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Characterization method for different powder nozzle types used in laser metal deposition

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Abstract

In laser metal deposition (LMD) blown powder is melted by the laser onto a substrate. This process is the preferred method for the generation of metallic near net shape large components or functional geometries on semi-finished parts. For the powder supply different types of powder nozzles are used. Two common types of nozzles are coaxial nozzles with annular gap or multi jet powder supply. Comparisons between these types are difficult due to their different powder propagation behavior.
In this work a line laser is used to illuminate the powder stream layer wise. The obtained images per layer allow to visualize and analyze the powder propagation behavior. The proposed characterization method allows to compensate for different symmetries of some nozzle types, thus making the characterizations between nozzle types comparable. The method can be used to calculate the powder focus spot diameter or determine the working distance of a nozzle.

Keywords: powder nozzle; powder stream propagation; laser metal deposition

1. Introduction

Additive manufacturing is a manufacturing technology with increasing importance in the field of metallic material processing (Schmidt et al. 2017). The process has a wide range of applications, like the production of prototypes, end products and also various tools. For the 3D printing laser metal deposition (LMD) process, the most commonly used nozzle types are discrete nozzles and continuous nozzles. The powder nozzles are of great importance in the process, especially for process stability. Many studies have shown the importance of

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nozzle influence on the process, such as (Zhu et al. 2012) and (Zekovic et al. 2007) who showed the strong sensitivity of powder defocusing on build capabilities in LMD.

(Ferreira et al. 2020) calculated a powder spot diameter by setting limits for an inner and external diameter at encompassing 1% and 86% of the maximal luminosity of the illuminated particles of continuous nozzles. This way a reconstruction of the powder stream caustic was build. Another way to define a laser spot diameter was presented by (Liu et al. 2021). They assumed that the powder at the stream waist has a gaussian distribution and defined their powder diameter as the range in which 86.5% of all detected particles are. A comparable method was proposed by (Li et al. 2021) who used 14% of the peak concentration of measured powder to calculate a powder spot diameter.

(Liu et al. 2015) proposed to distinguish the powder stream below the nozzle tip into three zones: annular zone, consolidation zone and dispersed zone. A similar distinction was made by (Gao et al. 2022) into pre-waist, waist and dispersion region. Another introduced separation was given by (Liu et al. 2021) where the waist region is the region where the powder stream has a gaussian distribution. (Wen et al. 2009). proposed for a continuous nozzle that the beginning of the waist region is where the powder stream merges to one stream and the end to be where the powder concentration in the center decreases and the powder stream then begins to diverge. The differentiation is of importance since a specific range in standoff distance to the nozzle will lead to a stable powder delivery and an accurate buildup geometry (Zekovic et al. 2007; Tabernero et al. 2012).

In summary it can be said that different methods for the characterization of powder streams have been presented, showing the growing interest in this research area. This paper introduces a method to characterize powder nozzles in regard to their powder spot size and working distance. This method can be utilized for different nozzle types since radially averaged characteristic values are applied.

2. Experimental Setup

The powder nozzle is a 6-jet discrete nozzle from GTV type PN6625, with a proposed working distance of 20 mm to 25 mm according to the manufacturer. An Oerlikon Twin-150 powder feeder is used with AISI 316L powder with a powder size of -106 µm + 45 µm. A stream of argon carrier gas carries the powder to the process zone, where additional argon shielding gas meets the powder stream. To examine only a single horizontal section perpendicular to the main axis of the nozzle a line laser is used for illumination. The line laser has a wavelength of 650 nm to 655 nm, 10 mW of power, an opening angle of 20° and an approximate height of 150 µm at the used distance. The laser is mounted onto a height adjustable table. A CCD-camera (Allied Vision Mako G030C) is attached coaxially onto the laser optics. The focus of the camera is adjusted for each illuminated section. The resolution of the recorded images is 18 µm per pixel. The powder enters the field of view approximately 5 mm underneath the nozzle opening. The shielding gas was set to 15 l/min and carrier gas to 2.5 l/min. The powder mass flow was 21 g/min. Videos are recorded with multiple frames and a constant exposure time. The standoff distance between each measurement is 1 mm.

3. Methods and Results

The data processing procedure is depicted in Figure 1. The obtained videos are merged into one mean image per layer. The intensity distribution image is displayed in false colors to make differences in intensity more distinguishable. The intensity spans between 0 and 1, indicating no light on the respective pixel or maximum intensity, thus the intensity is used as an indicator for powder population. The false color images are stacked to achieve an envelope of the powder distribution, similar to the caustic of a laser beam.

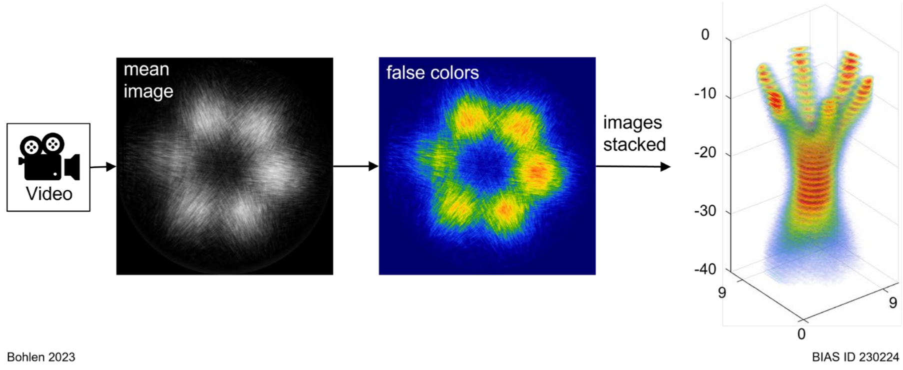

Fig. 1. Processing of recorded layer videos

To allow for comparison to different layers or different nozzles a radial-symmetrical representation of the powder distribution is calculated in each layer. This is done by evaluating concentric circles around the center of the nozzle. Along each circle the intensity is evaluated. An example for this can be seen in Figure 2. 10 mm from the nozzle exit the six powder streams have not yet merged. No powder can be seen near the center of the nozzle (orange line in upper diagram). In 4 mm distance to the center the six powder streams are clearly distinguishable (blue line in upper diagram) and it can be seen that the powder population is different for the six powder streams. When the standoff distance to the nozzle exits increases to 25 mm the powder streams have merged. A high intensity is measured 1 mm from the center of the nozzle (orange line in lower diagram). 4 mm from the center the intensity is already quite low, indicating low population of powder in this area (blue line in lower diagram).

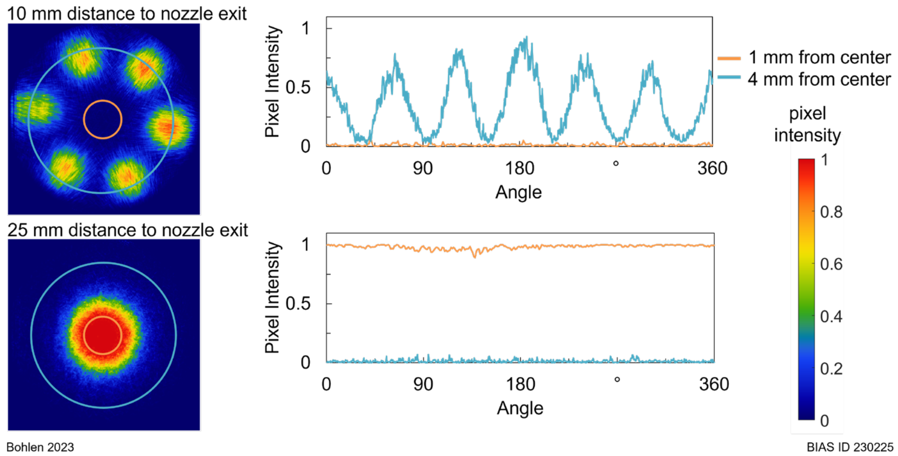

Fig. 2. Two layers from the powder distribution envelope with two concentric circles at 1 mm and 4 mm from the center with corresponding intensity lines.

A mean intensity is calculated for each concentric circle and the corresponding standard deviation. The standard deviation can be used as a factor of how symmetrical to the center the powder stream is. Figure 3 shows these means intensities and standard deviations for two layers (10 mm and 25 mm from nozzle exit).

Since 25 mm from the nozzle exit the powder streams have merged, the highest mean intensity is measured in the center (green line). Above the merging of the powder streams the streams are detected as a mean value with a high standard deviation due to the gaps between the streams (violet line).

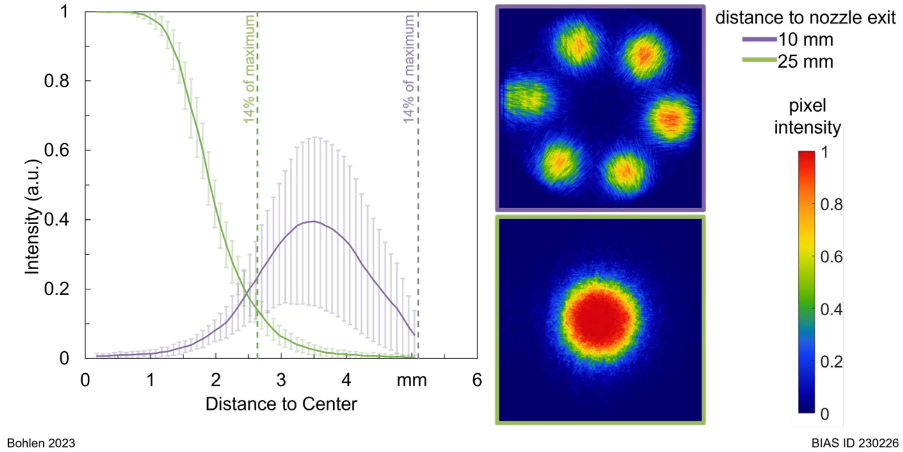

Fig. 3. Mean intensity and standard deviation for 55 concentric circles with a distance of 5 px (0.1 mm).

The mean intensity can be used to calculate an equivalent powder spot diameter. The chosen method in this paper is to set the boundary of the powder spot to where the intensity has fallen to 14% of the maximum measured mean intensity (indicated in Figure 3). This method has similarities to the D86 method used in laser beam measurements when the powder streams have merged. But the method also gives equivalent powder spot diameter above merging. This is because no gaussian distribution is needed and only the decline to 14% of powder maximum is calculated. In Figure 3 this can be seen for the violet line where 14% of the maximum is in the range where there are no measured values anymore due to the nozzle opening covering sight to the powder stream. The D86 method was also suggested by (Li et al. 2021) to be used for powder streams.

A high standard deviation indicates radial asymmetry. This is the case when the powder streams have not yet merge but can also be the case if the streams separate again after the powder stream waist. The working distance of a powder nozzle should ideally be where there is a homogenous powder distribution. Dividing this standard deviation by the mean value gives the coefficient of variation for each circle. Then the mean value of these coefficients is calculated within a proposed region of interest. The region of interest is set to be between the maximum intensity and the equivalent powder spot diameter. This is shown in Figure 4 for three distances to the nozzle exit, 10 mm, which is before the powder streams merge (violet graph), 20 mm the powder streams have merged (red graph), and 30 mm distance to the nozzle exit, where the single powder streams are diverging again (yellow graph).

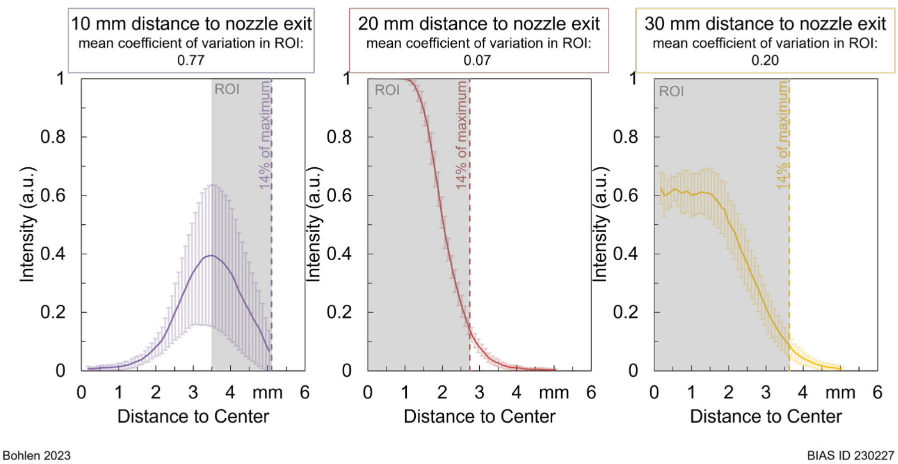

Fig. 4. Region of Interest (ROI) for calculating the mean coefficient of variation to determine the working distance for three different distances to the nozzle exit.

Figure 5 shows the calculated equivalent powder spot radius along the powder stream (left side) and the mean coefficient of variation (right side) for the same nozzle. The smallest diameter is at a standoff distance of 23 mm from the nozzle. The mean coefficient of variation starts at a high value and then decreases almost linearly until it reaches a rather steady level from 17 mm standoff distance till 26 mm standoff distance. The values then start to increase again.

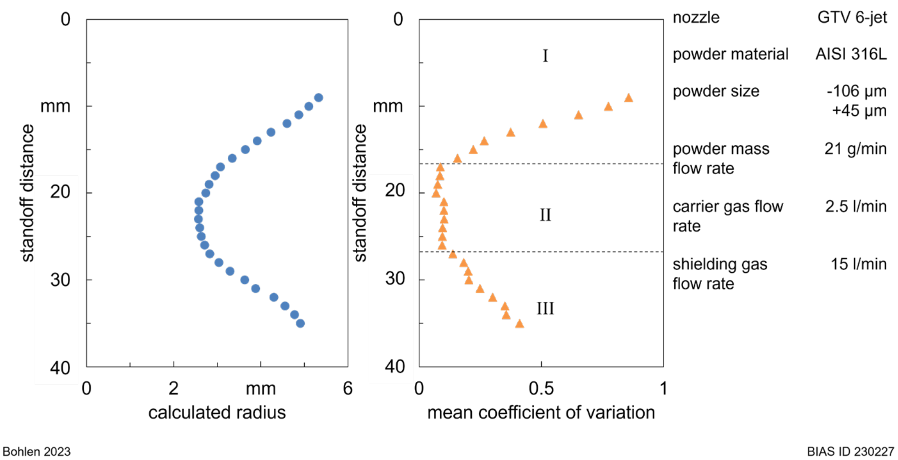

Fig. 5. Calculated radii and the mean coefficient of variation both in regard to the standoff distance. Region I: powder streams have not yet merged. Region II: powder streams have merged, and powder distribution is radially homogenous. Region III: powder streams start diverging again.

4. Discussion

In this work, a coaxial method for characterizing the powder stream is presented. A lateral observation can also be implemented by using image transformation (Bohlen et al. 2022). In both cases, radial asymmetries are compensated for by this method. These asymmetries always occur for discrete nozzles but can also be present for continuous nozzles if part of the powder channel is blocked. The equivalent radial powder distribution is calculated by the mean intensity over concentric circles (Figure 2 & Figure 3). The normalized standard variation (coefficient of variation) was used to calculate a working distance for the nozzle which corresponds well with the manufacturer's specifications (see Figure 5). The workings of (Liu et al. 2015) and (Liu et al. 2021) suggest that the powder stream is divided in three regions. In our proposed method, the mean coefficient of variation gives a strong indication of where the merging of the streams begins, thus the working distance should be where this value becomes reasonably small. The end of the working distance should be where the merging region ends, this is also indicated by the mean coefficient of variation.

5. Conclusion

A method was shown, which can be used to characterize the powder stream propagation behavior. The method also makes the comparison between different nozzle types possible. To compensate the radial asymmetry, mean intensities over concentric circles were calculated, which were subsequently used for the calculation of an equivalent powder spot diameter. The mean coefficient of variation is used to determine the beginning and end of the working distance of a discrete nozzle.

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