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The steady state of the residual temperature in additive manufacturing processes

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Abstract

The periodic energy input during additive manufacturing results in an accumulation of heat. The residual heat in previously added layers or beads increases the local temperature as new hot material is added. This may results in inhomogeneous distortion and inhomogeneous grain structures in subsequent layers or beads. In this work, the local temperature increase is described by an analytical model to compute the convergence of the residual temperature to a steady state for different additive manufacturing processes. The model is validated by means of infrared imaging during direct energy deposition and thermo-couple measurements during laser powder bed fusion. We demonstrate that the presence of a steady state temperature distribution during additive manufacturing is strongly dependent upon the thermal diffusivity of the material. Furthermore, the model indicates that materials with a high thermal diffusivity, for example Aluminium, require high laser power and high velocity to achieve steady state temperature during additive manufacturing.

Keywords: Additive Manufacturing; Direct Energy Deposition; Heat Accumulation; Cladding; Temperature Field

1. Introduction

Most additive manufacturing processes have in common that complex component geometries are produced by a multitude of single beads and layers added subsequentially in the molten phase. This sequential addition of molten material results in a periodic heat input, which may accumulate and lead to a continuous increase in residual heat in the part. This is accurately modelled by the method described in Hagenlocher et al., 2022a. The black curve in Fig. 1 presents the calculated periodic heating and cooling, which results from the sequential addition of molten material during DED-manufacturing of steel parts. The closed circles represent the residual temperature, calculated according to Hagenlocher et al., 2022a, which is still present at the process zone when the next layer is added.

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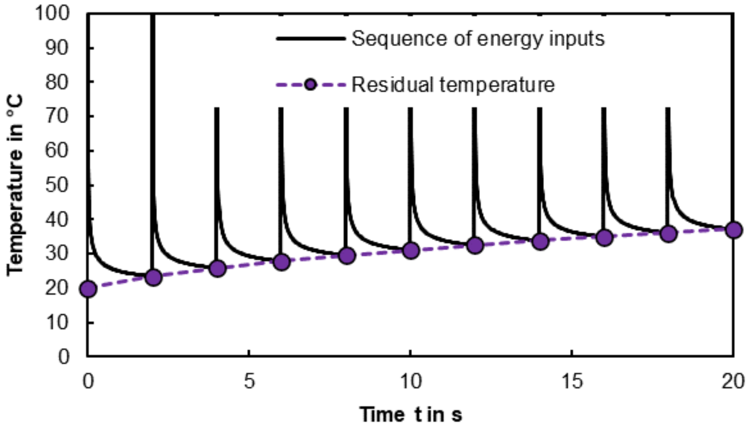

Fig. 1: Increase of temperature during DED-manufacturing of steel parts with a laser power of 3000W and a velocity of 3 m/min calculated according to the equations presented by Hagenlocher et al., 2022a, which are implemented in Python, see https://doi.org/10.18419/darus-2609

The heat accumulation effect was experimentally captured in the case of layer-wise material addition in laser direct energy deposition (DED-LB) processes by Hagenlocher et al., 2022c, Froend et al., 2019, and in Laser powder bed fusion (PBF-LB) processes by Chiumenti et al., 2017b. The accumulation of heat from bead to bead during cladding or additive manufacturing was shown in the work of Chiumenti et al., 2017a or by Ya et al., 2016 for DED-processes and by Denlinger et al., 2016 for LPBF-processes.

As described in Hagenlocher et al., 2022b, the continuous increase of the residual temperature results in a continuous change of the local temperature gradients and growth rates during solidification. This leads to an inhomogeneous grain structure in the final part, as presented in Hagenlocher et al., 2022c, which may impair the development of favorable mechanical characteristics in the printed part.

In order to produce parts with homogeneous grain structures and mechanical characteristics, a steady state of the residual temperature is sought instead of a continual increase. To describe the requirements for a steady state of the residual temperature, the equations presented by Hagenlocher et al., 2022a are analyzed for a convergence criterion. This identifies the crucial process parameters and material characteristics and enables the development of process strategies to achieve a steady state of the residual temperature in additive manufacturing and cladding processes.

2. Model

Fig. 2 sketches the heat flow in red, the coordinates in purple and the geometric quantities in black, as considered in Hagenlocher et al., 2022a to calculate the residual temperature, which results from a) layer-to-layer accumulation and from b) bead-to-bead heat accumulation.

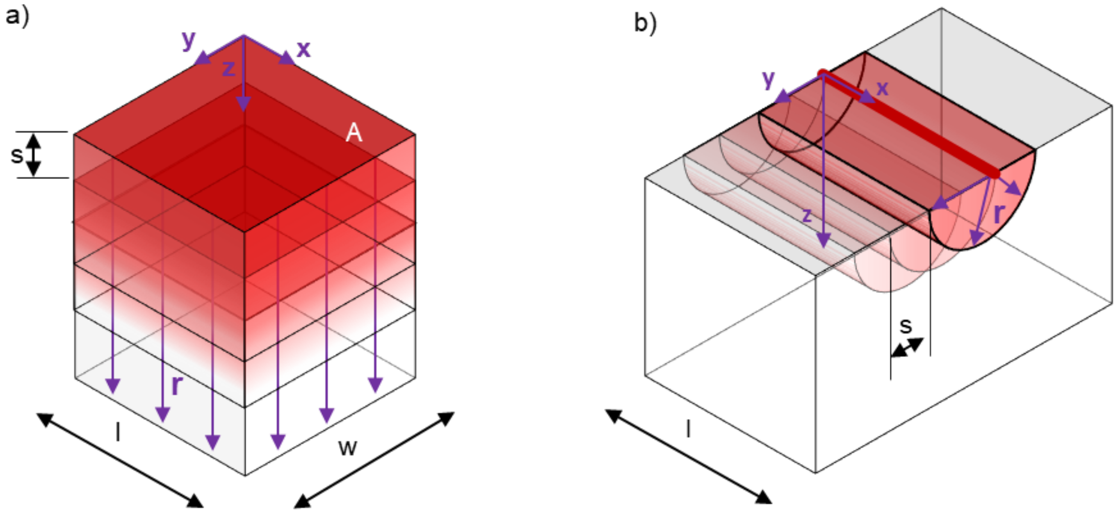

Fig. 2: (a) Sketch of the considered 1D heat flow in case of a layer-to-layer heat accumulation; (b) 2D heat flow in case of a bead-to-bead heat accumulation.

As shown in Hagenlocher et al., 2022a the increase of the residual temperature in the case of a layer-to-layer heat accumulation, as sketched in Fig. 2a, is described by

$$T_{Res}(r, N_L) = T_0 + \frac{1}{\rho \cdot c_p \cdot \sqrt{4\pi \cdot \kappa}} \cdot \sum_{N=1}^{N_L} \frac{Q_L}{\sqrt{N/f}} \cdot e^{\frac{-f}{N} \cdot \frac{(r-N\cdot s)^2}{4\cdot\kappa}} \tag{1}$$

and in case of a bead-to-bead accumulation, as sketched in Fig. 2b, by the sum

$$T_{Res}(r, N_B) = T_0 + \frac{1}{\rho \cdot c_p \cdot 4\pi \cdot \kappa} \cdot \sum_{N=1}^{N_B} \frac{Q_B}{N/f} \cdot e^{\frac{-f}{N} \cdot \frac{(r-N\cdot s)^2}{4\cdot\kappa}} \tag{2}$$

as a function of the coordinate r, which is the local distance to the current position of the considered heat source, and the number of added layers N_L or beads N_B. The material characteristics are included by the density ρ, the heat capacity c_p, and the thermal diffusivity κ. T_0 is the ambient temperature. The process parameters are represented by the frequency of layer addition or bead addition f and the layer thickness $s = s_L$ or hatching distance $s = s_H$. The energy of one layer $Q_L = \frac{Q_{heat}}{A}$ is normalized to the area of the layer and the energy of one bead $Q_B = \frac{Q_{heat}}{l}$ is normalized to the length of the bead.

The convergence analysis presented in Hagenlocher et al., 2022a results in the formulation

$$\lim_{N_A\to\infty} \Delta T_{Res}(N, r=0) = \begin{cases} \infty & for\ f\cdot s^2 \ll 4\cdot\kappa \\ \dfrac{Q_{nD}}{\rho\cdot c_p\cdot\sqrt{\left(\dfrac{4\pi\cdot\kappa}{f}\right)^{n_D}}}\cdot Li_{\left(\frac{n_D}{2}\right)}\left(e^{-\frac{f\cdot s^2}{4\cdot\kappa}}\right) & for\ f\cdot s^2 \approx 4\cdot\kappa \\ not\ valid & for\ f\cdot s^2 \gg 4\cdot\kappa \end{cases} \qquad (3)$$

which states, that a convergence of the residual temperature is present if $f\cdot s^2 \approx 4\cdot\kappa$. $Li_{\left(\frac{n_D}{2}\right)}$ is the polylogarithmic function of the $\frac{n_D}{2}$ order. The dimension of heat conduction is considered by n_D, which is $n_D = 1$ in the case of a layer-to-layer heat accumulation (Fig. 2a) and $n_D = 2$ in the case of a bead-to-bead heat accumulation (Fig. 2a). From these equations, one can conclude that to achieve a steady state of the residual temperature in additive manufacturing of materials with high thermal diffusivity κ, requires higher frequencies of material addition or larger layer thickness/hatching distance. As discussed in Hagenlocher et al., 2022a, these findings explain the presence of a steady state residual temperature in the majority of literature about additive manufacturing of Titanium, which has a very low thermal diffusivity compared to Aluminium.

3. Steady state in cladding processes

To analyze the steady state of the residual temperature during cladding of a steel substrate, equation (2) was solved for different frequencies. Assuming a constant layer thickness s_L and a constant hatching distance of $s_H = s_L$ = 0.5 mm and a rectangular cross section of the bead, the required minimum line energy

$$Q_B = s_H\cdot s_L\cdot\rho\cdot(T_{liq}\cdot c_p + h_s) \qquad (4)$$

results from the area of the cross section, $s_H\cdot s_L$, which must be molten per added unit length of the bead. For the sake of simplification, the material characteristics were assumed to be constant as listed in Table 1:

Table 1. Material characteristics of steel

Quantity	abbreviation	value	unit
Density	ρ	7800	kg/m³
Liquidus temperature	T_{liq}	1440	°C
Heat capacity	c_p	470	J/kg
Latent heat of fusion	h_s	290000	J/kg
Thermal diffusivity	κ	$7.9\cdot10^{-6}$	m²/s

The curves in Fig. 3 present the resulting residual temperature as a function of the number of added beads in the case of DED-LB cladding of a steel substrate with bead frequencies from 1 Hz up to 18 Hz, calculated according to equation (2) and (4) with the material characteristics listed in Table 1. The curves below 5 Hz

(blue, orange, and grey) show a consistent increase of the residual temperature, i.e. no steady state, within the first 50 beads. This agrees well with the criterion given in equation (3). The curves above 10 Hz clearly converge towards a constant temperature after adding more than 10 beads. This convergence demonstrates that a steady state of the residual temperature is present if the frequency is sufficiently high to meet the criterion
$f \cdot s^2 \approx 4 \cdot \kappa$, (equation (3)). Furthermore, the temperature of convergence increases with increasing frequency, which allows for an adjustment of preheating conditions during cladding.

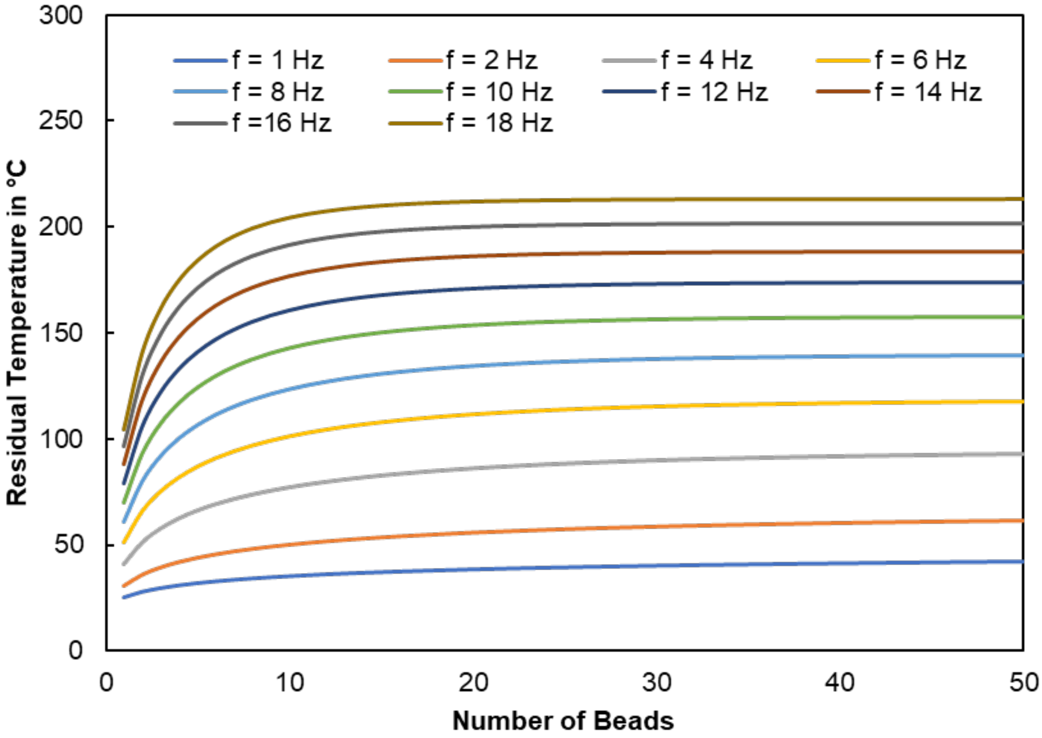

Fig. 3: Residual temperature during DED-cladding of steel with different bead frequencies

4. Conclusion

A constant temperature field, constant solidification, and homogeneous mechanical strength in additive manufacturing require a steady state of the residual temperature. The convergence analysis of the equations of Hagenlocher et al., 2022a leads to the criterion that there is no convergence of the residual temperature if the heat source moves much slower than the thermal diffusivity. This criterion can be captured by the inequality $f \cdot s^2 \ll 4 \cdot \kappa$, which compares the product between frequency of material addition f and the squared layer thickness/hatching distance s^2 with a multiple of the thermal diffusivity $4 \cdot \kappa$. These results show that for the example of cladding a steel substrate, with layer thickness and hatching distance of s = 0.5 mm, a steady state residual temperature is achieved after approximately 10 beads in the case of bead frequencies above 10 Hz. Future work will cover the adjustment of the temperature convergence to adjust the preheating conditions of the material for metallurgical optimization approaches.

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