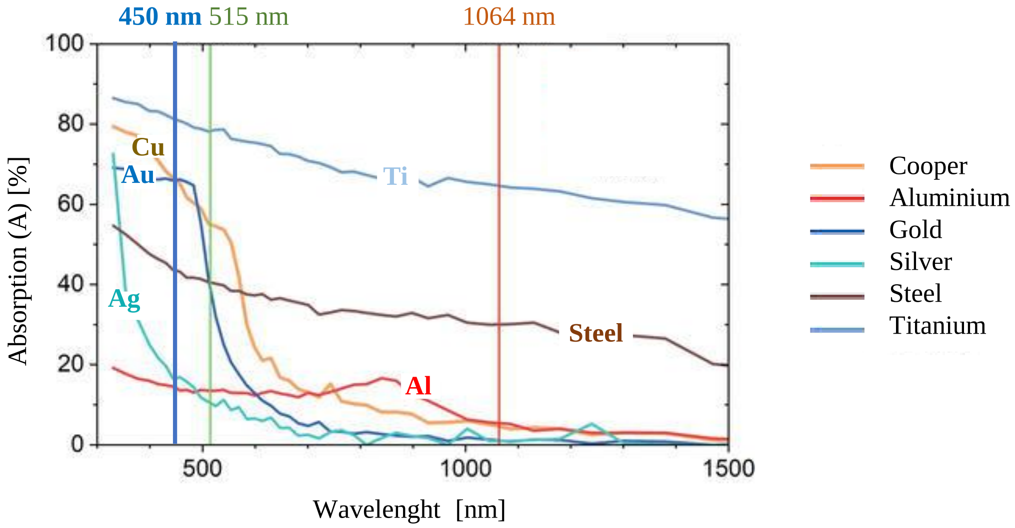


Figure 1. Absorption of laser output at different wavelengths varies according to the materials involved (Spisz et al., 1969 apud Stepien et al., 2022).

An alternative that has been under research is the use of blue laser sources with a wavelength λ = 450 nm (Hummel et al., 2020). Copper had an absorption coefficient A up to 60 % at a wavelength λ = 450 nm (Spisz et al., 1969 apud Hummel et al., 2020). As an approximation, all "yellow" and "red" shinning metals and alloys are particularly suitable for processing in the blue spectral range. For these metals, the blue light is clearly superior to the near infrared light. Increasing the absorption rate also improves the sustainability by saving the energy required for the additive manufacturing (AM). In the field of copper processing, blue laser systems have particularly interesting applications in the generative manufacturing process (e.g. Laser Powder Bed Fusion Process for Metals, PBF-LB/M) for the production of complex 3D microstructures. PBF-LB/M is an additive manufacturing process in which a powder is melted by the application of a laser beam. Using a laser, the powder is fused at a specific location for each layer subject to the design (ASTM, 2022). With the PBF-LB/M process it is possible to manufacture complex and lightweight parts within the manufacturing constrains (Cruz et al., 2017; Uhlmann et al., 2015).

In order to achieve the research objective of verifying the possibility of processing copper powder with a low-cost blue laser system, a laser system is developed as part of this study. Initially a system based on a desktop CNC machine and a low-cost diode laser are integrated to enable the first investigations on this topic. This paper describes initial investigations regarding the possibility melting of copper powder with this blue laser system.

2. MATERIALS AND METHODS

2.1 Machine and laser system

For the conducting of the tests a small CNC (Computerized Numerical Control) desktop machine from Stepcraft, Model 2/300, Menden, Germany, with working dimensions of 210 x 300 x 80 mm was equipped with a low-power blue laser system. A blue laser from the company SLS, Bad Leipzig, Germany, was installed in place of the milling head of the CNC machine. The fiber coupled laser diode modules works in the visible light spectrum that the human eye can view. The low-power laser uses blue diodes with a fiber core diameter of D = 100 µm. It´s offer a maximal power P_L = 10.8 W in cw (continuous wave) at a wavelength of λ = 450 nm, with a numerical aperture of fiber NA = 0.22 (STEP, 2023; SLS, 2023). To define the thickness of the powder layers to be processed, an adjustable table was adapted on the machine. This table allows to fix the used metal powder covered substrates and a precise adjustment of the positioning of these specimens on the z-axis of the machine. Figure 2 shows the integrated laser system and the adjustable table into the CNC machine.

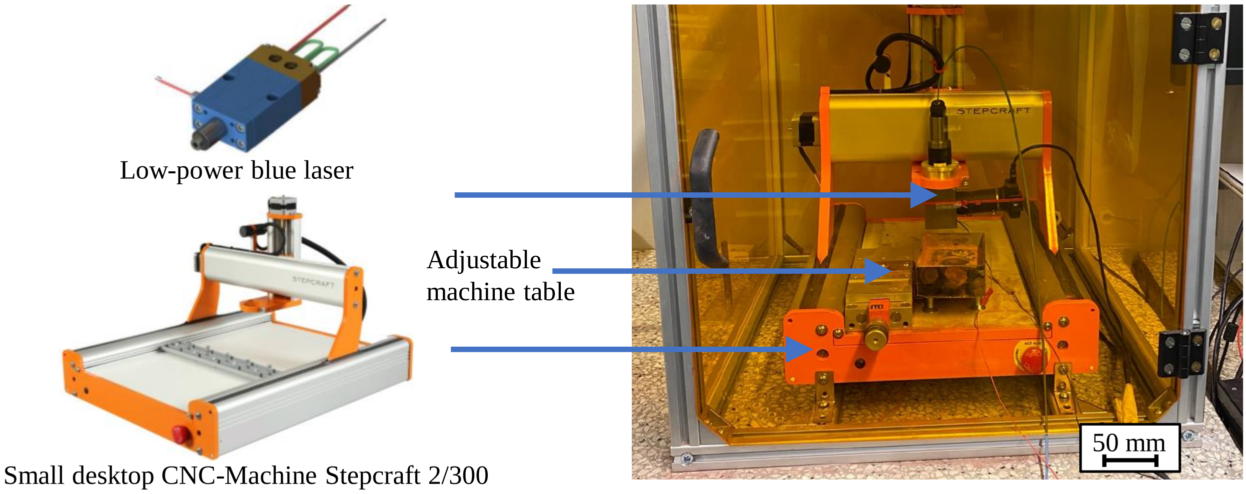


Figure 2. Desktop CNC-Machine and a fiber coupled laser diodes module (STEP, 2023; SLS, 2023).

2.2 Process Setup and Experimental Plan

In the present research, pure copper powder with an average particle size of d = 45 µm and a bulk density of ρ = 1,28 g/cm^3 was used as raw material for the investigations. A few auxiliary tools, as a pincer, laboratory spoon and spatula, assisted in placing the copper powder on the machine table to obtain a defined layer thicknesses in the range between 50 µm up to 500 µm for the laser investigations, Figure 3.

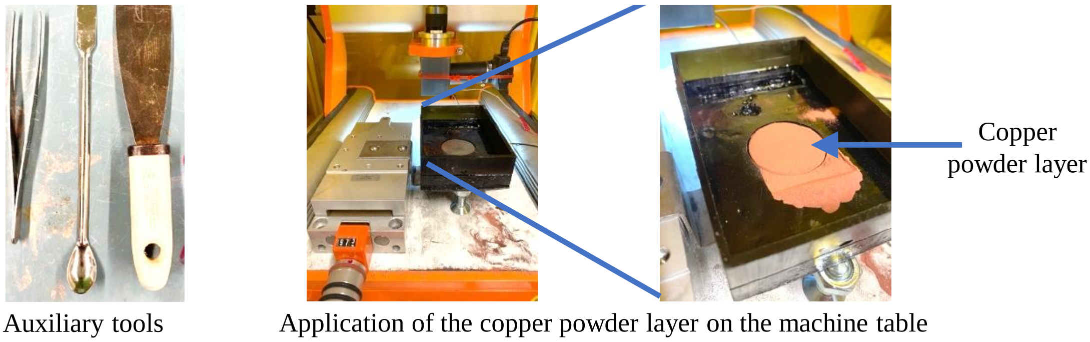


Figure 3. Process Setup – Application of powder layer on the machine table.

The exposure and hatch parameters used for laser processing of the copper powder are shown in Table 1. As an exposure strategy, parallel laser tracks with a length of 10 mm were programmed with G-Codes by the CNC machine. In some tests it was performed a second application with a laser tracks in a perpendicular orientation to the first one. The blue laser employed was set for the tests in cw and in pulsed mode, with a laser pulse duration τ_P = 50 ms. Following experimental investigations were carried out: investigations to define an ideal hatch distance H_d, effects of the laser exposure strategy, influence by applying more layers and different layer thickness of powder and influence of the laser feed rate v_s on the quality of processed copper powder samples. After the laser investigations, the specimens were analyzed with an optical microscope.

Table 1. Used exposure parameters.

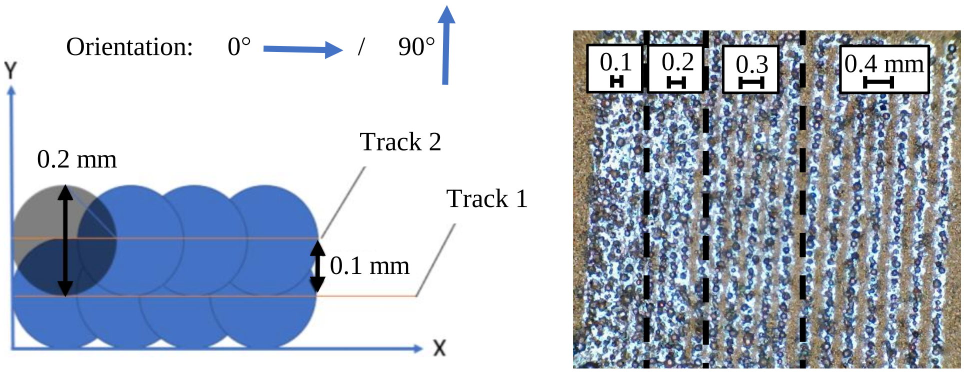
Exposure parameters	
Laser pulse duration τ_P [ms]	cw; 50
Laser wavelength λ [nm]	450
Laser feed rate v_s [mm/min]	30; 120
Hatch distance H_d [mm]	0.1; 0.2; 0.3; 0.4
Laser track orientation [°]	0 / 90
Layer thickness Lt [µm]	50; 300; 500
Number of layers	1; 2; 3

3. RESULTS AND DISCUSSION

First tests were carried out with the intention of determining an optimal laser processing position by varying the z-position of the laser focus in relation to the samples. Different laser focus position x_F [mm] at intervals of 0.2 mm between the distances of 16 mm and 18 mm were analyzed. The most stable and reproducible results were achieved at positioning $x_F = 17$ mm. A focal distance of 17 mm was therefore selected for the experiments carried out throughout this work.

Laser power P_L, laser feed rate v_s, hatch distance H_d and the layer thickness L_t are important process parameters that directly influence the volume energy density of the process. High laser feed rates are required to achieve high productivity within the operating range of the volumetric energy density for the material to be processed. However, the possible applicable laser feed rates v_s of the developed system are significantly lower than those of commercial systems using galvo scanners.

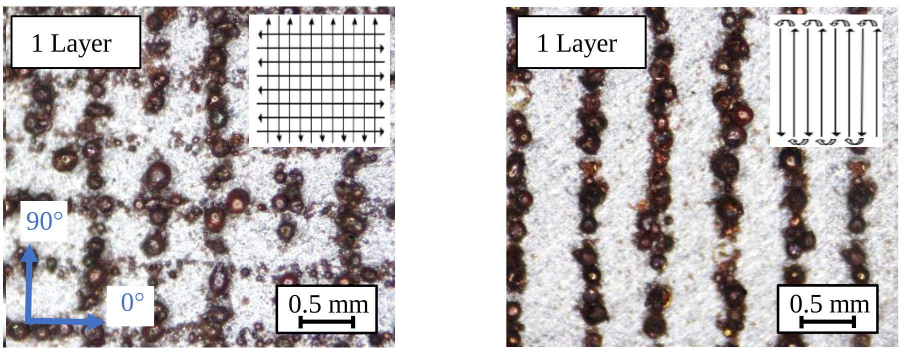
In figure 4 are shown the results of the investigations to verify the influence of the hatch distance H_d on the laser-processed copper powders. It can be observed that each laser track is approximately two times wider than the fiber core diameter of the laser system. The heat generated from the laser is conducted to the surrounding powder particles, incorporating them into the melting pool and making the pool larger than the diameter of the laser used (Renishaw, 2019). With the application of a hatch distance of $H_d = 0.3$ mm and 0.4 mm a gap is observed in the specimen between the tracks. To produce micro weld seams, it is important that the seams interact with each other. This occurs when part of the previous weld seam is re-melted by the current track. For this reason, hatch distances of $H_d = 0.1$ mm and 0.2 mm will be further analyzed in this study.



Process Parameters:
$\tau_p = 50$ ms
$v_s = 120$ mm/min
$H_d = 0.1; 0.2; 0.3; 0.4$ mm
Lt = 50 µm
Laser track orientation = 90°
Workpiece:
Cooper Powder d = 45 µm

Figure 4. Investigations to verify the influence of the hatch distance H_d.

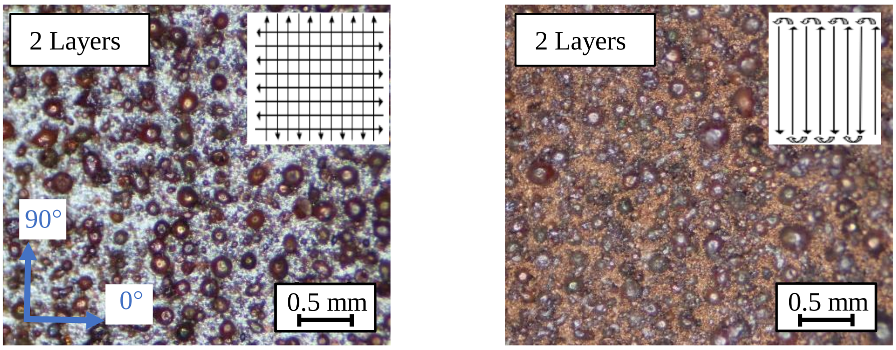
Figure 5 shows the results of the investigations to verify the influence of the laser exposure strategies on the copper powder. In this case a distance between the hatch lines of $H_d = 0.4$ mm was chosen to generate a region without powder fusion between the laser-processed lines for a better analysis of the results. A pulsed laser mode of $\tau_p = 50$ ms was chosen in order to reduce the required power. A layer thickness of $L_t = 50$ µm was applied. On the left side of Figure 5, it can be seen that the crossed lines in 0° and 90° orientations produce a crosshatched structure of the processed powder. On the right side of Figure 5, it is observed that the use of parallel lines tracks also generated a surface of parallel lines of the processed powder. In both strategies, agglomeration of the copper powder into spherical particles can be observed. This effect is also called in the literature as balling phenomenon (Li et al., 2012).



Process Parameters:
$\tau_p = 50$ ms
$v_s = 120$ mm/min
$H_d = 0.4$ mm
Lt = 50 µm
Laser track orientation = 0° and 90°
Quantity of powder layers = 1
Workpiece:
Copper Powder d = 45 µm

Figure 5. Effects of the laser exposure strategy.

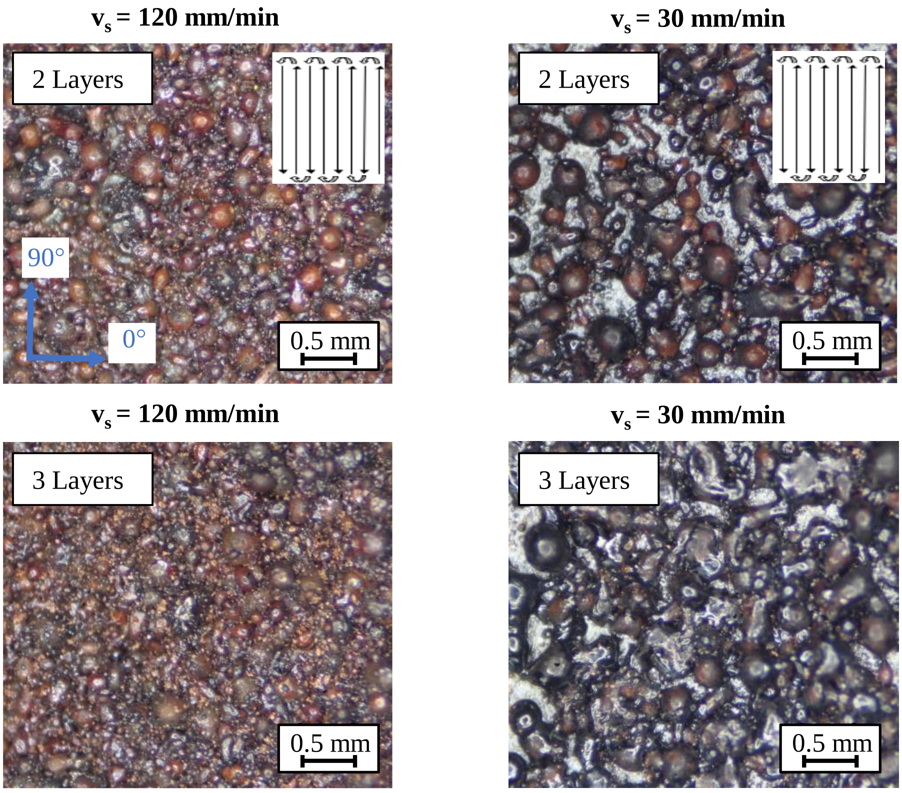
In the next tests, shown in Figure 6, the same parameters were used as in the laser exposure strategy tests. The only difference was the setting of a parameter for reducing the distance between the hatching lines H_d. In order to try to achieve a homogeneously fused powder surface a H_d = 0.2 mm was selected. With this same intention, it was opted to apply 2 layers of copper powder. In both pictures of Figure 6, it can be noted that with the new parameters applied, the two laser exposure strategies generated a homogeneous surface of the processed powder. Structures with dominantly spherical particles are still being generated. Especially with the parallel hatch lines strategy, almost an entire layer of molten copper powder is observed.



Process Parameters:
τ_P = 50 ms
v_s = 120 mm/min
H_d = 0.2 mm
Lt = 50 µm
Laser track orientation = 0° and 90°
Quantity of powder layers = 2
Workpiece:
Copper Powder d = 45 µm

Figure 6. Influence by applying more layers of powder by different laser exposure strategy.

In the following investigations the number of powder layers was increased and the distancing of hatch lines H_d = 0.1 mm, as well as the laser feed rate, were significantly reduced. With these applied settings, it can be noted in all pictures of Figure 7 that the sizes of the generated copper spheres are larger than those produced in the earlier tests. The results of the tests with feed rates of v_s = 30 mm/min show that at certain positions on the surface small geometries, similar to small weld seams, were also generated.



Process Parameters:
τ_P = 50 ms
v_s = 120 and 30 mm/min
H_d = 0.1 mm
Lt = 50 µm
Laser track orientation = 90°
Quantity of powder layers = 2 and 3

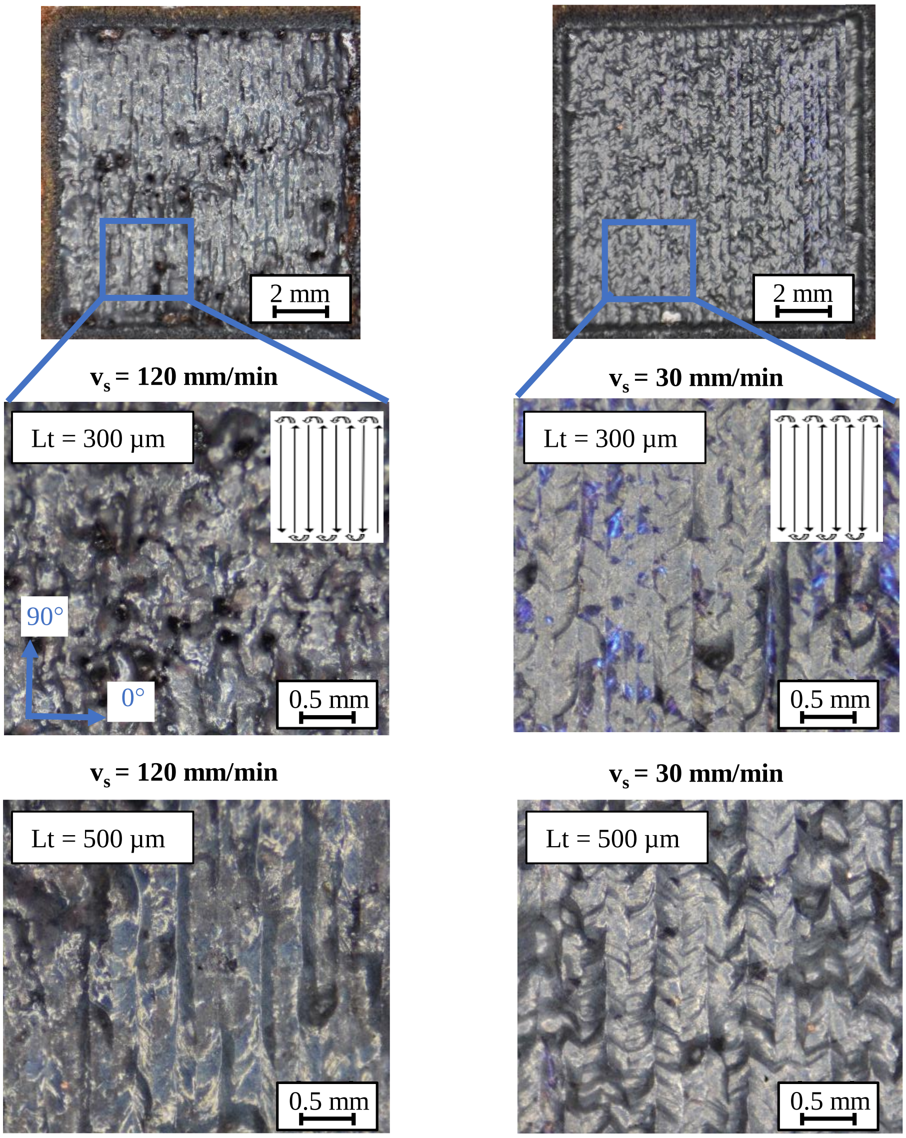
Workpiece:
Copper Powder d = 45 µm

Figure 7. Influence of the laser feed rate v_s.

The results of the previous investigations appeared quite promising. Another important point was that it was possible to recognize clear contours of weld seams at the turning points of the laser beam. These characteristics are due to the slower movement of the laser in these areas. In order not to exceed the limits of the machine by further slowing down its feed rate, it was decided to double the laser frequency for the next test, resulting in a continuos wave (cw) laser beam. This new series of tests was performed with a maximization of the power offered by the blue laser system.

The blue laser was now employed in cw-mode with exactly the same process conditions as shown in Figure 7. However, these tests did not produce satisfactory results. The material did not adhere to the substrate and had a huge deformation. Therefore, it was decided to increase the thickness of the copper powder layer applied for the further experiments. These results are shown in Figure 8.

In both of the results of the tests shown in Figure 8, the laser processed copper powder results in a homogeneous surface. In particular, the tests with a feed rate of v_s = 30 mm/min show the most satisfactory results. It can be concluded that a minimum thickness of L_t = 300 µm is required when applying the blue laser with maximum power in cw-mode.



Process Parameters:
τ_P = cw
v_s = 120 and 30 mm/min
H_d = 0.1 mm
Lt = 300 und 500 mm
Laser track orientation = 90°
Quantity of powder layers = 1

Workpiece:
Copper Powder d = 45 µm

Figure 8. Influence of cw-Laser and high layer thickness L_t at different feed rates. v_s.

4. CONCLUSIONS AND OUTLOOK

The results of the experimental investigations show that copper powder can be processed with a blue laser. In the experimental tests it was verified that by optimizing the laser feed rate v_s, the Hatch distance H_d, the laser modus and the layer thickness L_t a specific fusion of the copper powder can be achieved. Thus, the use of a low power and low-cost blue laser has a great potential to be applicable in additive manufacturing systems within the category of PBF-LB/M processes.

However, the results presented in this paper are initial results and there are still many factors to be optimized in the additive manufacturing process of copper with a low power blue laser. In further experiments it is intended to investigate the use of copper grains with different grain sizes under the influence of inert gases as well as the combination of different layer thickness and laser exposure strategy. In addition, a metallographic analysis of the quality of the processed powder surfaces must also be performed.

Furthermore, the possibilities of the low power blue laser used in the present work are currently being investigated for the micro welding of thin copper wires in order to repair welding on printed circuit boards. In addition, it is intended to apply the laser system for buildup welding for the repair and maintenance of microelectrodes for Die-Sinking Electrical discharge machining.

5. ACKNOWLEDGEMENTS

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