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Additive manufacturing of highly resolved pure copper parts

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Abstract

The general feasibility of pure copper using the laser assisted powder bed fusion (L-PBF) process has been repeatedly demonstrated over the last few years. The high thermal and electrical conductivity combined with the geometric freedom of the L-PBF process offers a wide range of applications. However, these studies also reveal that it is difficult to achieve a high density combined with a high surface quality and resolution. This shows that the thermal management, which in general is crucial in L-PBF processes, is even more important for high thermally conductive materials. We demonstrate the fabrication of pure copper parts offering a homogeneous and high density above 99 %, superior surface quality with an average roughness around 3 µm combined with a high resolution with features below 250 µm.

Keywords: laser assisted powder bed fusion; copper; high resolution; thermal management

1. Introduction

The utilization of geometric freedom offered by the laser assisted powder bed fusion (L-PBF) process combined with the high thermal and electrical conductivity of pure copper offers a wide range of applications. The general feasibility of copper as a material was repeatedly demonstrated over the last years, e.g. from Qu et al., Stoll et al., Gruber et al.. In these publications copper parts with high in-volume densities are presented. However, the specimens generally exhibit a poor surface quality with average roughness's above 10 µm. These degraded surface properties indicate an unstable melting regime. To be able to understand where these instabilities come from, a simple heat diffusion model is utilized to understand the temperature evolution

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close to the part’s boundary regions. Furthermore, a compensation method based on the results is used to significantly improve the surface quality of copper parts fabricated using the L-PBF process.

2. Thermal diffusion approximation of the involved thermal volume

To improve the degenerated surface quality a basic understanding of the temperature evolution in the boundary regions during processing is required. To do so, the Fourier’s equation is solved under the approximation that the thermal diffusion in the surrounding powder bed is negligible and acts as a perfect insulator. This strong assumption can be made because the thermal conductivity of the powder is about 2 to 3 orders of magnitude lower compared to the already fabricated solid part. Together with a very short effective dwell time the thermal diffusion in the powder can be neglected. To get an impression of the generated temperatures in a region where re-melting is expected, the temperatures are evaluated around 4 to 5 layers below the processed layer centered below the laser spot. Assuming a stationary laser heat source the solution of the Fourier’s equation proposes a semi-spherical heat diffusion profile if the laser spot is far away from the outer surfaces. Using this heat diffusion profile, we can approximate the thermally involved volume V_{therm} [m^3] in our component by choosing the radius to be the thermal diffusion length $r_{th} \propto \sqrt{\alpha\tau}$. With the thermal diffusivity α [m^2 s^{-1}] and an effective dwell time τ [s] which depends on the scanning speed v and the focus diameter d.

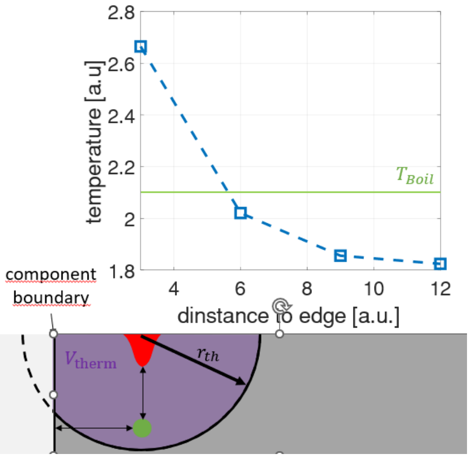


Fig. 1. Qualitative illustration of the temperature evaluation 4 to 5 layers below the surface (green point) of the component in dependence of the distance of the laser beam (red) to the outer component boundary. The thermally involved volume close to the component boundary is indicated in purple.

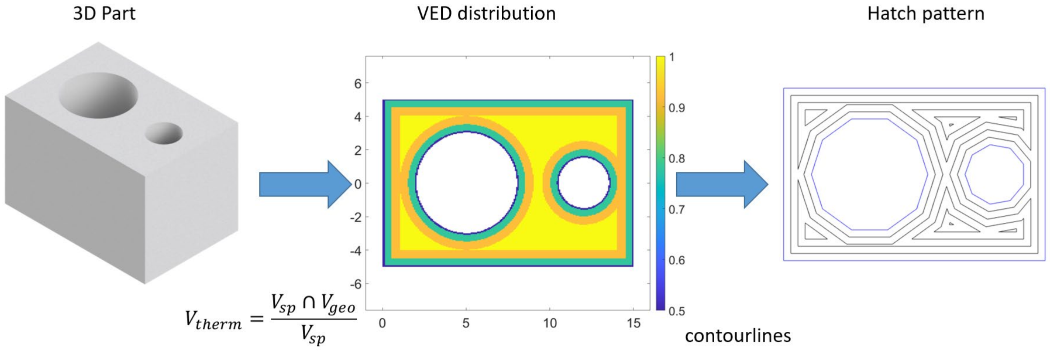
Using constant processing parameters, it is found, that the temperature is quite constant in regions far away from the outer surfaces of the component, because V_{therm} is not affected by the parts geometry. If the laser is approaching the boundary of the component, the thermally involved volume is influenced by the geometry of the component and the temperature rises significantly (cf. Fig. 1.). The temperature above the boiling point will lead to significant vaporization of the material which destabilizes the melting process and will lead to excessive fusion, which is the reason for the degraded surface quality. This result indicates that a stabilized process at the outer boundaries can be achieved by controlling the temperatures. This means that an adjustment of the laser parameters during the process is required.

3. Geometry dependent laser parameters

To stabilize the process at the component boundaries it is necessary to keep the deposited energy per thermally effected volume constant. This can be achieved by the introduction of a scaling variable for the laser parameters. If we assume that a high density is achieved for a given volumetric energy density

$$VED = \frac{P}{v\,h\,d}\ [\mathrm{J\ m^{-3}}]$$

where P [W] is the laser power and h [m] is the hatch distance, we can define a localized energy by scaling the VED with the thermally involved volume V_{therm}. Which by definition is the intersection of the volume of the semi-spherical diffusion profile V_{sp} and the volume of the already fabricated part V_{geo}.



$$V_{therm} = \frac{V_{sp} \cap V_{geo}}{V_{sp}}$$

Fig. 2. Schematic of the slicing process to adapt the laser parameters to the thermally involved volume. For each layer the overlap of the dermal diffusion sphere with a radius corresponding to the thermal diffusion length needs to be calculated. With the overlap the required laser energy is defined as a function of the laser position. The hatch pattern is then given by the contour lines of equal energy.

To transfer this approach to the experiment, the calculation of the energy distribution is required during the slicing process. A schematic of the approach for an extruded structure is given in Fig. 2. For any layer the overlap volume V_{therm} needs to be calculated, which defines the required energy for any point. To avoid constantly changing laser parameters during hatching the hatch pattern is selected to be contour lines of equal energy on this distribution. Thereby any hatch line has constant process parameters.

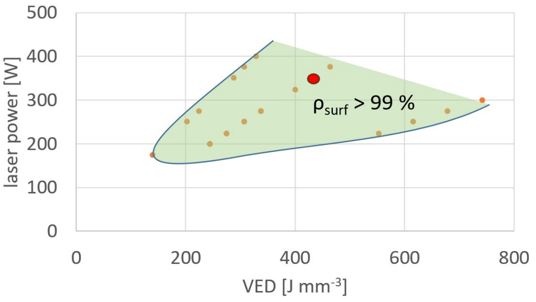


Fig. 3. Laser power as a function of the volumetric energy density. The data points represented the set of laser parameters for which relative densities above 99 % were achieved. The green colored area serves as a guide to the eye indicating the usable parameter window.

4. Experimental realization

To test the approach, we used the same setup described in a previous article [Kohl et al.] using a continuous wave fiber laser at a laser wavelength of 1070 nm. The laser parameters were chosen to be in the middle of the usable parameter field for high densities (cf. Fig. 3). This guarantees high densities despite variations in laser power. The laser parameters were as follows:

Laser power:	350 W
Ø Laser spot:	30 µm
Scanning speed:	500 mm s^{-1}
Hatch distance:	80 µm
Layer height:	20 µm

As mentioned in Section 2. the thermal diffusion length, which is required to define the semi-sphere diameter depends on the thermal diffusivity and an effective dwell time. The latter is not easy to predict, since it is very sensitive to the melt pool dynamics. The single line width corresponding to the laser parameters was found to be a good approximation, in this case around 250 µm.

5. Results

As a test structure, a cylinder with highly resolved features in the center was produced. In Fig. 4. a) The as build part is shown, for the microscopic picture the last layers were removed by grinding to increase the contrast between part and cavity which otherwise is limited by the depth of field. The adjustment of the laser parameters and hatching along the contour as given by the hatching algorithm enables the fabrication of features below 200 µm. Fig. 4. b) shows the measured surface profiles for two parts. The first one was fabricated with constant laser parameters which exhibits strong surface degradation effects caused by excessive fusion and the second fabricated by adjusting the laser parameters to the thermally involved volume.

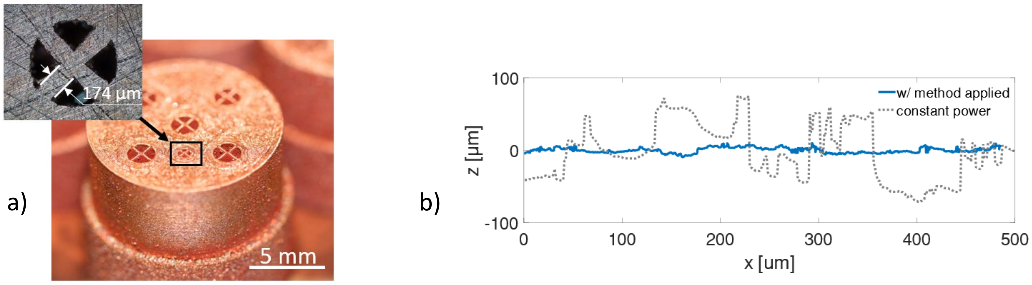


Fig. 4. a) Cylindrical structure to demonstrate the improvements in surface quality and resolution. The microscopic image of the fine structure in the top left was taken after grinding of the top surface. 4. b) Measured surface profile of a part fabricated with constant laser power (dotted gray) and for a part fabricated using the geometry dependent adjustment of the laser parameters (solid blue).

The average surface roughness (cf. Fig. 4.) on the later part was measured perpendicular and parallel to the build direction to 2.8 µm and 3.1 µm, respectively.

6. Conclusion

Additively manufactured pure copper parts usually exhibit a high surface roughness, which results in a poor resolution. In this work, it was demonstrated how a simple approach adjusting the laser parameters to the thermally effected volume can significantly increase the surface quality and resolution of those parts. The used model can be reduced to a purely geometric problem. This makes it easy to implement and computationally efficient. Furthermore, all required parameters can be determined experimentally. By applying the model, a mean surface roughness around 3 µm was achieved. To the best of our knowledge, these are the best as-built results for parts fabricated using the laser assisted powder bed fusion of pure copper.

Conflicts of Interest

A patent application was filed for the method to improve the surface quality and resolution via geometry-dependent laser parameter adjustment.

References

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