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Procedia CIRP 67 (2018) 197 – 202

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11th CIRP Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME '17

Multi-scale modelling approach for contributing to reduced distortion in parts made by laser-based powder bed fusion

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Abstract

Within this paper, a control volume-based multi-scale approach for heat input modelling in laser-based powder bed fusion of metals is described. Thereby, the Rosenthal equation is used to analyse beam-powder interaction for a single laser track. Based on both the Rosenthal results for melt pool dimensions and experimentally determined melt pool depth, a single layer model is developed. Results for the temperature field, gathered by applying the single layer model, serve as data for validating the control volume-based approach on the build-up scale. Finally, a case study with a turbine blade delivers the proof-of-concept for the applied modelling approaches, because process-related distortions are reduced by more than 40 % through pre-deforming the blade according to build-up simulation results.

Peer-review under responsibility of the scientific committee of the 11th CIRP Conference on Intelligent Computation in Manufacturing Engineering

Keywords: Additive manufacturing; Powder bed fusion; Laser beam melting; Selective laser melting; Simulation; Distortion; Heat input modelling.

1. Introduction

Additive manufacturing technologies have been increasingly applied as production technology during the recent years. Originally, the only field of application for these technologies was the time-efficient production of prototypes – also known as Rapid Prototyping. During the last years, a significant increase in applications and business models [1] for direct part production could be observed [2,3]. Most applications were realized in the aerospace industry, the medical industry, and in the general engineering industry. Hereby, especially laser-based powder bed fusion of metals (terminology according to [4]: Laser Beam Melting) has gained significance as production technology [3]. [5,6] investigated this process and identified influencing process parameters.

However, process design for laser-based powder bed fusion of metals in order to manufacture distortion minimized parts is considered as almost impossible without simulation tools [7]. Therefore, multiple research groups have been working on simulation approaches that allow for e.g. predicting and, ultimately, pre-compensating distortions.

Nomenclature

a	absorption coefficient
c_p	specific heat capacity
d_F	laser focus diameter
d_s	layer thickness
e_h	element height
e_s	element length
h_{SVB}	height of layer compound
LB-PBF	Laser-based powder bed fusion of metals
λ	thermal conductivity
l_{SI}	edge length of the area surrounded by the melting isotherm
P_L	laser power
ρ	relative density
T_0	starting temperature
t_{SB}	depth of the melt pool
V_c	scanning velocity

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Peer-review under responsibility of the scientific committee of the 11th CIRP Conference on Intelligent Computation in Manufacturing Engineering
doi:10.1016/j.procir.2017.12.199

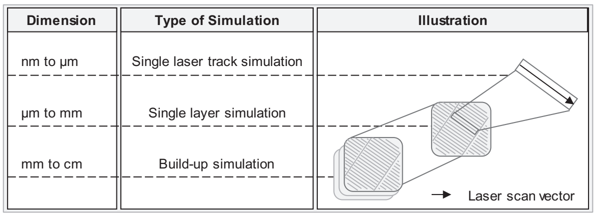

Fig. 1. Illustration of simulation approaches on different scales.

[8] describe a set of models developed at Lawrence Livermore National Laboratory (USA) to investigate beam-powder-interaction, microstructure development and also build-up models. To perform the simulation runs, a self-developed finite-element software as described by [9] is utilized. [10] and [11] provide an overview on simulation models for laser-based powder bed fusion of metals developed at University of Louisville (USA). The focus of this group is on the development of specific numerical approaches that allow for time-efficient calculation of temperature fields during laser-based powder bed fusion of metals. Time-efficient approaches for the direct simulation of mechanical properties using the inherent strain-method are described by University Bremen (Germany) [12,13,14]. Sequentially coupled thermo-mechanical simulation models were introduced by Technical University of Munich (Germany) [15,16,17,18,19].

A common challenge of the presented state-of-the-art is the development of valid heat input models for the build-up simulation of parts. Multi-scale approaches demonstrated to be beneficial to increase understanding of the simulation of laser-based powder bed fusion of metals [20,21]. Within this contribution, a multi-scale approach is introduced to derive a validated heat input model for the build-up simulation of parts. The regarded scales are illustrated in Figure 1.

2. Multi-scale approach for heat input modelling

This section comprises explanations on the general setup of the structural model applied for this work to simulate process-related part distortions. One core element within this structural model, also referred to as build-up model, is heat input simulation which is in the focus of this contribution. In order to determine a both valid and computation time efficient heat input model, a multi-scale approach as introduced within subsection 2.2 was developed. The core elements within this approach are illustrated in Fig. 1 and described in subsections 2.3 and 2.4.

2.1. General setup of the overall applied structural model (build-up model) to simulate process-related part distortions

For the presented work, a sequentially coupled thermo-mechanical model was used. Therefore, temperature fields during build-up were calculated in a first step within a thermal simulation. These results were then used as thermal loads for the mechanical simulation. Core elements of the model have been described in previous work [23] and comprise:

- Geometry modelling on the basis of laser scan vectors provided in machine data [24]
- Isotropic material modelling on the basis of experimentally gathered material data [22]

The approach applied for heat input modelling is in the focus of this contribution and described within the following subsections.

2.2. Concept of the multi-scale approach

As described in section 1 of this work and also in [25], it is state of the art for build-up models not to represent a part with the layer thickness applied in the laser-based powder bed fusion machines (20 µm to 100 µm), but with layer compounds instead (250 µm to 1.000 µm). The main reason for the application of this abstraction is the reduction of the number of finite elements, calculation steps and ultimately calculation time needed [26]. As a result, challenges in terms of geometry, but also heat input modelling, have to be overcome. With regard to heat input modelling, there is a need for temporal and spatial abstraction, Fig. 2 illustrates the differences between real process and build-up model setup.

In contrast to single laser track or single layer modelling, whereby typically a moving heat source with the diameter of the molten pool is applied [8,21,26], heat input within a build-up simulation is modelled instantaneously on each layer compound as a whole or on segments of it [18,21,25,26].

The multi-scale approach, introduced within this work, contributes to determining the load parameters (load value, load time) to realize a plausible heat input modelling for layer compounds. The core assumption is that the layer compound, or respectively the regarded segment of it (cf. [25]), exhibits the same behaviour as a 3D control volume with the x-y-dimensions according to the melt pool and a depth in z-dimension that equals the height of the layer compound. For this reason, the three detailing levels of simulation (cf. Fig. 1) are needed to:

- determine melt pool dimensions (single laser track model)
- determine resulting temperatures through layer solidification (single layer model)
- be validated with regards to the applied heat input load parameters (build-up model)

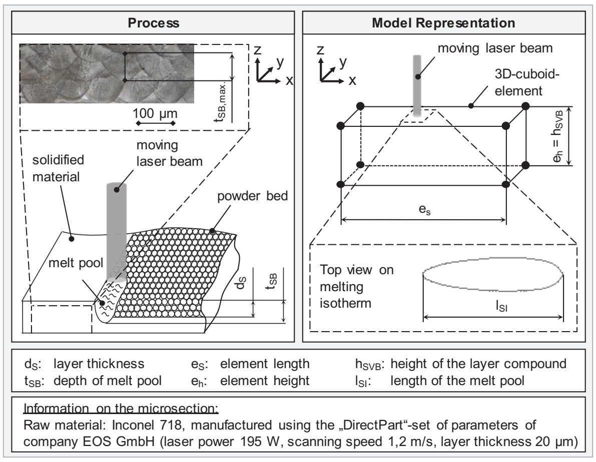

Fig. 2. Comparison of process and typical build-up simulation setup.