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Scaling precision and build rate in additively manufactured components by melt pool control

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Abstract: Additive manufacturing (AM) enables the fabrication of customized components. In medical applications where components contain both dense and lattice material, the process has a significant influence on the design process impacting mechanical properties and manufacturing accuracy. Currently, both build rate and strut thickness of thin-walled lattices cannot be scaled leading to low build rates, inaccurately fabricated lattices, and high unit costs. Here, a method is presented to determine the melt pool geometry material independently. The proposed scaling laws can be utilized for scaling the build rate, precise fabrication of thin-walled lattice structures, and correlating process parameters with resulting component properties.

I. Introduction

Laser powder bed fusion (LPBF), the most prominent representative of ´AM technologies, enables a new degree of freedom for customized and complex products such as medical implants containing both dense and lattice material. The reliable fabrication of lattice structures, its integration to the dense component, and prediction of mechanical properties require customized process parameter development [1]. Therefore, melt pool control to correlate melt pool geometry with process parameters and thermophysical material properties [2,3] is crucial for manufacturing the lattice structures with the as-designed mechanical properties and quality, such as porosity, particle adhesion, and surface roughness. Maximizing the build rate $\dot{V}$ to reduce unit cost while maintaining the technical requirements is thus highly desired. The build rate is defined as

$$\dot{V} = l_s d_h v, \tag{1}$$

where l_s, d_h, and v are the layer thickness, hatch distance, and scan speed.

Characterizing the melt pool geometry during LPBF is researched extensively because it can indicate melt pool dynamics and spatter formation during melting, the size-dependent cooling rate determines residual stresses, and it serves as a quantity to determine the resulting porosity as well as melt track stability. Accordingly, accurate modeling of the melt pool is highly interested in research [2-4,6]. It could be shown, that the melt pool depth d correlates with the specific enthalpy

$$d \propto \frac{\Delta H}{h_s} = \frac{A\,P}{\pi\,\rho c_p\,\Delta T\,\sqrt{Dv\sigma^3}}, \tag{2}$$

where $A, P, \rho c_p, \Delta T, D$, and σ are the absorptivity, laser power, specific heat capacity, the difference between liquidus and source temperature, thermal diffusivity, and laser beam diameter [4]. The melt pool width w can further be described by the function

$$w \approx \sqrt{\frac{P}{v} \cdot \frac{8\,A\,D}{e\,\pi\,\lambda\,\Delta T}}, \tag{3}$$

where λ denotes the conductivity [5]. Such scaling laws as well as dimensionless numbers characterizing the melt pool find increasing consideration in research [6]. However, efficient, material-independent and closed-form analytical solutions to utilize the melt pool geometry in the component design process are rarely available in the current literature.

In recent publications [2,3] we have derived non-dimensional numbers, i.e. Peclet number Pe and specific laser power P_+

$$\mathrm{Pe} = \frac{wv\rho c}{\lambda}, \mathrm{P}_+ = \frac{APv\rho c}{\lambda^2 \Delta T}, \tag{4}$$

showing a physical correlation between process parameters, thermophysical properties, and melt pool width. This material-independent correlation enables the utilization of the melt pool geometry as a design quantity for thin-walled lattice structures. The coefficients are dependent on the exposure type and need to be determined experimentally. This has been done for single scan tracks [2], two adjacent scan tracks [3], and contour exposure [1]. Here, we introduce two further exposure strategies and show in an exemplary application, how these scaling laws can be used to obtain customized functionally graded thin-walled components, such as medical implants.

II. Material and methods

The experiments have been carried out on an EOS M 290 machine using commercially available AlSi10Mg powder. For the single track, double track (rectangular cross-section), and contour (circular cross-section) exposure with a constant hatch distance of 100 µm, the experimental conditions are described in previous publications [1-3]. To

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obtain thinner struts, point exposure has been investigated. The struts were printed in cups (Fig. 1), filled with resin, ground, and measured under a light microscope ZEISS Axioskop A1 HAL 100. The laser power has been varied between 100 and 350 W, scan speed between 50 and 4500 mm/s. Beam diameter, layer thickness, and build plate temperature were held constantly at 80 µm, 30 µm, and 160 °C, respectively.

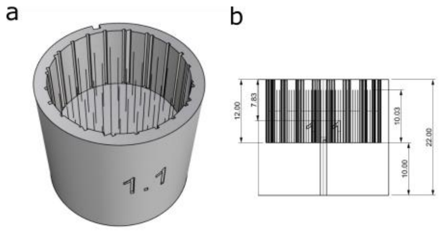

Figure 1: Cups with struts printed by point exposure with different laser powers and exposure times to determine the influence on the strut thickness. (a) schematic picture, (b) sketch with dimensions.

III. Results and discussion

The melt pool formation follows the scaling law $\mathrm{Pe} = b\ \mathrm{P}_+^t$, where b and t are constants that need to be determined experimentally. The scaling law predicts the melt pool width independently of the chosen material, which has been demonstrated for the commercially available alloys 316L, IN625, AlMgSc, AlSi10Mg, MS1, and Ti6Al4V [2,3].

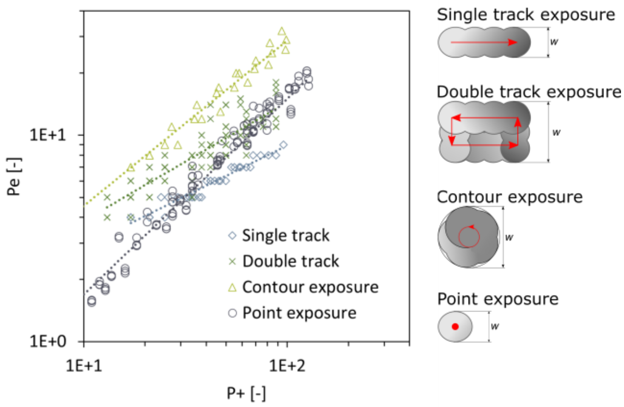

Figure 2: Non-dimensional correlation of melt pool width, thermophysical properties, and process parameters for different exposure strategies.

However, the coefficients vary for different exposure strategies, as is demonstrated in Fig. 2 for single track, double track, contour, and point exposure.

Table 1: Coefficients for melt pool width scaling law for different exposure types

Exposure	b	t
Single track	0.94	0.49
Double track	1.02	0.57
Contour	0,72	0.8
Point	0.19	0.94

It is evident from Table 1 that higher local energy input, as is the case for contour exposure with circular cross-section and point exposure, leads to different coefficients of the scaling law. Here, a non-solidified melt pool is present during the entire exposure leading to higher enthalpies, cf. Eq. (2). This circumstance results in larger melt pools, as represented in Eqs. (2) and (3).

Being able to scale the melt pool and resulting strut thickness of a component enables the manufacturing of customized functionally graded structures such as medical implants. For demonstration purposes, a bionic maple seed has been developed with topology optimization yielding struts with different strut thicknesses.

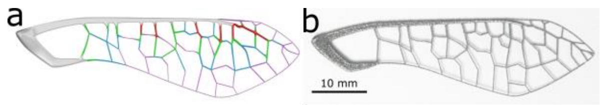

Figure 3: Design and manufacturing of a thin-walled airwing using scaling laws to obtain customized as-designed strut thicknesses

The designed structure shown in Fig. 3 was realized in manufacturing by segmenting the struts and assigning the corresponding process parameters obtained from the scaling laws in Fig. 2.

IV. Conclusions

Scaling law coefficients to determine the melt pool width have been determined for different exposure types allowing a precise manufacturing of strut thicknesses between 106 and 564 µm. and were utilized to fabricate a bionic maple seed as designed. The research presented enables users of LPBF to utilize the process in the design process to manufacturing customized thin-walled components. Future research should focus on enhancing the scaling laws and correlate additional process-relevant parameters with the melt pool geometry as well as finding correlations between quality features, e.g. porosity or surface roughness, and process as well as thermophysical properties.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

References

[1] A. Großmann, J. Gosmann, C. Mittelstedt, Lightweight lattice structures in selective laser melting: Design, fabrication and mechanical properties, Mater. Sci. Eng. A 766 (2019) 138356
[2] A. Großmann, J. Felger, T. Frölich, J. Gosmann, C. Mittelstedt, Melt pool controlled laser powder bed fusion for customised low-density lattice structures, Mater. Des. 181 (2019) 108054
[3] A. Großmann, J. Mölleney, T. Frölich, H. Merschroth, J. Felger, M. Weigold, A. Sielaff, C. Mittelstedt, Dimensionless process development for lattice structure design in laser powder bed fusion, Mater. Des. 194 (2020) 108952
[4] W.E. King, H.D. Barth, V.M. Castillo, G.F. Gallegos, J.W. Gibbs, D.E. Hahn, C. Kamath, A.M. Rubenchik, Observation of keyhole-mode laser melting in laser powder-bed fusion additive manufacturing, J. Mater. Process. Technol. 214 (2014) 2915-2925
[5] M. Tang, P.C. Pistorius, J.L. Beuth, Prediction of lack-of-fusion porosity for powder bed fusion, Addit. Manuf. 14 (2017) 39-48
[6] T. Mukherjee, V. Manvatkar, A. De, T. DebRoy, Dimensionless numbers in additive manufacturing, J. Appl. Phys. 121 (2017) 064904