

Observation and numerical simulation of melt pool dynamic and beam powder interaction during selective electron beam melting

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Abstract

Selective electron beam melting (SEBM) is an additive manufacturing method used to produce complex parts in a layer-by-layer process utilizing Ti6Al4V powder. To improve the very good properties of built parts even more and to use the full capacity of the process, the fundamental understanding of the beam powder interaction is of essential relevance. Numerical simulations and observation with a high speed camera of powder melting show the strong melt pool dynamic and its lateral extent clearly. Furthermore, the immediate effect of beam parameters, e.g. beam current and velocity, on the melting behavior of the powder can be resolved in time steps of a few milliseconds.

Introduction

In the field of powder based additive manufacturing, selective electron beam melting represents an interesting alternative to established additive processes like laser melting. In both of the processes, beams are used to form complex and individual parts from metal powders, achieving very good mechanical properties. Among the advantages of the electron beam are high power, a high degree of efficiency and high speed. The beam can be deviated almost instantaneously reaching very high speeds, leading to a very high build speed. However, the overall potential of the electron beam cannot be used to full capacity neither regarding material diversity nor process speed. A substantial reason is the still incomplete understanding of the process.

The general aim of our research interest is to improve the understanding of the influence of process parameters such as the beam current, beam deviation speed and powder layer thickness on the parts quality. An improved understanding of the process could allow to find the process limits and to increase process speed, while maintaining the part quality. Simulation and observation of the melting process gives remarkable information on the melt pool movement and the shape, giving a good imagination of the process.

Experimental

EBM Process

The experimental setup, consisting of a *SEBM-S12* system from *Arcam AB* with additional observation equipment, is schematically shown in

Figure 1. The build takes place in a vacuum chamber containing the build tank, two powder hoppers as powder reservoirs and the rake system for the powder application. The electron beam gun is located on top of the vacuum chamber, emitting electrons from a doped tungsten filament, accelerated by a voltage of 60 kV. Electromagnetic lenses are used to

focus, deviate and form the beam's shape. Most of the kinetic energy of the electron beam on the powder bed is transformed into thermal energy. Dependant on the energy input, the powder particles are molten partially or entirely. The maximum build size in the *EBM-S12* is 200 mm x 200 mm x 250 mm, with a maximum beam power of 3.5 kW and a spot size between 0.2 mm and 1.0 mm, which is continuously adjustable. During the process pressure in the vacuum chamber is held at $2 \cdot 10^{-3}$ mbar with a low gas pressure of helium. The build rate for TiAl6V4 is approximately up to 60 cm³/h, depending on the amount of melting area. The powder is applied in layers with a layer thickness from 0.05 mm to 0.1 mm.

The parts are designed in a CAD program and later on sliced into layers of constant thickness. After preheating the steel start plate, the process itself is separated into four steps, schematically shown in Figure 2. The process starts preheating the powder layer with a defocused electron beam. For Ti 6Al 4V a temperature between 700 °C and 750°C is advantageous to reach a sintering of the loose powder but avoids a transition of the melting temperature. In the second step the powder is molten following the CAD contours with beam parameters, adapted to the structure and geometry of the part. This step is followed by lowering of the build table and applying a new powder layer ².

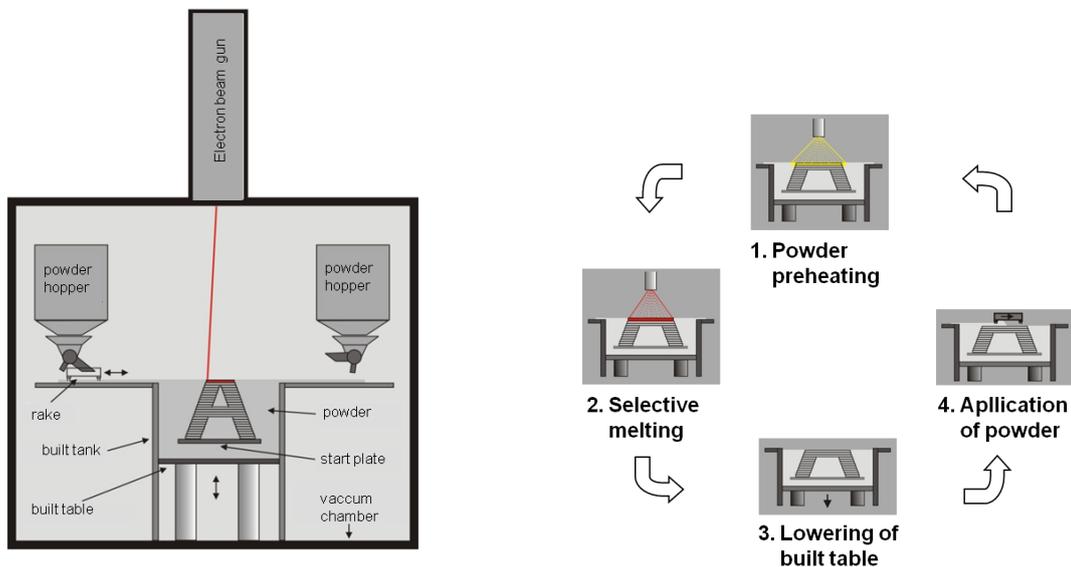


Figure 1: Schematic of the vacuum chamber with powder hoppers and part.¹

Figure 2: Circuit of process steps with preheating, melting, lowering of the table and application of new powder.¹

Finally part and powder cool down in a helium atmosphere. Powder blasting with Ti 6Al 4V powder is used to remove loose powder from the part. Hence, after sieving loose and blasted powder can be reused for the next build without difference in material properties¹.

The investigated process was the building of a hollow cylinder with a 2 mm diameter with a beam velocity of 160 mm/s and a beam power of 120 W. This way the influence of beam parameters on melt pool movement could be studied.

Process Observation

The basic understanding of the process and its parameters is essential for the improvement of process control. Therefore, an *ARCAM A2* machine has been equipped with a high speed camera of type *Photron Fastcam SA 3*.

The high speed camera provides a maximum of 120,000 fps with a maximum resolution of 1024 x 1024 pixels for lower frame rates. Due to the high image frequency a Cavitar Cavilux HF laser is required for illumination. Pictures and films recorded with the high speed camera offer valuable information regarding melt pool size and movement as well as their dependence on beam parameters and powder material parameters. The combination of the illumination laser together with a filter, transparent for the laser light, allows the observation of the process without any reflections and effects of the glowing of melt and powder.

A frame rate of 4,000 fps with a resolution of 640 x 640 pixels is the basis for the measurement of the melt pool life time. The total duration of the video is 675 ms with a frame interval of 0.25 ms.

Simulation

The numeric simulation of the EBM process is another very important tool employed in order to improve the process understanding. Therefore, a Lattice-Boltzmann method for free surface flows is used, which resolves the powder on the microscopic scale, consisting of individual powder particles. This method takes into account many of the physical phenomena involved in the process such as thermal conduction, melting, solidification and the fluid dynamics of the melt, governed by surface tension. This way, the melting process can be simulated in the vicinity of the beam.⁴ Especially the two phases of solid and liquid material, the movement of the liquid melt pool and the temperature distribution in the surrounding of the electron beam give insight into the interaction between beam and powder as well as the solidification behaviour.

The simulations show good agreement with the experimental results. Hence, the simulation appears to be a promising tool for the prediction of the process, particularly the influence of process and material parameters.

Results

The build of the hollow cylinder results in a circle in a two dimensional cross section (*Figure 3*). The high speed camera shows the interaction of the electron beam with the grey powder bed as a diffuse white point. The molten powder is visible as the black curved line. The diameter is 2 mm in the CAD contour, fitting into the cameras optical range.

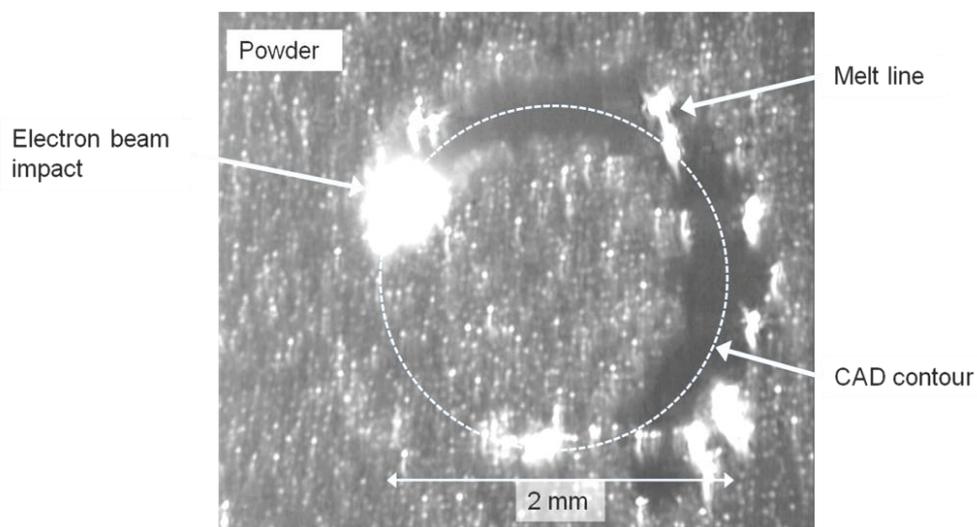


Figure 3: High speed camera image of a hollow cylinder with a diameter of 2mm.

Changing reflections indicate the movement of the melt pool. This involves the life time of the melt pool. Moving reflections indicate the phase state as liquid or solid. In time steps between two images of 0.25 ms (*Figure 4*) the time for moving reflections can be estimated with an accuracy of 0.5 ms.

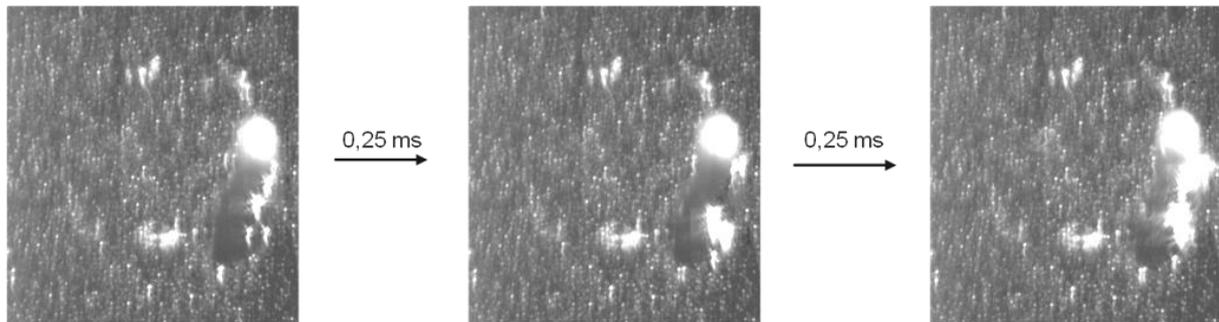


Figure 4: Image sequence of melting process in time steps of 0.25 ms.

Evaluating the sequence in single pictures (*Figure 5*) a life time of 10 ms can be assumed until there is no more movement in the molten line, meaning that there is no more changing reflection.

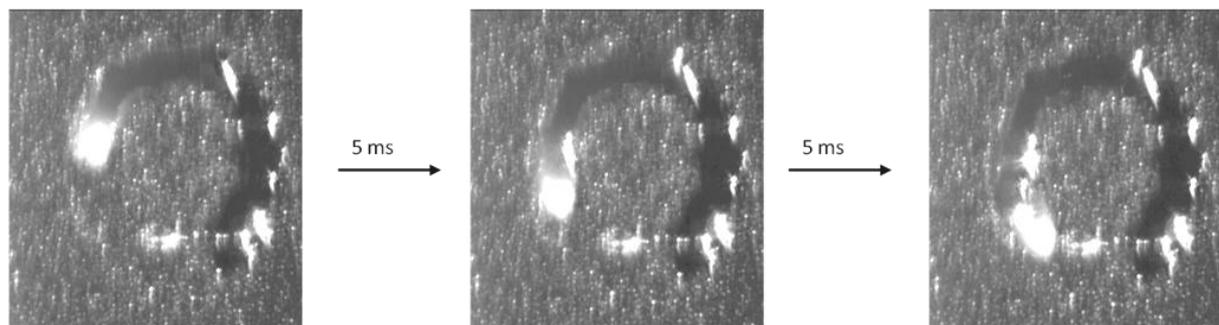


Figure 5: Solidifying melt pool with a time resolution of 5 ms per time step.

The speed of 160 mm/s the melt pool reaches a maximum length of 1.6 mm. The solidification front now exhibits the same speed as the electron beam. This is supposed to be the equilibrium state of beam movement and solidification.

The results in simulation predict the same effect. Parameters used for the simulation are a beam energy of 3.0, a velocity of 0.02 a beam width of 350 μm and a voltage of 60 kV. *Figure 6* shows the melting of the powder with its vigorous moving melt pool in a time step resolution of 0.45 ms. Temperature distribution in the building area and the distribution of fluid and solid material are shown in correlation to the beams position.

The movement in simulation is caused by the surface tension, attracting the melt to already solidified areas, especially the lower layer. The melt pool has a rather long life time and is moving vigorously. However, for the short lines, investigated primarily because of limited computational power, an equilibrium state between the solidification speed and the beam deviation velocity cannot be achieved. A reason for this is not accounting for evaporation and radiation losses at the surface.

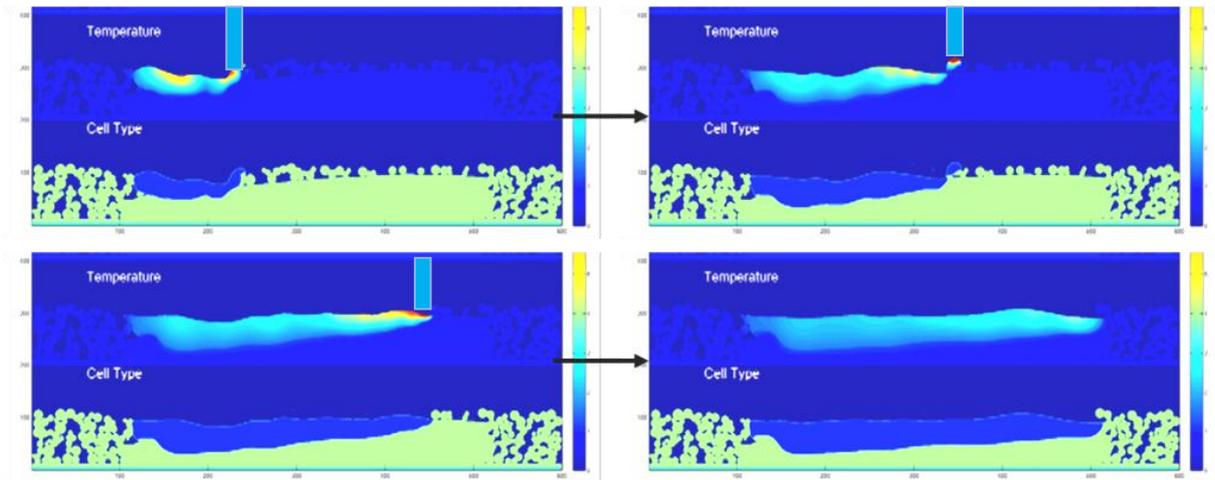


Figure 6: Melting of a single line in simulation with time steps of 0.45 ms leading to liquid melt line. The pictures show the temperature distribution in the building area and the distribution of fluid and solid material. The beam parameters are a beam energy of 3.0, a velocity of 0.02 a beam width of 350 μm and a voltage of 60 kV. The beam is shown as a box.

Hence, the energy induced into the powder bed is generally significantly overestimated, resulting in a much bigger melt pool. The equilibrium length of the melt pool thus would exceed the size of the built line, which can be seen in *Figure 7*.

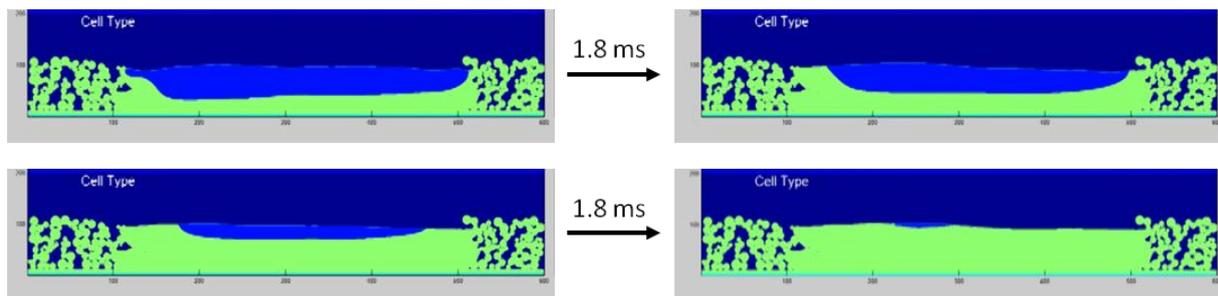


Figure 7: Simulation of a single line, with strong melt pool movement in three time steps. The simulation shows the cell type, fluid or solid for the material before interacting with the beam and afterwards. Parameters for the simulation are a beam energy of 3.0, a velocity of 0.02 a beam width of 350 μm and a voltage of 60 kV.

Conclusion

The melt pool is strongly moving and stays liquid for a long time of approximately 10 ms for the parameters used. Adjusting the scanning strategy on the melt pool life time is essential for a controlled process with defined contours. Therefore the observation allows the measuring of the melt pool length and its life time. The simulation gives quantitative, good according results showing the same effects regarding melt pool movement and life time.

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