Review Article

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Development of a hollow laser beam for micromachining

Abstract: Current laser cladding technologies have limited resolutions of about 50 μm. A new solution has been developed within the project 'Nanomicro' to improve the spatial resolution. The 'micro hollow laser beam system' and a deposition system for highly focused metal micropowders are innovative parts within a high-precision 3D micromanufacturing laser cladding platform. We demonstrate, here, a new hollow laser sintering concept that is aiming on more efficient laser cladding and manufacturing of highly precise and functional parts in the range of a few microns.

Keywords: hollow laser beam; LAM; laser cladding; microfocus; micromanufacturing; optical system.

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1 Introduction

In direct metal deposition processes, a laser beam is used in order to apply the power density that is necessary to melt the additives, usually metal powders [1]. Future applications for this technology can be found, for instance, within the field of microtooling, photovoltaic, and the surface treatment of medical implants [2, 3]. The resolution in direct laser additive manufacturing (LAM) of microparts is currently limited to approximately 50 μm [4, 5]. A smaller focus, and thus a higher resolution, is usually not applicable. Achieving a spatial resolution of 50 μm is not ensuring that the manufactured parts are usable directly. Often, the surface quality achieved is not sufficient enough for functional surfaces, and a subsequent treatment is necessary, if possible. To overcome this gap, the manufacturing process must be able to deliver a better resolution than required for the dimensions of the produced part itself.

2 Objectives

Within this project, the hollow laser beam has to be focused to a diameter <5 μm to reach sufficient shape resolution. Owing to the new design of the prototype platform, it was necessary to define the process requirements, limits, and restrictions. Considering the general requirements for the hollow beam system, including the

- achievement of a focus diameter ≤5 μm,
- off-axis focusing with maximum amount of beam incidence, on-axis is strictly not allowed due to a device which is fed axially,
- sufficient distance between the optical system and additive mass.

It was important to determine the dimension limits, process contaminations, and physical conditions of laser focusing. Special attention was given to the issue of focusing. A detailed understanding of the optical parameters that drive the optical system performance is critical in order to produce useful results. Also, it is particularly difficult to prevent the contamination of the optical system, especially if the precision optics is not in sufficient distance to the melting zone. In the actual melting process of laser additive manufacturing spatter cannot be really prevented. Owing to this, it was important to protect the optical system either by protective glasses or by distance. Furthermore, the ideal optical system should be robust against environmental variables such as varying temperature and vibrations of machine systems. Obviously, no optical system we discussed was suitable and, therefore, could not fulfill the general requirements. Especially, the non-axial arrangement of the optical system excluded many known techniques to create a hollow laser beam. As previously mentioned in the requirements, a hollow laser beam concept was necessary due to a device, which is fed axially.

The successful achievement of the objectives can be summarized in three principal stages:
- review of general conditions, requirements, and restrictions,
- design/modeling of hollow laser concepts and principles,
- development of micro hollow laser beam.

3 The hollow laser concept

Numerous hollow beam optical configurations exist. Several of these design concepts have been evaluated at the Laser Zentrum Hannover e.V. (LZH) within the scope of this project. We have reviewed the different methods that work from an axicon lens (conical lens) generating a ring spot beam to diffractive optical elements generating hollow donut beams by interference pattern. Several alternative solutions, based on multispot beams and multiple rotary laser scanning beams, were also considered. The evaluation process included the viability of the required physical parameters that significantly influence the beam. In order to reach the focal points of 5 µm or less without compromising the other requirements, the limitations of each concept design were clarified, and the potential no-go criteria were defined. The requirements of each concept design were listed and tested for their applicability. Compliance with the optimal parameters was crucial in order to meet the demands. Only a few methods remained suitable after applying the selection criteria noted above: a piezo scanning system, a multispot optical system, and a system with tailored beam shape optics.

3.1 Laser beam and microfocus

Propagation characteristics show that laser beams do not diverge linearly. Diffraction causes laser beams to spread transversely as they propagate. Divergence is defined as the angular measure of the increasing diameter. Close to the beam waist, where the beam radius is smallest, divergence is negligible. Far from the waist, the divergence angle approaches the asymptotic limit (Figure 1). Therefore, it is impossible to get a perfectly collimated laser beam or to focus the beam to a required size with an acceptable focal length.

Thus, focusing a laser beam to a microspot size is affected by the divergence of the laser source. In addition, it is also strongly affected by the wavelength, the laser beam diameter, and the focal length of the precision lens optic used (Formula 2, 3).

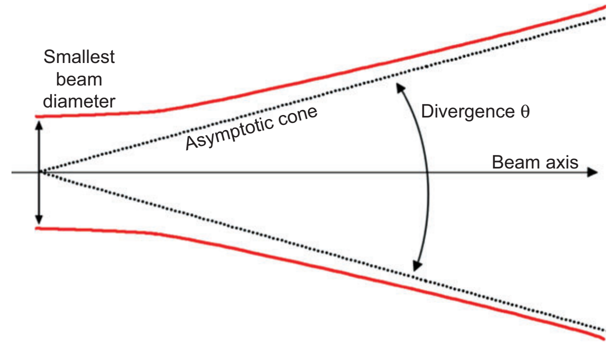

Figure 1 Transversal spreading by diffraction, based on [6].

The beam waist of a focused laser beam is
- proportional to the optical focal length,
- proportional to the beam divergence,
- proportional to the wavelength,
- inversely proportional to the beam diameter.

The beam spot size of 5 µm can be achieved with the best beam quality (M^2 or K factor) and low Gaussian mode (TEM00). The beam quality factor M^2 is derived from the uncertainty principle and describes the propagation of an arbitrary beam. M^2 is a measureable quantity in order to characterize the real mixed-mode beams.

$$\text{divergence angle}[\theta]=2\frac{\text{wavelength}[\lambda]}{\pi*\left(\text{beam}\frac{\text{waist}[d0]}{2}\right)} \tag{1}$$

$$\text{focal radius}[wf]=\frac{\text{divergence angle}[\theta]}{2}*\text{focal length }[f] =\frac{\text{wavelength}[\lambda]*\text{focal length }[f]}{\pi*\left(\text{beam}\frac{\text{waist}[d0]}{2}\right)} \tag{2}$$

A perfect Gaussian TEM00 beam mode, typically determined at the $1/e^2$ level (=86.5%), has the lowest beam divergence of 1. The low divergence results in a smaller focused spot and a greater Rayleigh length (Figure 2). The Rayleigh length, defined as the distance over which the beam radius spreads by a factor of √2, is given by the following formula.

$$\text{Rayleigh length}[zr]=\frac{\pi*\left(\text{beam}\frac{\text{waist}[d0]}{2}\right)^{z}}{\text{wavelength}[\lambda]} \tag{3}$$

Further details and test methods of beam divergence and propagation are described in ISO 11146 [7].

Table 1 shows the theoretically achievable focal spot diameter and the Rayleigh length in comparison to the

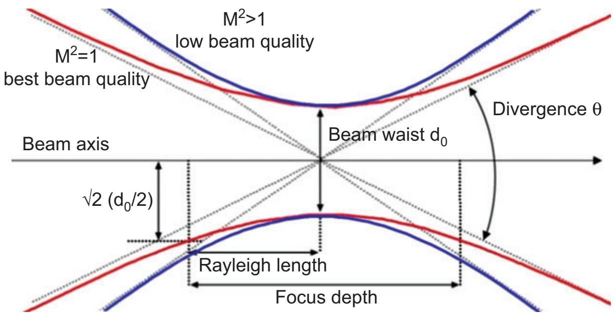

Figure 2 The beam waist of a focused laser, based on [6].

radius of the collimated beam. Generally, it can be said that the smaller the focal length, the smaller the spot size, but also, the smaller the working distance.

In designing the optical setup, we noticed a strong dependence of correct alignment and the achieved projection quality. Additionally, there have been significant deviations in the results in using different types of microfocus optics. Not only is it due to the different focal ranges, but also, it is due to the quality and type of the microfocus lenses such as aspheric, plano-aspheric, or monochromatic. Regarding the achievable focal spot radius, partially significant differences have been detected between the calculated and the experimental results. Our investigations have shown that even if the microfocus lenses were type-specific corrected, there can be deviations from the theoretical values regarding the focal spot size and the Gaussian profile accuracy due to diffraction and aberration [8, 9].

3.2 The multifocus optical system

The multifocus optical system was our system of choice as it best complied with the hollow laser beam concept and our requirements. In this paper, we will focus on that method and the optical system that addresses the requirements best. A detailed analysis and discussion of the multifocus system is, therefore, given in following paragraph.

The implemented solution involved three individual lasers. Each laser was equipped with a precision multiaxis positioner unit and a microfocus generator. The lasers were concentrically arranged so that their focal points met in a common point (Figure 3).

This concept would differ from a beam shape but serves the same purpose of a shape and fulfills the requirements. Three lasers are used to guarantee a directional independence of the melting process. If only one laser was used, it would lead to the directional dependence of the melting process. The directional dependence in our implemented optical system was eliminated by the symmetrical and concentric arrangement of the focus generators with respect to each other. A similar concept, though based on beam splitting optics, has been used successfully within the BMBF project 'Flexilas,' to realize a directionally independent macroscale wire-cladding head.

The angle of the beam incidence is related to the degree of beam absorption, which mostly depends on the material, surface texture, wavelength, polarization, substrate temperature, and the angle of the beam incidence [10].

The laser source, in our case a fiber laser, has a wavelength of 1070 nm. All the other relevant parameters can be controlled. The most important factor affecting absorption is the angle of incidence, which had to be as steep as possible. Figure 4 shows the degree of absorbance for nonparallel or parallel polarized beam with a wavelength of 1060 nm. Owing to the structural restrictions, we were not able to achieve a beam incidence of more than 60°.

3.3 Laser source and power density

Owing to the specific requirements regarding the beam source such as beam quality, size, and sufficient power to

Beam radius w0	2.5 mm	2.5 mm	3.5 mm	3.5 mm
Wavelength λ		1070 nm		
Focal length f	10 mm	20 mm	10 mm	20 mm
Focal spot radius wf	1.36 μm	2.72 μm	0.97 μm	1.95 μm
Rayleigh length Zr	~6 μm	~24 μm	~3 μm	~12 μm

Table 1 Achievable focal spot and depth of focus.

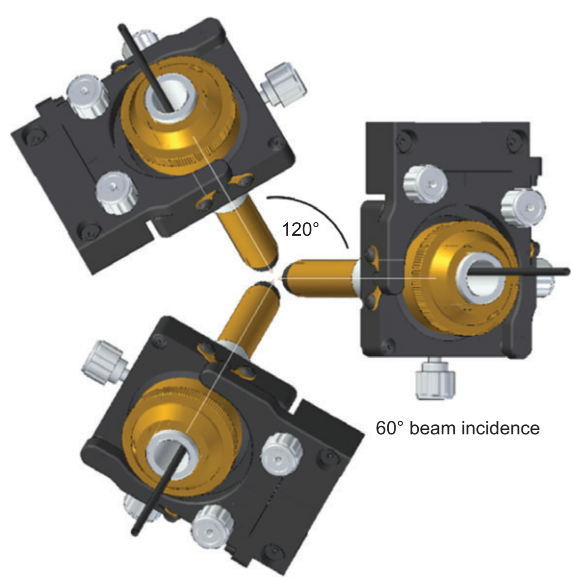

Figure 3 Arrangement of the adjustment units.

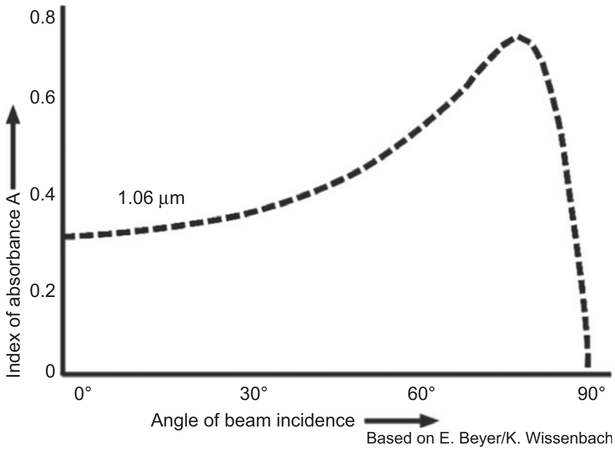

Figure 4 Absorbance as a function of beam incidence at a wavelength of 1060 nm, based on [11].

melt the additive, we opted for a single-mode fiber laser with multiple outputs. The single-mode fibers ensure a very good Gaussian TEM00 mode. Compared with the conventional laser sources used in layer direct manufacturing, the power of our beam source was unusually low. However, due to the microfocus of 5 µm, the power density required to melt the additive powder was already achieved at a low power. Table 2 shows the theoretical power density at the focus point.

Measurements done with the Primes Micro Spot Monitor (MSM), to determine the power density profile of the single spots, correspond almost to the theoretically calculated density values from the table above.

Slight deviations are reasoned by the Gaussian beam profile and the calculation method of the measurement device, which determines its data at the $1/e^2$ level. Anyway, the measurements showed promising results in the expected spot size range (Figure 5).

At maximum, the laser offers a power output up to 2 W at each fiber, which allows an increase in the application speed in the future process development. In Figure 6 is shown the required power density as a function of the application speed.

4 Discussion and conclusion

The evaluation process of microfocusing has shown that the hollow laser beam concept is suitable to achieve the set requirements. The close distance to the working platform makes it still difficult to reach an optimal angle of beam incidence. Therefore, we could not achieve an entirely high heat input for melting the additive powder. A certain amount of beam radiation is reflected and is

Ø spot	5 mm	5 µm	5 µm	5 µm	5 µm
Power	20 W	20 W	2 W	200 mW	20 mW
Power density	~102 W/cm^2	~102 MW/cm^2	~10 MW/cm^2	~1 MW/cm^2	~102 KW/cm^2

Table 2 Power density as a function of spot diameter.

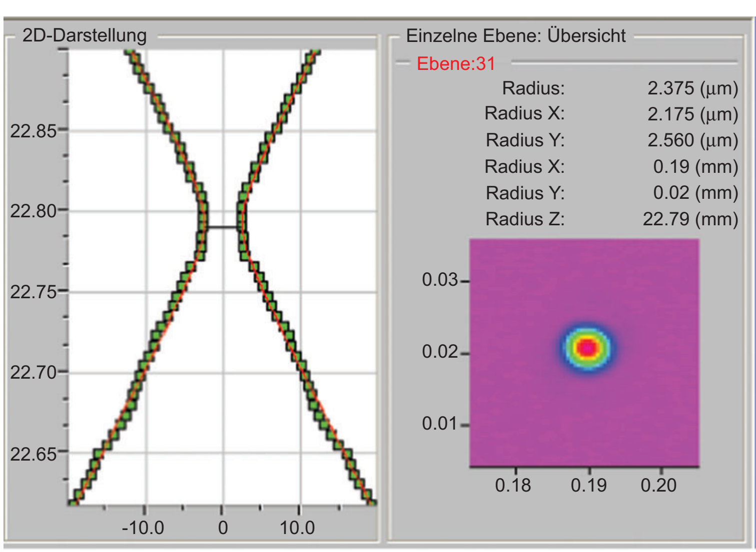

Figure 5 A 5-µm microfocus beam caustic (f=15 mm, single spot).

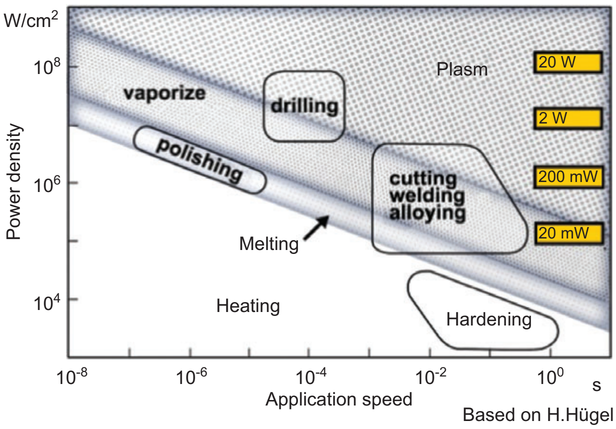

Figure 6 Power density as a function of application speed, based on [10].

lost for the melting process. The lower heat input can be compensated and tuned by varying the laser power level; however, doing so also increases the beam quality M^2. As shown above, the increase in the beam quality will result in a larger beam waist diameter. Measurements done with the Primes MSM have previously shown a significant increase in the microfocus to more than 5 µm, if we increased to a higher laser output level. All in all, we have realized a microfocus system with a sufficiently large working distance of about 13 mm and a depth of focus in the range of 60–70 µm. We arranged the focal points concentrically in a way that they met in a common point. A prerequisite for this arrangement was a completely vibration-free construction of the optical system as well as of the other moving parts of the laser additive micromanufacturing machine, which was conducted as good as possible. An issue that we had previously neglected became more obvious during the test stages, namely, the effect of room temperature fluctuation having effects on the parts of the optical system. Temperature fluctuation makes it difficult to guarantee a sufficiently stable microfocus system with a suitable focus depth. Theoretically, there is also a possibility to generate microfocuses of 5 µm with a larger focus depth from a precollimated beam diameter greater than the one used in our microfocus generators. Table 1 shows that the larger beam radius results in a larger focus depth (2x Rayleigh length). But this would require structural changes in the optical system and would result in a beam incidence smaller than 60°, probably leading to an increased amount in spatter and ablation due to the high power density.

Temperature stabilization and further improvements will be implemented in the further course of this work.

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