International Journal of Refractory Metals & Hard Materials 72 (2018) 1–8

Contents lists available at ScienceDirect

International Journal of Refractory Metals & Hard Materials

journal homepage: www.elsevier.com/locate/IJRMHM

Fundamental analysis of the influence of powder characteristics in Selective Laser Melting of molybdenum based on a multi-physical simulation model

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ARTICLE INFO

Keywords:
Selective Laser Melting
Multi-physical simulation
Powder
Molybdenum
Comsol Multiphysics
LIGGGHTS

ABSTRACT

Selective Laser Melting (SLM) offers great potential for the processing of molybdenum as it allows the production of parts that can hardly be fabricated in a classical way. The workpiece is built up by melting up powder layer by layer. Besides the applied laser parameters, the characteristics of the powder and the deposited powder layer have a crucial influence on the dynamics of the process and the final processing result. In order to get a fundamental understanding of these influences, numerical simulations are a versatile tool as they allow a detailed look on isolated parameters. In this contribution a coupled thermo-fluid dynamical simulation model for SLM is applied for a fundamental analysis of the influence of powder characteristics in SLM of molybdenum. The results allow a deeper insight into the influences of powder particle size and powder particle arrangement on the SLM process and the formation of the molten track.

1. Selective Laser Melting — a promising technology for the processing of molybdenum

In industrial manufacturing significant changes occur currently, caused by the increasing digitalization of production. Those changes due to the connection between production and information technologies are predicted to be as dramatic as those observed when mechanization, mass production and electronics led to revolutions of industrial fabrication in the past. Therefore, it is generally talked about the fourth industrial revolution or Industry 4.0 [1]. In order to make Industry 4.0 work new manufacturing technologies are required that allow a fast, precise, efficient and flexible fabrication of functional products from digital data. At this additive manufacturing by Selective Laser Melting (SLM) is highly promising as it allows the fabrication of fully functional metal machine and tool parts. SLM offers unique design possibilities at arbitrary lot sizes and is highly material efficient [2]. In SLM a workpiece is built up from a powder bed. A thin powder layer as well as a part of the subjacent layer is molten up by a laser controlled by a scanner system. When the material solidifies again, a melt metallurgic connection between adjacent and subjacent lines is formed. The building platform is lowered, a new powder layer is delivered and the process starts from the beginning [3]. At this layer-wise 3D printing of massive, metal free form components can be realized. The principle of SLM is shown in Fig. 1a. Fig. 1b shows the SLM process during operation. Whereas SLM of materials like aluminum, steel, titanium, nickel and cobalt chromium alloys is already well established and already applied in industrial production, the processing of molybdenum by SLM is still a big technical challenge as the processing window is significantly narrower. Nevertheless, for complex workpiece geometries, SLM is an attractive alternative to classical powder metallurgical fabrication routes and by a proper choice of processing parameters complex geometrical structures can be fabricated. Figs. 1c and d show examples of thin walled, tapered grid structures as well as massive demonstrator parts that were fabricated at Plansee SE by SLM of molybdenum.

For a successful, stable and repeatable processing of molybdenum by SLM a fundamental process understanding is essential. For this aim multi-physical transient process simulations are a powerful tool in order to analyze the process on a mesoscopic level, study defect formation mechanisms and to learn about the influence of processing parameters and powder characteristics on process dynamics and processing result. However, modelling of laser beam-matter interaction is a challenging task, as it requires a coupling between optics, thermo- and fluid-dynamics. Approaches for multi-physical laser beam-matter interaction modelling have been developed for a variety of laser processes [4–10] including SLM [11–15]. Similar models have been developed for the electron beam melting process [16–18]. At Plansee SE a thermo-fluid dynamical simulation model following those approaches was developed and applied for an analysis of SLM of molybdenum [19–22]. In this work a fundamental analysis of the influence of powder characteristics in SLM of molybdenum is performed. The results were presented at the 19th Plansee Seminar 2017 in Reutte (Austria) [23].

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https://doi.org/10.1016/j.ijrmhm.2017.11.034
Received 20 October 2017; Accepted 25 November 2017
Available online 01 December 2017

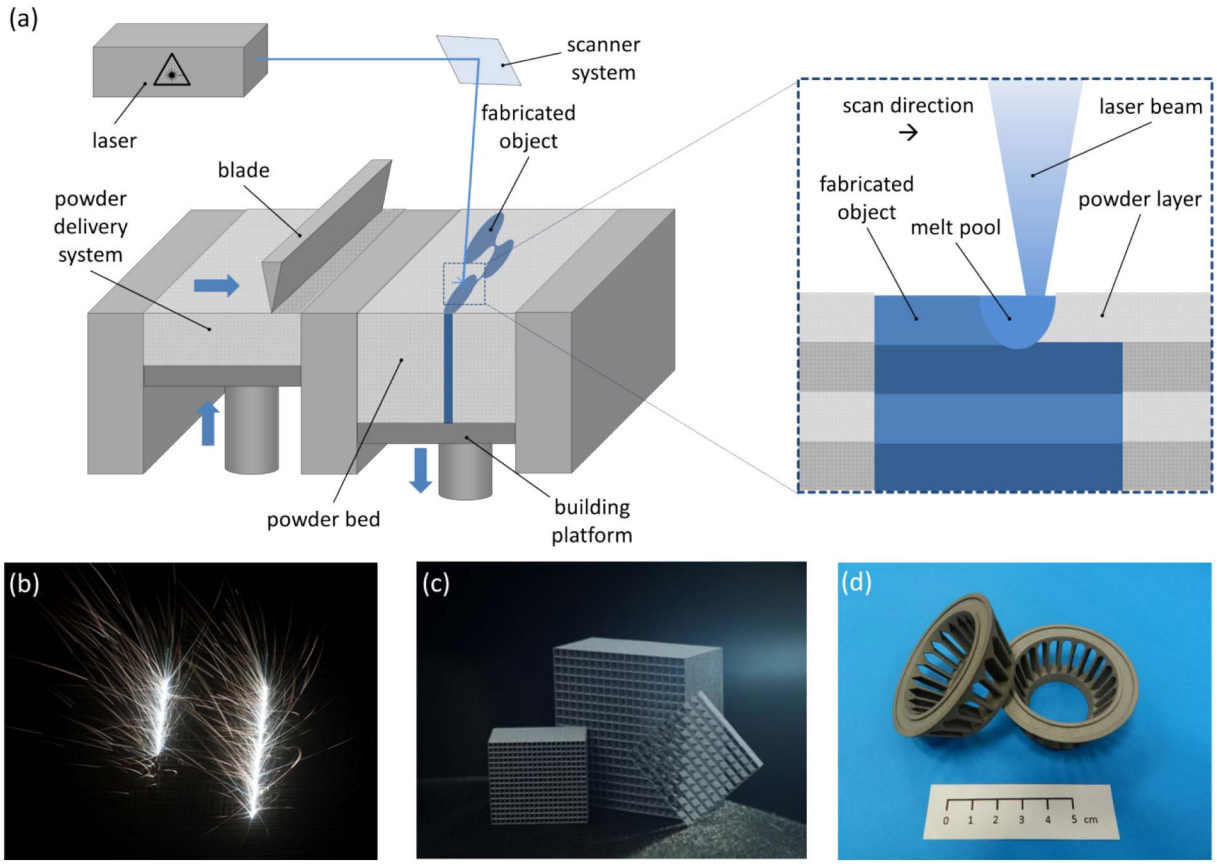

Fig. 1. Selective Laser Melting (SLM): (a) technology principle, (b) process during operation and (c, d) molybdenum demonstrator parts fabricated by SLM at Plansee SE.

2. Multi-physical simulation model for Selective Laser Melting

The multi-physical simulation model for SLM is based on Comsol Multiphysics. It includes the absorption of laser radiation on the metal surface, conductive and convective heat transfer in metal and atmosphere as well as melting, solidification, evaporation and condensation processes. The thermo-fluid dynamical multi-phase description is based on the phase field approach [24]. Depending on the temperature the model distinguishes between solid, liquid and vapor metal. The solid metal is treated as a high viscous fluid and the surface tension is restricted to the liquid phase. Evaporation modelling takes into account the density change between solid and vapor as well as the resulting mass flux by following an approach described in [25]. Fig. 2 shows a result obtained with the simulation model for SLM of steel at typical processing parameters for this material and demonstrates the included physics. The model geometry consists of a powder layer on a massive base plate. The laser radiation is absorbed on the top surface of the metal powder. The material heats up, a melt pool is formed and evaporation occurs. The laser moves along the powder bed and when the material solidifies again, the molten track is formed.

The simulation model uses temperature dependent material data taken from [26–30] (see Table 1). A detailed description of the simulation model, the contained physics and its implementation in Comsol Multiphysics can be found in [22]. In the past the model was applied in order to analyze the influence of process parameters in line and layer buildup from steel and molybdenum [19–21]. Fig. 3 shows simulation results for SLM of molybdenum at standard parameters for volume buildup. It was shown that the model is able to describe material specific differences in SLM. Whereas for steel at typical processing parameters there is a long melt pool and evaporation occurs (compare Fig. 2), for molybdenum the melt pool is significantly shorter and no evaporation can be observed in the simulation at the regarded parameters (compare Fig. 3). In accordance to experimental data the simulation results showed that for molybdenum the dependency of line width and surface roughness on the power P [W] is severely pronounced, whereas for steel the energy input ρ_E [J/m] is the dominant process parameter. This is due to the high thermal conductivity of molybdenum [19–21].

3. Simulation results and discussion

Beside material and processing parameters, in SLM the process dynamics and the processing result are also significantly determined by the characteristics of the deposited powder layer. Therefore, the multi-physical simulation model for SLM described in the previous section shall be applied as follows in order to analyze the influence of powder size and arrangement in SLM of molybdenum. Beside regular arrangements of powder particles in the powder bed (i.e. periodic simple cubic packaging), a more realistic powder distribution with irregular powder packaging obtained from a discrete element simulation model shall be considered.

3.1. Idealized powder arrangement

In a first step four idealized molybdenum powder arrangements on a massive base plate were considered in order to analyze the influence of particle size, layer thickness and packing density. The following powder configurations were compared to each other: one and two layers of simple cubic arranged 20 µm powder, one simple cubic layer of 40 µm powder and one layer of simple cubic 20 µm powder with one line of particles missing. Emanating from standard energy input $\rho_{E0,\ Mo}$ and standard power $P_{0,\ Mo}$ for volume buildup from molybdenum, the influences of a reduced relative energy input $\rho_E/\rho_{E0,\ Mo}$ and a reduced relative power $P/P_{0,\ Mo}$ were analyzed. Relative energy input $\rho_E/\rho_{E0,\ Mo}$